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YUNIBESITHI YA PRETORIA

EFFECT OF SOIL NUTRIENT STATUS ON GROWTH, REPRODUCTIVE DEVELOPMENT AND YIELD COMPONENTS OF MAIZE IN A LONG TERM FIELD TRIAL

BY

ZAID ADEKUNLE BELLO

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LIST OF ABBREVIATIONS

B:	Boron
Ca:	Calcium
Cl:	Chlorine
O:	Control
Cu:	Copper
CGR:	Crop growth rate
FAO:	Food and Agriculture Organisation
FSSA:	Fertilizer Society of South Africa
g:	gram
ha:	hectare
IPAR	Intercepted photosynthetically active radiation
IPARP	Intercepted photosynthetically active radiation per plant
Fe:	Iron
Kg:	kilogram
LAD:	Leaf area duration
LAI:	Leaf area index
LSD:	Least significant difference
LAN:	Limestone ammonium nitrate
M:	Manure
Mg:	Magnesium
Mn:	Manganese
m:	meter
mm:	millimetre
M:	Molar
Mo:	Molybdenum
NAR:	Net assimilation rate
N:	Nitrogen
%:	Percentage
P:	Phosphorus
PAR:	Photosynthetically active radiation
K:	Potassium
RI	Radiation
RGR:	Relative growth rate

SAS:	Statistical Analysis System
S:	Sulphur
W:	Water
Zn:	Zinc

DECLARATION

I, Zaid Adekunle Bello, hereby declare that this dissertation for the degree M.Sc (Agric): Agronomy at the University of Pretoria is my own work and has never been submitted by myself at any other University. The research work reported is the result of my investigation, except where acknowledged.

Z. A. BELLO

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ABSTRACT

The research objectives were to examine the effect of soil nutrient status on the growth rate, reproductive development, yield components and yield of maize in a long-term trial. On the Experimental Farm of the University of Pretoria, treatments selected for this investigation were O (control), PK (nitrogen deficient), NK (phosphorus deficient), NP (potassium deficient), NPK (balanced nutrient), and WNPKM (mixture of balanced nutrient and manure). Growth analyses were performed, embryonic tassel and ear development recorded, developmental stages and rate of tasseling and silking were monitored while yield components were determined at maturity.

The balanced nutrient treatment (WNPKM) plants showed the highest growth rate and produced the highest biomass while the P and K deficient treatments resulted in low growth rates and low biomass. The PK and NPK treatments were intermediate in terms of growth rate and biomass production. The WNPKM, NPK and PK treatments exhibited a high net assimilation rate (NAR) and crop growth rate (CGR), illustrating that an adequate supply of N, P and K is required for high growth rate and biomass production.

Plants in the WNPKM plots exhibited early tassel initiation and ear differentiation and larger reproductive organs. Reproductive development in the PK treatment was ahead of those of the NP and NPK treatments. Nutrient stress delayed initiation and differentiation resulting in smaller reproductive organs. A linear relationship was found between leaf area indices (LAI) and the sizes of the reproductive structures. The higher the LAI the larger the size of the reproductive structures. Emergence of inflorescences was timely in plants exposed to the balanced nutrient but delayed in nutrient deficient treatments. Grain yield and the yield components were positively

affected by the balanced nutrient treatment while the nutrient stress treatments reduced the yield.

CHAPTER 1

GENERAL INTRODUCTION

Maize is the third most important food crop in the world following wheat and rice. Though it is grown over a wider range of climatic conditions than wheat and rice, production is limited to the warmer areas (Arnon, 1975). Maize is presently cultivated in more areas of the world than any other crop. The global production is approximately 600 million tons of grain, of which 50% is produced in developing countries (FAO, 2003). Maize is a staple food for a large percentage of the South African population. The maize industry stimulates the economy directly by providing secondary industries with over a billion Rands worth of business each year. Increased population pressure, high input costs, and extreme poverty force smallholder farmers to implement low input farming systems (Banziger *et al*., 1999).

Limiting factors for maize production in many developing countries include drought and insufficient levels of plant nutrients, especially nitrogen (N), phosphorus (P), and potassium (K). A vast amount of scientific information exists on the mineral nutrition of maize and suitable fertilizer guidelines are available for most situations (FSSA, 2000). Rational fertilization and management of soil fertility are among the most important of all farming practices to improve grain yield and water use efficiency, towards sustainable crop production that will be required to meet the food demand of the growing world population (Fan *et al*., 2005).

Long-term sustainability of agricultural systems can be realized through long-term experiments (Regmi *et al*., 2002; Camara *et al*., 2003). The advantages of long-term trials over short-term trials include the information gained regarding the sustainability of fertilizer treatments over a number of seasons. In long-term fertilizer trials, cropping over many years can exhaust initial adequate supplies of mineral nutrients in the soil. Over time, crop yields will reflect the sustainability of specific treatments. Experimental data obtained from long-term trials serve as a means of relating potential crop yield to the harvested yield obtained from different nutrient applications. Where the treatment combinations include unbalanced applications of N,

P, and K, such long-term trials provide the opportunity to characterise the reaction of the test crop to specific nutrient deficiencies. Many long-term experiments have been used to test effects of fertilization on grain yield and soil properties (Jenkinson, 1991; Wang *et al.,* 2002).

The long-term maize fertilization trial on the Experimental Farm of the University of Pretoria was initiated in 1939 and is a prime example of the contribution of such trials towards understanding the principles and practices of crop production (Nel *et al*., 1996). The wide range of soil fertility conditions, which have developed over the decades, are visible in the crop growth in this experiment.

To improve maize yield under nutrient stress situations, it is essential to understand how stress affects the components of yield, and at what stage of plant development the effects are initiated. Nutrient stress limits maize yield by affecting canopy size and duration and yield components like kernel numbers per row, total kernel number per cob and final kernel mass. Nutrient deficiency may delay differentiation of buds into cobs. Delayed silk emergence affects synchronisation with pollen availability and can decrease the grain filling period, and thus the potential grain yield. Very little information exists in the literature as to whether the potential size of maize cobs is actually determined soon after initiation, or whether the supply of assimilates and other growth substrates later in the pre-anthesis stage is the key factor.

The objectives of this research were to determine:

(1) the effect of soil nutrient status on growth of maize,
(2) the effect of soil nutrient status on development of the reproductive structures of maize,
(3) how the effect of soil fertility will be reflected in the yield components at maturity,
(4) the effect of soil nutrient status on grain yield and
(5) the influence of shading on reproductive development of maize.

CHAPTER 2

LITERATURE REVIEW

Maize is the most important crop in South Africa. Major factors limiting maize production include unpredictable climatic conditions, especially drought, soil acidity and nutrient deficiencies.

2.1 NUTRIENT STRESS

Environmental conditions that are not favourable will lead to plant stress. Tollenaar & Wu (1999) defined stress as a factor that causes, through its presence or absence, a reduction in yield. Consequently, stress is defined in terms of the plant's response to a causal factor. Management practices can alleviate stress either by modifying the plant genetically or by influencing the causal factor such that its impact on plant grain yield is reduced (Tollenaar & Wu, 1999). Nitrogen (N), phosphorus (P) and potassium (K) are essential nutritional elements for grain production in maize and often do not occur in sufficient quantities in the soil.

Nitrogen is a vital plant nutrient and a major yield-determining factor required for maize production (Adediran & Banjoko, 1995; Shanti *et al*., 1997). In cereals nitrogen deficiency is characterized by poor tillering, which severely reduces number of ears per unit area and the number of grains per ear (Mengel & Kirkby, 2001; Grundon, 1987). The grains are small but often higher in protein content due to the fact that carbohydrate imported into the grains is reduced (Mengel & Kirkby, 2001). Nitrogen deficiencies can cause damage to the photosynthetic factory of the crop. According to Below *et al.* (2000) nitrogen has a direct role in grain filling by controlling the ability of the kernel to utilize carbon. Silking and ear growth, which involves cell division and expansion of the grain, requires adequate nitrogen (Tollenaar, 1977). Ma *et al.* (1999) suggested that selection of hybrids which maintain uptake capacity as late as possible in the season should be coupled with a fertilization strategy that maintains high levels of soil nitrogen during the grain filling period.

Phosphorus often is a limiting nutrient in maize production. Maize with phosphorus deficiency is more likely to be found on soils with low organic matter, that has been depleted due to continuous cropping, highly weathered soil or where the topsoil has been lost due to erosion (Grundon, 1987). In cereals, where tillering is decreased, the plants may produce only one small ear with fewer, smaller kernels and reduced grain yield (Mengel & Kirkby, 2001; Grundon, 1987). Plenet *et al.* (2000a) observed a reduction in leaf size in P deficient maize, and resulting in reduced interception of solar radiation and consequently reduced biomass production and grain yield.

Potassium deficiency is more common on light sandy soils with low organic matter content and where K^+ has been leached (Grundon, 1987). Soils that have been heavily cropped and where K^+ is fixed into a non-exchangeable form can result in potassium deficiencies (Ulrich & Ohki, 1966). Potassium deficiency severely reduces maize yield as one small ear, which is often very pointed and underdeveloped at the tip, with kernels smaller than normal may be produced (Grundon, 1987). Potassium is highly required for rapid growth during pretasseling period (Welch & Flannery, 1985).

2.2 REPRODUCTIVE DEVELOPMENT

2.2.1 Tassel initiation and differentiation

During the early vegetative stage, leaves and axillary shoots are produced by the apical meristems and the internodes of the stem remain short. Initiation of the tassel at the elongated transitional stem tip signifies the beginning of reproductive development (Bonnett, 1954). It coincides with the time the basal internodes of the main stem begin to elongate. This stage may be reached as early as two weeks after emergence under favourable conditions (Kiesselbach, 1949; Galinat & Naylor, 1951). The first parts of the tassel to differentiate are the branch primordia. The primordia from which the spikelets initials differentiate are produced acropetally as long as the axes increase in length (Bonnett, 1954). Tassel development is completed when the anther dehiscents. While the tassel and its parts differentiate and develop, the axillary shoots undergo various stages of development to form the ear (Bonnett, 1954; Kiesselbach, 1949).

2.2.2 Ear initiation and differentiation

Ears differentiation is initiated from one or more of the axillary shoots of the stem soon after tassel differentiation has commenced (Bonnett, 1948; Kiesselbach, 1949). The axillary shoot is enclosed in a leaf-like structure called the prophyllum, which enlarges and persists as one of the husks. The early stages of ear development are similar to the corresponding stages in the development of the tassel, except that there are no branches on normal ears (Kiesselbach, 1949). Elongation of the growing point of the axillary shoot and the differentiation of lateral projections from the central axis of the ear initial is an indication of ear differentiation (Bonnett, 1948). The number of kernel rows per ear is determined by the number of rows of branch initials that differentiate. Each branch initial divide into two spikelet initials and each initial has one fertile flower in which a kernel is produced resulting in an even number of rows of kernels in maize cobs (Bonnett, 1948; Kiesselbach, 1949).

2.2.3 Influence of environmental conditions on reproductive development

Environmental conditions like moisture, drought, soil fertility and light intensity as well as duration affect reproductive development. Acker & Laubscher (1980) observed that day length affects initiation and differentiation of reproductive structures in different maize cultivars. Short day length hastens the rate of development in early maize genotypes more than in late genotypes. Unfavourable conditions in the early growth stages may reduce the number of silks that emerge, resulting in poor pollination of the ovules, which restrict the number of kernels that develop (Bassetti & Westgate, 1993). In an investigation carried out by Herrero & Johnson (1981) drought stress during flowering delayed silking until after all pollen had been shed. Low water potential does not affect pollen viability but prevents embryo development which leads to large losses in grain yield (Westgate & Boyer, 1986). Delayed ear differentiation and growth of ear primordia can be associated with barrenness in high plant populations (Jacobs & Pearson, 1991). A detrimental effect of high plant population may be due to a reduction in the number of spikelets differentiated per ear. Lemcoff & Loomis (1986) demonstrated that high densities may result in limiting carbon and nitrogen availability to the ear causing abortion after pollination.

2.3 INTERCEPTED RADIATION, GROWTH RATE, GRAIN YIELD AND SOURCE-SINK RELATIONSHIPS

Source and sink are functional descriptions of plant organs and tissues, recognizing their ability to supply or use a particular metabolic substance. Grain yield may be limited by the source strength, the sink capacity, or co-limited by both at a particular period in their growing cycle (Jones *et al*., 1996). In cereals, grain yield is mainly determined by the number of kernels per unit of land area (Fischer, 1975). This is strongly dependent on genotype, environmental and management factors (Egli, 1998). Important aspects of active plant growth include biomass accumulation and partitioning of assimilates to reproductive structures (Reekie & Bazzaz, 1987; Hartnett, 1990), which also serve as key determinants of crop yield (Andrade *et al*., 1999). Intercepted radiation, both pre- and post-anthesis, can be used as determinant variables of kernel set. In many studies, intercepted radiation per plant has a direct linear relationship with kernel set (Kiniry & Knievel, 1995; Otegui & Bonhomme, 1998). Andrade *et al.* (2000) observed a great response of number of kernels to intercepted photosynthetically active radiation (IPAR) in a plant population trial probably associated with high crop growth rate. During grain filling, a higher crop growth rate allow more grains to be set, leading to higher grain yields (Andrade *et al*., 1999). Kernel number per plant can be predicted from the intercepted photosynthetically active radiation per plant (IPARP) in maize. Grain yield in response to reduced row distance was closely related to the improvement in light interception during the pre-anthesis and post-anthesis stages. Therefore, the response of the grain yield to narrow rows can be analyzed in terms of the effect on the amount of radiation intercepted (RI) during the period of kernel set (Andrade *et al*., 2002).

Kernel number per plant is determined during anthesis as the potential kernel number is established at this period. During anthesis, plant growth rate per kernel can be used to estimate the source: sink ratio (Gambin *et al*., 2006). Biomass produced per kernel during the grain filling period was used to explain the maize source-sink relationship at this period (Uhart & Andrade, 1995; Borras & Otegui, 2001). According to Gambin *et al.* (2006) kernel mass is not controlled by the plant growth rate per kernel during the effective grain filling period but a linear relationship between final kernel mass and plant growth rate per kernel at the pre- and post-anthesis stages was reported.

Previous research on individual kernel sink potential have shown that kernel growth conditions early in grain development influenced their later growth (Gambin *et al*., 2006). Borras *et al.* (2004) confirmed that any decrease in the post-flowering source-sink ratio promoted a large reduction in final kernel mass, while increasing the ratio had minimum effect. The small kernel mass response to increased assimilate availability during the effective grain filling period suggests that maize plants set an individual kernel sink potential early in grain filling. Rajcan & Tollenaar (1999) used relative change in stover mass from silking to maturity in two maize hybrids to demonstrate early source-sink relationships for kernel development. Changes in the source: sink ratio during grain filling is frequently accompanied by a dramatic change in stover mass. The supply of assimilate by the sources and the demand of assimilate by the sinks is buffered by assimilates temporarily stored in the stover. Nutrient deficiencies affect both source and sink capacity, but from the available literature it is not clear whether specific deficiencies affect either source or sink to a larger extent.

2.4 EFFECT OF WATER AND NUTRIENT FACTORS ON GRAIN YIELD AND YIELD COMPONENTS

Maize grain yield can be described as a function of the rate and duration of dry matter accumulation by the individual kernels multiplied by the number of kernels per plant (Westgate *et al.,* 1997). The physiological condition of the crop at the flowering period is one of the determining factors of the yield components and grain yield at harvest (Jacobs & Pearson, 1991; Otegui & Andrade, 2000).

Water stress affected yield and yield components in an experiment performed by Kamara *et al.* (2003). For all the maize genotypes the grain yield, kernel number per ear and kernel mass were reduced due to a water deficit. Maize response to irrigation deficit varied with the nutrient status of the soil. The crop utilized water much more efficiently when adequate nutrients like nitrogen were available (Pandey *et al.,* 2000). Kernel number, kernel mass and number of cobs per unit area were similarly reduced. It was reported that maize yield declined as the plant population increased beyond the optimum plant density due to a decline in harvest index (Tollenaar *et al.,* 1997). Planting at a rate beyond optimum plant density leads to an increase in barrenness and

decreased kernel numbers per plant and kernel size. This is due to limited supplies of carbon and nitrogen caused by interplant competition for incident radiation, soil nutrients and soil water (Lemcoff & Loomis, 1994). In an experiment to determine the yield components of apical and subapical ears in prolific maize, kernels per plant was increased at low plant population due to increased kernels on the apical ears (Svecnjak *et al.,* 2006). However, the row number was not affected when either the apical or subapical ear was allowed to develop.

Nitrogen deficiency can reduce dry matter partitioned to the reproductive sink, resulting in a reduction in kernel number (Uhart & Andrade, 1995). According to Kogbe & Adediran (2003) grain yield increased with an increasing rate of nitrogen applied irrespective of the cultivars and the area. After the optimum rate of nitrogen fertilizer application was exceeded, the yield declined for all the cultivars. The time of application of nitrogen during crop growth affects the uptake and grain yield. Delaying application of nitrogen fertilizer on nitrogen deficient plots till the six leaf stage resulted in a decrease in grain yield of maize (Binder *et al.,* 2000). Bruns & Ebelhar (2006) also found that grain yield and kernel mass increased with increasing nitrogen fertility but no significant difference was observed in yield and kernel mass in potassium fertility treatments. In phosphorus and potassium trials, the deficient plots had the lowest yields for all the cultivars and at all locations.

2.5 IMPORTANCE OF LONG-TERM TRIALS

The importance of long-term trials has been well reviewed. Long-term experiments are indispensable sources of information. They are vitally important in monitoring, understanding and proving the changes in soil fertility occurring as a result of long-term cropping operations (Debreczeni & Korschens, 2003). Poulton (1995) concluded that long term trials are the best practical means of studying the effects on crop growth and soil properties of factors such as soil acidification or declining levels of organic matter.

Various interactions within the soil-plant-environment continuum are not well understood. Through long-term experiments some of these interactions will be

unravelled (Brown, 1991). Increasing crop production and soil fertility maintenance is of global importance. Poulton (1995) concluded that long-term experiments are valuable resources to be fully exploited in an attempt to understand those factors influencing soil fertility and sustainable production. Information from long-term trials can be used to develop or validate mathematical models. This can be used to predict the likely effects of management practices and climate change on soil properties, the productive capacity of soils and the wider environment (Johnston & Powlson, 1994).

This study will deal with the effect of soil nutrient status on growth rate of maize in the next chapter. The effect of soil nutrient status on development of reproductive structures, grain yield and yield components will be dealt with in consequent chapters respectively.

CHAPTER 3

EFFECT OF SOIL NUTRIENT STATUS ON GROWTH OF MAIZE

3.1 ABSTRACT

The effect of nutrient availability manifests early and is reflected in the performance of maize plants at all stages of development. This experiment was carried out to examine the effect of soil nutrient status on the growth of maize in a long-term trial. The parameters examined were leaf area index (LAI), leaf area duration (LAD), total dry mass, net assimilation rate (NAR), crop growth rate (CGR), and relative growth rate (RGR). Treatments selected for growth analysis were the O, PK, NK, NP, NPK, and WNPKM treatments. The WNPKM treatment (receiving macronutrients and organic manure) had the highest LAI (5.39), LAD (15.41weeks) and total above ground dry mass (90g/plant). Plants on the PK plots produced a reasonably large canopy (LAI 2.9, LAD 8.1 weeks) and dry mass of 33.8g per plant after 8 weeks. This is probably due to the capacity of the specific soil to store and supply nitrogen. The phosphorus deficient plots (NK and O) produced the smallest canopies, with LAI of 0.86 and 0.96, and LAD of 3.47 and 4.15 weeks respectively, and low dry mass of 4.85g and 7.09g per plant respectively. A linear relationship between leaf area duration and biomass was confirmed. The longer a large canopy is maintained, the more dry matter can be produced. The WNPKM, NPK and PK treatments exhibited high NAR and CGR values, illustrating that an adequate supply of N, P and K is required for efficient photosynthesis and biomass production. The O, NK and NP plots had low NAR and CGR values due to inefficiency of the canopies to intercept and convert solar radiation to dry matter, where the macronutrients N, P or K were deficient or not adequate.

3.2 INTRODUCTION

Maize is a member of grass family Poaceae. Nutrient deficiencies affect vegetative growth, reproductive development, and yield. The effect of nutrient stress in maize manifests early and is reflected in its performance at different stages of development. Nitrogen, phosphorus and potassium play important roles in maize nutrition. Deficiencies of any of these elements will restrict development of the plant.

Nitrogen, a component of chlorophyll, is a major yield-determining nutrient in maize production (Adediran & Banjoko, 1995). A nitrogen deficient plant is characterised by pale yellow leaves and poor growth. Nitrogen deficiencies produced maize with decreased growth, kernel number and grain yield and caused delays in both the vegetative and reproductive phenological stages (Uhart & Andrade, 1995). Lemcoff & Loomis (1994) observed that nitrogen stress reduced the leaf area and decreased kernel numbers and kernel size. Reduced kernel numbers resulted from a reduction in silk emergence due to decreased cell division. The benefit of nitrogen application depends on the degree of nitrogen deficiency. The greater the nitrogen deficiency, the earlier the nitrogen had to be applied for high grain yield (Binder *et al*., 2000).

Phosphorus is the major element involved in the conservation and transfer of energy. Phosphorus deficiency symptoms include dwarfism, purple colouration of leaves and malformed ears (Nel *et al*., 1996). Phosphorus deficient maize exhibit severe reductions in leaf area index (LAI), resulting in limited interception of solar energy, low biomass production and low yield (Plenet *et al*., 2000a & b).

Crops require large amounts of potassium compared to other minerals (FSSA, 2000). Main symptoms of a potassium deficiency are severe stunting, leaves with yellow stripes and necrotic margins, lodging and premature death of plants. Potassium deficiency retarded the rate of formation of chlorophyll in maize seedlings (Lawanson *et al.,* 1977). According to O`Toole *et al*. (1980) net photosynthetic rate decreased drastically in potassium deficient plants. Adequate levels of potassium promote stem strength, resistance to drought and improve fruit quality (FSSA, 2000). In an experiment performed by Premachandra *et al*. (1991) potassium nutrition increased production of maize exposed to drought stress.

Results from long-term trials are representative of cropping conditions over many years. Short-term experiments on the effect of nutrient deficiencies on different growth parameters often do not sufficiently explain the influence of nutrient stress. The advantage of long-term trials on plant nutrition is that the nutrient status of the soil are established over years and the long term sustainability of fertilizer application can be established. In short term field trials soil reserves may be just adequate to mask potential nutrient deficiencies or imbalances. On the Experimental Farm of the University of Pretoria a long-term maize fertilization trial was initiated in 1939 (Nel *et al*., 1996). This trial presents a unique opportunity to characterise the reaction of the test crop to a wide range of soil fertility situations.

The objectives of this chapter are to examine the effect of soil nutrient status on the growth rate of maize in a long-term trial. The effect of nutrient stress on leaf area index, dry mass production, net assimilation rate, crop growth rate and relative growth rate were determined.

3.3 MATERIALS AND METHODS

Observations were carried out on the long-term fertilization trial on the Experimental Farm of the University of Pretoria (25°45′ N, 28°16′ E). It lies at an altitude of 1372m above sea level in a warm summer rainfall area. The field trial was established in 1939 and is one of the oldest field experiments in southern Africa. The aim of the experiment was to investigate the long-term effects of organic and inorganic amendments on soil properties and yield of maize (Nel *et al.,* 1996).

3.3.1 FERTILIZATION TREATMENTS AND EXPERIMENTAL DESIGN

The general layout of the experiment is a randomised block design with four replicates. Originally there were 32 treatments combinations factorially arranged with five factors; nitrogen (N), phosphorus (P), potassium (K), water (W), and manure (M). Each factor is represented at two levels resulting in a 2^5 factorial experiment with four replications and 128 plots. The treatments selected for this growth analysis experiment were O (control), PK, NK, NP, NPK, and WNPKM. These treatments represent a range of soil fertility levels, which have developed over more than 65 years. The present soil fertility status of the selected treatments is summarized in Table 3.1. As can be seen in Table 3.1 the experimental treatments since 1939 have affected the chemical composition of the soil to such an extent that it is not strictly correct to interpret the treatment effects simply in terms of different levels of available N, P and K. Much more complex fertility regimes were created over the years, but the original treatment terminology of N, P, K combinations are retained in this report for the sake of clarity. Apart from N, P, K levels differences occur in soil pH, content of Ca, Mg, Fe, Zn and other essential elements. A phenomenon that requires much more attention is the similar levels of total nitrogen in the soil of different treatments, even on plots, which have received no nitrogen fertilization. This may partly be explained by nitrogen present in rainwater and irrigation water, but adequate information was not available. Contributing factors may also be the differences between plots in the activity of denitrifying bacteria. This is an aspect worthy of an in depth study, but not addressed in this thesis.

Each plot has a gross size of 8.32 by 6.30 m and a net of 7.47 by 4.93 m. Soil dikes surround each plot to prevent runoff. Marais (1948) reported that the experimental field was under dryland maize cropping, between 1921 and 1938 before initiation of the experiment and no fertilizer was used. Field pea was grown in rotation with maize until 1989. Preceding 1983, residues of the pea crop were incorporated into the soil. Phosphorus application was discontinued in 1983, as levels on some plots had increased to 200 mg P kg^{-1}. For the past decade nitrogen was applied at 100 kg ha^{-1} and potassium at 80 kg ha^{-1}.

3.3.2 GROWTH ANALYSES

Sampling started three weeks after emergence. Two plants per plot from each of the four replications were sampled randomly every week until eight weeks after emergence. Leaf area (laminas) was measured with a Licor Li-3000 leaf area meter. Plant tissues were oven dried to constant mass to determine the dry mass. Leaf area and dry mass values were used to calculate leaf area index (LAI), leaf area duration (LAD), net assimilation rate (NAR), crop growth rate (CGR), and relative growth rate (RGR). These growth analysis parameters were calculated using the following equations:

LAI = leaf area per plant x plant population

$RGR = [(\ln W_2 - \ln W_1)/(t_2 - t_1)]$ (Gardner et al., 1985)

$LAD = (LAI_2 + LAI_1)(t_2 - t_1)/2$ (Gardner et al., 1985)

$NAR = [(W_2 - W_1)/(t_2 - t_1)]\ [(\ln L_{A2} - \ln L_{A1})/(L_{A2} - L_{A1})]$ (Gardner et al., 1985)

CGR = LAI x NAR

where L_{A2} and L_{A1} are leaf areas at time 2 (t_2) and time 1 (t_1) respectively. W_2 and W_1 are total above ground dry mass at t_2 and t_1 respectively. LAD is measured in weeks while NAR is expressed in g m^{-2} leaf area $week^{-1}$, CGR in g m^{-2} field area $week^{-1}$ and RGR is expressed as mg g^{-1} $week^{-1}$.

3.3.3 CULTURAL PRACTICES

The soil of the experimental site is classified as a silt clay loam of the Hutton form that belongs to the Suurbekom family (Soil Classification Working Group, 1991). In the 2005/2006 season, a rotovator was used to prepare the field for planting. The first planting failed due to bird damage. Re-planting was done on 16 January 2006 with 'Pioneer Phb 32W71`, an early maturing cultivar. Planting was done with hand planters at a spacing of 90 cm between rows and 20 cm within rows. Atrazine was applied on the third day after planting as a pre-emergence herbicide. Plots were protected with bird netting until two weeks after emergence. Emergence of the seedlings commenced five days after planting. Metachlor and a pyrethroid were applied three weeks after emergence. Final weed control was done at the ninth week after emergence with metachlor.

Two weeks before the initial planting, the fertiliser was applied as indicated in Table 3.2 and incorporated into the soil. Nitrogen was applied in the form of limestone ammonium nitrate (LAN) and potassium in the form of potassium chloride (KCl). Phosphorus was not applied due to the excessive build up of soil P during previous years. No fertilizer was applied during replanting, except a top dressing with LAN on NPK plots nine weeks after planting. Irrigation was through a sprinkler system. Prior to planting, adequate water was applied to bring the soil to field water capacity. Supplementary irrigation was supplied to alleviate water stress during dry periods.

3.3.4 STATISTICAL ANALYSIS

Statistical analyses of the data were carried out using the Statistical Analysis System (SAS) programme for Windows V8 (Statistical Analysis System Institute Inc, 1999-2001). Analysis of variances was performed for all growth rate parameters. Means were compared using the least significant difference (LSDs) test at a probability level of 5% using the Duncan Multiple Range tests.

Table 3.1: Average topsoil analysis indicative of the nutrient status of the selected treatments

Treatments	pH (KCl)	pH (H_2O)	P	K	Ca	Mg	Na	S	Fe	Mn	Cu	Zn	B	Org C	Ni Tot*
			mg kg^{-1}												
O	6.1	6.8	3.2	40.8	599.9	233.4	6.3	6.2	38.1	155.2	4.2	5.1	1.5	0.8	23.8
PK	5.9	6.7	30.8	85.7	636.3	206.3	6.5	6.4	38.1	133.5	4.1	3.5	0.1	1.1	25.1
NK	5.4	6.1	3.0	110.7	453.3	148.2	5.5	9.3	35.2	111.7	3.7	2.4	0.1	0.8	20.8
NP	5.3	6.0	35.7	27.1	531.0	181.4	5.8	9.9	51.7	106.3	4.1	3.3	0.2	0.9	27.0
NPK	4.8	5.5	32.1	91.4	405.4	122.5	6.0	8.7	56.1	107.8	4.7	2.8	0.1	0.9	27.4
WNPKM	5.4	6.1	77.0	101.2	741.0	162.3	6.4	8.1	71.5	109.9	4.0	8.9	0.2	1.0	28.2

Ni Tot*: Total inorganic nitrogen.

Soil analyses courtesy of Omnia Nutriology®, P.O.Box 69888, Bryanston, 2021

Table 3.2: Rates of N, P and K fertilizers and compost (kg ha^{-1}) applied at planting in the 2005/2006 season

Treatments	N	P	K	Compost
O	0	0	0	0
PK	0	0	80	0
NK	100	0	80	0
NP	100	0	0	0
NPK	100 + 50*	0	80	0
WNPKM	100	0	80	9560**

*Nitrogen applied as top dressing on NPK plots.

**Compost applied in 2003/2004, 2004/2005, and 2005/2006.

3.4 RESULTS AND DISCUSSION

In the 2005/2006 season the maize did not perform as good as in the previous seasons due to the late planting date and excessive rainfall. Figures 3.1 to 3.3 illustrate the general appearance of some of the treatment plots, while typical N, P and K deficiency symptoms eight weeks after planting are illustrated in Figures 3.4 to 3.8.

Figure 3.1: Appearance of plants in an unfertilised plot (Note the prominent border effect).

Figure 3.2: Crop development in a nitrogen deficient plot (PK).

Figure 3.3: Phosphorus deficient plot (NK) in comparison to surrounding plots.

Figure 3.4: Potassium deficient (NP) plot with prominent border effect.

Figure 3.5: Plot of balanced treatment (WNPKM) with better plant development.

Figure 3.6: Yellow leaves and stunted growth, symptoms of nitrogen deficiency.

Figure 3.7: Purple colouration of leaves that characterised phosphorus deficient maize.

Figure 3.8: Potassium deficient maize characterised by stunted growth and leaves with yellow stripes and necrotic margins.

3.4.1 LEAF AREA INDEX (LAI)

The leaf area indices of the different treatments over the growing period are illustrated in Figure 3.9 and summarised in Appendix Table A3.10. The LAI increased for all the treatments over the sampling period. Three weeks after emergence the LAI of WNPKM was already about five times higher than the LAI of the other treatments. This advantage was maintained and after eight weeks, at anthesis, the LAI of the WNPKM treatment was still much higher than the other treatments. Rapid increase of the leaf area between the fifth and seventh week was observed on WNPKM plots. The maximum LAI of 5.39 in the WNPKM treatment was about five fold the maximum LAI of 0.86 for NK. The amount of solar radiation intercepted and converted to dry matter primarily depends on the canopy structure of the crop (Gardner *et al.,* 1985). Leaf area index (LAI) is a canopy structure parameter and light intercepted by a crop is a function of LAI (Jones & Kiniry, 1986). Development of the leaf canopy during the growing season varies with maize genotype, environmental conditions and cultural practices. The maximum LAI for late maturing hybrids is higher than for short season hybrids (Tollenaar & Dwyer, 1999). The WNPKM treatment produced a large canopy

(LAI ≈ 5), which exceeds the maximum leaf area defined as critical LAI by Gardner *et al*. (1985). The critical LAI is the leaf area index at which 95% light is intercepted by the canopy. In a maize study by Maddoni & Otegui (1996) 90% of light interception was reached at LAI of 4. The maximum LAI reached by the WNPKM treatment resemble models proposed by Gallo *et al.* (1993) & Muchow *et al.* (1990). They proposed a LAI of 5 for maximum fraction of photosynthetically active radiation to be intercepted by a maize crop. Annandale (1987) and Serrano *et al.* (1995) agreed that balanced nutrition encourages adequate development of the photosynthetic factory in crops. The other treatments resulted in mature canopies with LAI between 1 and 3 (Figure 3.9), with the implication that productivity in terms of biomass production per unit land area would be similarly affected. The relatively high LAI of the PK treatment may be explained by the high total nitrogen content of the soil (Table 3.1). Nutrient deficiencies greatly reduced the LAI of maize. The NK and O treatments produced the smallest canopies, which were as low as LAI 0.86 and 0.96. This confirms that phosphorus deficient crops experience severe reduction in LAI, low biomass production and yield (Plenet *et al*., 2000a & b).

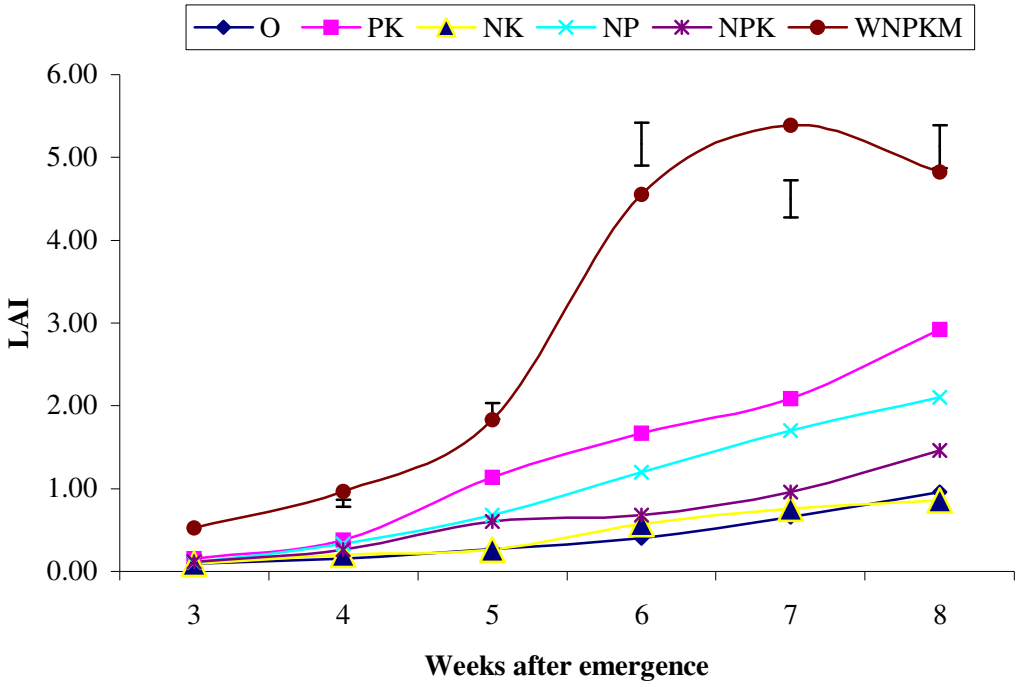


Figure 3.9: Leaf area index for the selected treatment combinations until eight weeks after emergence (Treatment means in Appendix Table A3.10).

3.4.2 LEAF AREA DURATION (LAD)

Leaf area duration takes into account not only the canopy size but also how long it lasts (Hunt, 1990). It is the product of leaf area index and the relevant growing period, and represented by the area covered by a LAI curve. The curve of leaf area index against time reflects the whole opportunity for assimilation, which a crop possesses. Leaf area duration exhibited a similar pattern as LAI. The LAD up to anthesis (8 weeks) was 15.41 weeks for the WNPKM treatment, 6.80 weeks for the PK treatment, and the lowest LAD of 2.01 weeks was recorded for the control (O) treatment (Table 3.3).

Table 3.3: Leaf area duration (weeks) of selected treatments from three weeks after emergence until anthesis (pre-anthesis LAD)

Treatments	Weeks after emergence					
	4	5	6	7	8	Total
O	0.13	0.21	0.33	0.53	0.81	2.01
PK	0.27	0.76	1.40	1.88	2.50	6.80
NK	0.15	0.23	0.42	0.67	0.81	2.27
NP	0.22	0.51	0.94	1.45	1.90	5.02
NPK	0.19	0.43	0.64	0.82	1.21	3.30
WNPKM	0.75	1.40	3.19	4.97	5.11	15.41
LSD (0.05)	0.04	0.11	0.30	0.36	0.32	

During this pre-senescence period the time factor is the same for all treatments (8weeks) and the LAD profile will reflect LAI data (Table 3.3). The size and duration of the canopy is of special importance for the period following anthesis, as under most circumstances most of the carbohydrates in the grain are derived from photosynthesis during this period (Evans *et al.*, 1975). Differences in canopy persistence during crop maturation is also quantified by LAD estimates during grain filling and maturing. However, for this trial records are only available up to week 8. The LAD for the first eight weeks (pre-anthesis) determines vegetative biomass production and the potential grain sink size.

The relationship between total dry mass produced during the first 8 weeks and leaf area duration (LAD) is presented in Figure 3.10. The biomass was linearly related to LAD. Annandale (1987) used this linear relationship to explain grain yield of wheat under different soil fertility and water supply conditions in a similar long-term field trial. The longer a large canopy is maintained, the more dry matter is produced. Variations in leaf area index and/ or canopy duration, which are functions of LAD, have a direct impact on the dry matter accumulation (Tollenaar, 1989).

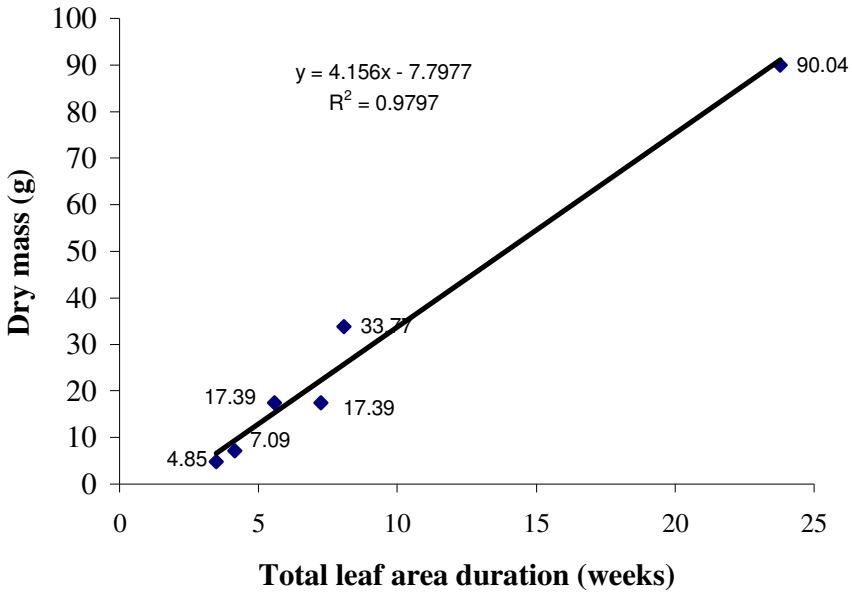


Figure 3.10: Relationship between total leaf area duration and total dry mass per plant.

3.4.3 TOTAL DRY MASS

Growth measurements are often only based on net above ground biomass production because obtaining estimates of root biomass is difficult (Sinclair & Muchow, 1999). At the end of the eighth week, the WNPKM treatment had the highest total dry mass of 90g per plant, while NK had the lowest with 4.9 g (Figure 3.11). Total dry matter yield is a result of crop canopy efficiency in intercepting and utilizing the solar radiation available (Gardner *et al.*, 1985). Balanced nutrient treatments produced more dry mass due to larger canopy size. In accordance with the study of Annandale (1987)

on effect of soil fertility and water supply on wheat, the phosphorus deficient treatment (NK) resulted in the lowest biomass.

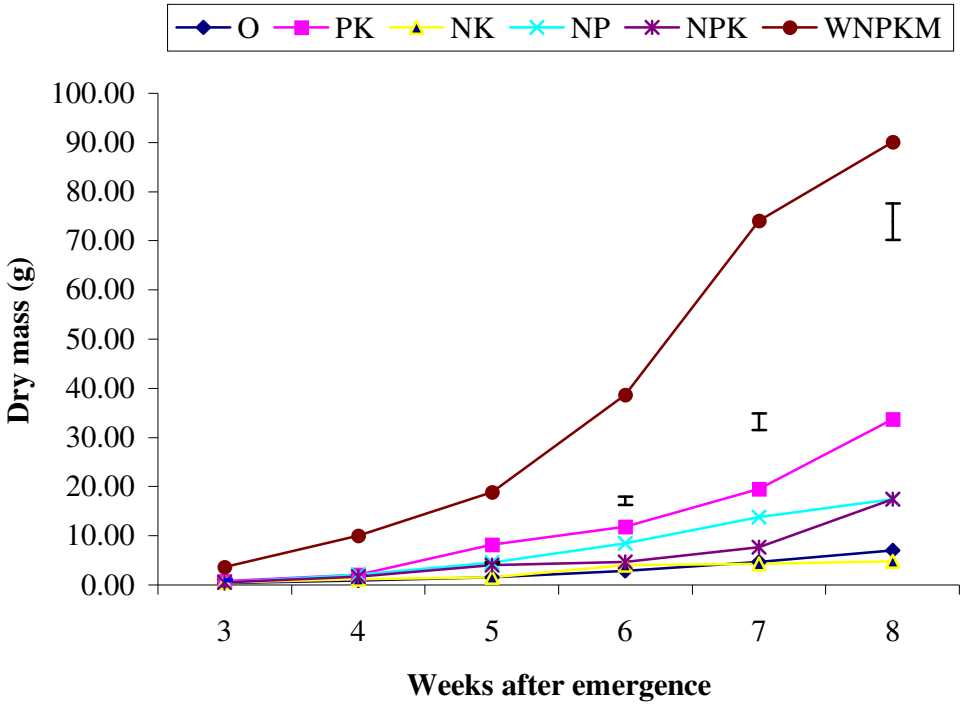


Figure 3.11: Effect of soil fertility on total dry mass per plant (Treatment means in Appendix Table A3.12).

3.4.4 NET ASSIMILATION RATE (NAR)

Gain in photosynthetic assimilate per unit leaf area per unit time is called net assimilation rate (Gardner *et al.*, 1985). It is an efficiency index of the photosynthetic system. The considerable variation in NAR data can be observed in Figure 3.12. Although polynomial functions fitted the data best, much of the variation cannot be adequately explained. A major contributing factor is the small samples, which may not be representative. There tended to be a gradual decline in net assimilation rate for most of the treatment combinations as the season progressed. This is in accordance with ontogenetic downward drift with aging and shading of lower leaves (Gardner *et al.,* 1985). The NK and NP treatments, where influence of aging and prominent P and K deficiencies manifested early in the growing period, exhibited a sharp decline in NAR. The NAR of this experiment is low in comparison to NAR values reported in a

study to investigate sensitivity of field maize to ultraviolet- B radiation where an average of 200 g m^{-2} $week^{-1}$ were reported (Correia *et al.,* 1998). Low values obtained in the Pretoria trial may also partly be due to chlorotic and necrotic areas in the P and K deficient leaves resulting in overestimating the productive leaf area.

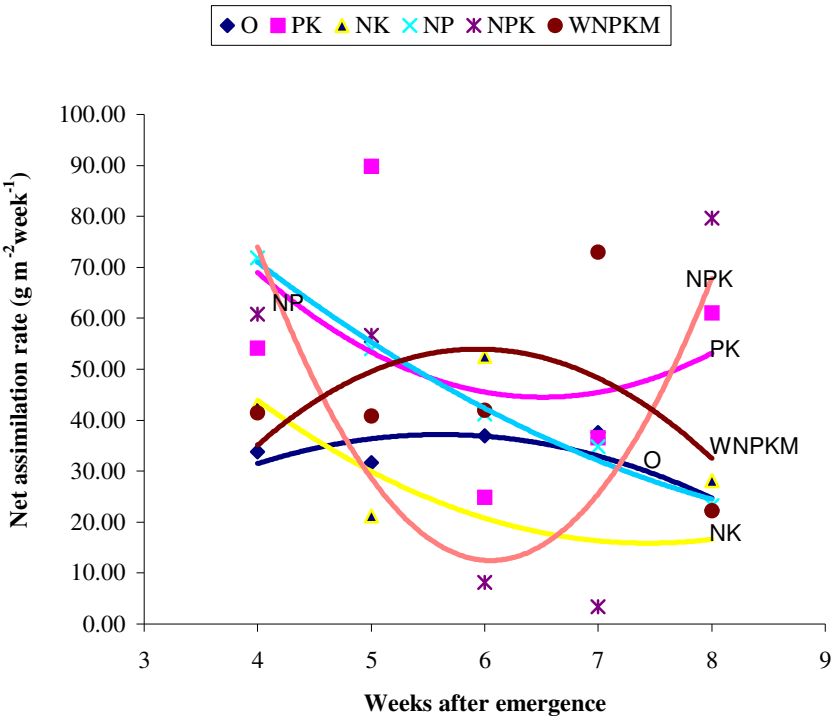


Figure 3.12: Effect of soil fertility on net assimilation rate (Treatment means in Appendix Table A3.13).

3.4.5 RELATIVE GROWTH RATE (RGR)

The relative growth rate is an indication of the effectiveness of a plant in producing new material per unit mass of the plant (Gardner *et al*., 1985). The decline in the relative growth rate occurs due to the fact that a decreasing portion of the plant biomass participates in photosynthesis as non-photosynthetic organs (i.e. stems) develop and efficiency of the lower leaves decreases (Hunt, 1990). Polynomial functions fitted the data best but much of the variation cannot be adequately explained. This may be due to the lack of large enough samples. The relative growth rate declined steadily from the fourth week after plant emergence (Figure 3.13). The highest relative growth rate was 1313 mg g^{-1} $week^{-1}$ (NP) while the lowest was 659 mg g^{-1} $week^{-1}$ (O) at the fourth week after plant emergence. The pattern and values of

the maximum and minimum relative growth rates observed compare closely with rates reported in the literature, for example that of pigeon pea planted at different plant populations (Rowden *et al.,* 1981). The increase in the RGR of NPK at the seventh week may be due to the initial poor performance of the treatment and later improvement due to top dressing with nitrogen.

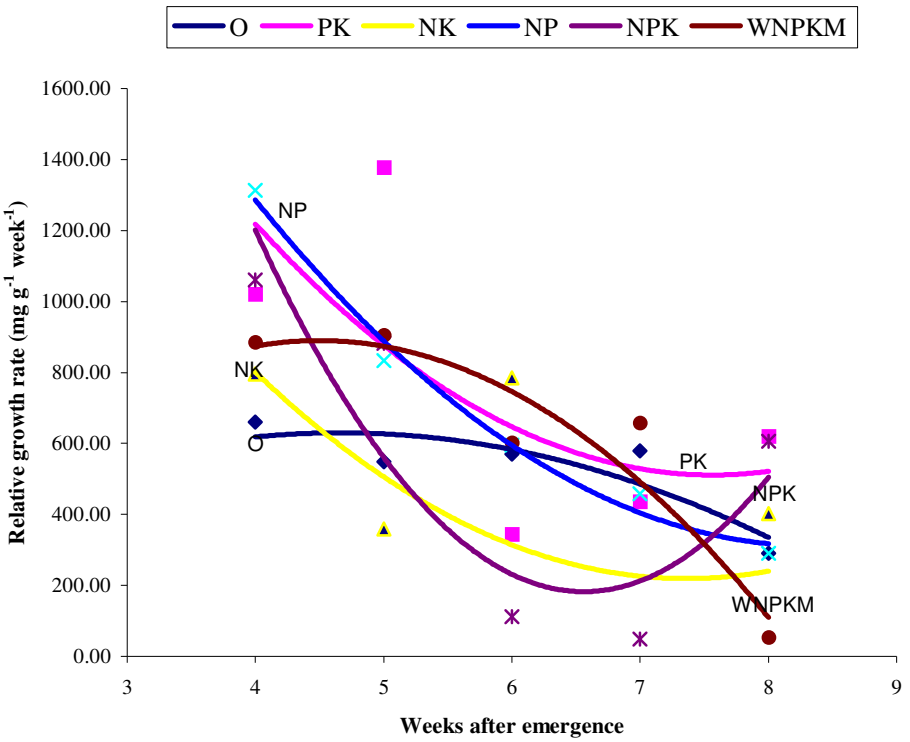


Figure 3.13: Relative growth rate for the selected treatments over five weeks (Treatment means in Appendix Table A3.14).

3.4.6 CROP GROWTH RATE (CGR)

Crop growth rate represents the increase in biomass per unit land area per unit time, and can be calculated as the product of LAI and NAR. Generally, crop growth rate will increase as the LAI increases over the season. Therefore, a linear relationship typically exists between LAI and CGR (Rowden *et al.,* 1981), explaining the similarity between LAI and the CGR of the WNPKM treatment (Figure 3.9 & Figure 3.14). The WNPKM treatment exhibited the highest crop growth rate of 233 g m^{-2} $week^{-1}$ at the seventh week, followed by NPK treatment with 130 g m^{-2} $week^{-1}$ at the eighth week after emergence. The NK and O treatments had the lowest maximum crop growth rates, with rates of 19 g m^{-2} $week^{-1}$ and 17.7 g m^{-2} $week^{-1}$ respectively. In

agreement with Plenet *et al*. (2000b), the O and NK treatments showed that phosphorus deficiencies resulted in low rates of conversion of solar energy to dry matter. Potassium deficiency symptoms are first observed in the older leaves of the plant, thus, the performance of the NP treatment suggests that younger leaves still contributed effectively to assimilate production.

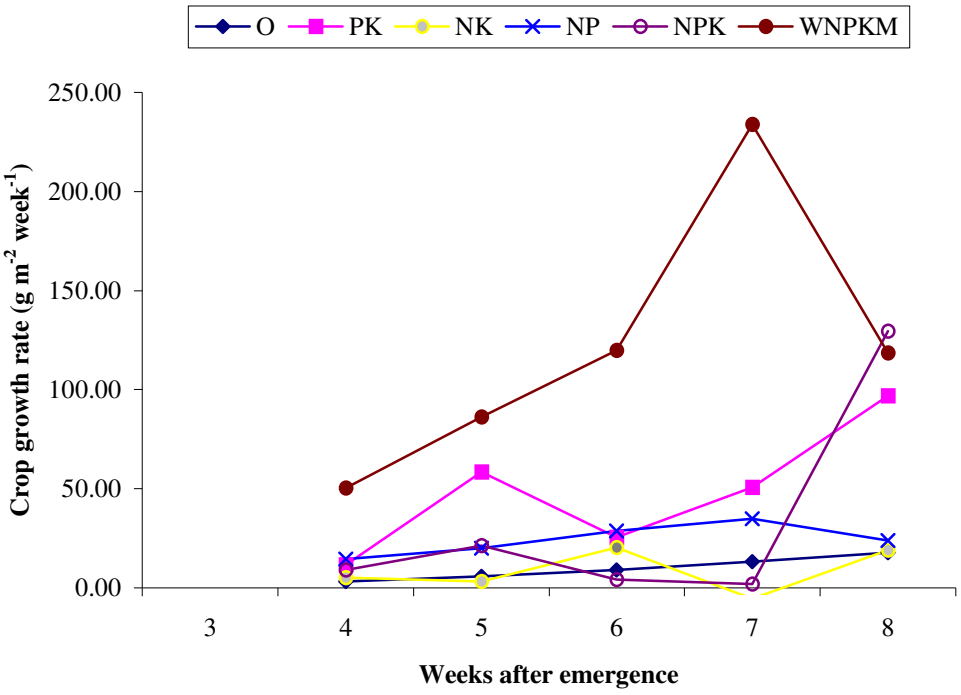


Figure 3.14: Crop growth rate of the selected treatments over five weeks (Treatment means in Appendix Table A3.15).

3.4 CONCLUSIONS

The effect of soil nutrient status on maize growth (biomass) was reflected by the NAR, RGR and CGR parameters, although a lot of variation in the data was observed. Such variation is an almost inevitable effect of sampling, as sample size is often limited by practical considerations, and unrepresentative samples increase variability. Unfortunately, this decreased the application of growth analyses to explain the treatment effects. However, the effect of soil nutrient status on reproductive development will be examined in Chapter 4.

CHAPTER 4

EFFECT OF SOIL NUTRIENT STATUS ON DEVELOPMENT OF THE REPRODUCTIVE STRUCTURES

4.1 ABSTRACT

Good management decisions depend on accurate identification of growth stages in crops. Initiation of the tassel signifies the beginning of the reproductive development in maize, followed by ear development from one or more of the axillary shoots of the stem. The objectives of this study were to examine the effect of soil nutrient status on the initiation and development of the reproductive organs and yield components. For this study the O, PK, NK, NP, NPK, and WNPKM treatments were selected. Maize plants were regularly sampled, dissected and microscopically inspected to monitor the stage of reproductive development. Rate of tasseling and silking was monitored. At maturity yield components were determined. Plants from the balanced nutrient treatment (WNPKM) exhibited early tassel initiation and ear differentiation, and had larger reproductive organs than those of other treatments during all stages of development. Nutrient stress delayed initiation and differentiation resulting in smaller reproductive organs. Reproductive development of the PK treatment was ahead of the NP and NPK treatments. A linear relationship was found between leaf area index (LAI) and the size of the reproductive structures. The higher the LAI the larger the size of the reproductive structures. Delayed initiation and differentiation of the reproductive structures at least partly explains lateness in emergence of inflorescences. Kernel number per cob determined grain yield rather than mass per kernel. Grain yield was positively affected by the balanced nutrient treatments while the nutrient stressed treatments reduced the yield.

4.2 INTRODUCTION

Accurate identification of growth stages in crops is essential for sound management decisions. Maize reproductive development begins with the initiation of the tassel at the elongated transitional stem tip (Bonnett, 1954). It coincides with the time the basal internodes of the main stem begin to elongate. Under favourable conditions, this stage may be reached in about two weeks after emergence (Kiesselbach, 1949 & Galinat & Naylor, 1951). Ears develop from one or more of the axillary shoots of the stem, after tassel differentiation has commenced (Bonnett, 1948 & Kiesselbach, 1949). The axillary shoot is enclosed in a leaf-like structure called the prophyllum, which enlarges and persists as one of the husks. The early stages of ear development are similar to the corresponding stages in the development of the tassel, except that there are no branches on normal ears (Kiesselbach, 1949).

Maize performance is influenced by stress and stress management practices at different growth stages (Kumudini & Tollenaar, 1998). Studies have been carried out on the effect of environmental factors such as drought, temperature, irradiance, photoperiod and mineral nutrition on reproductive development of maize. A general conclusion was that environmental stress prolongs the period from planting to silking (Tollenaar, 1977). Water shortages during anthesis resulted in low grain numbers, which was attributed to poor synchronization in emergence of male and female flower components (Herrero & Johnson, 1981; Westgate & Boyer, 1986). Low grain number is also attributed to incomplete ovary fertilization due to high plant densities (Tollenaar, 1977). Carcova & Otegui (2001) observed that lateral heating of the ear resulted in reduced kernel number per ear, but does not influence the rate of silk emergence. Timing of flower initiation, rather than rate of flower development, is affected by photoperiod. Some varieties require short photoperiods while others prefer long photoperiods for flower initiation (Galinat & Naylor, 1951). In a review by Tollenaar (1977), it was reported that cessation of ear growth resulted from low amounts of intercepted irradiance during the flowering period. Nitrogen stress resulted in reduced leaf area and fewer kernel numbers due to reduced emergence of silks (Lemcoff & Loomis, 1994).

Existing information on the effect of nutrient stress on the development of reproductive organs of maize is limited. Whether the effects can be observed directly after organ initiation and persist to influence grain yield is not clear. This chapter examines the effect of soil fertility status on the initiation and development of the reproductive organs, and the effect on yield components and grain yield.

4.3 MATERIALS AND METHODS

4.3.1 DEVELOPMENT OF REPRODUCTIVE ORGANS

Development of the reproductive organs was monitored on treatments O, PK, NK, NP, NPK, and WNPKM of the Long-term trial during the 2005/2006 season. Two plants per plot were sampled weekly from the third till the eighth week after emergence. The apical meristems of the main shoots were microscopically inspected and photographed to identify the time of tassel initiation and subsequent differentiation. Leaf number is not reliable to determine time of initiation as early cultivars have fewer leaves than late ones by the time tassel differentiation begins (Bonnett, 1954). The axillary shoots were dissected to record ear development. Ears develop from one or more of the upper axillary shoots of the stem depending upon whether they are single or multiple ear types (Bonnett, 1954; Kiesselbach, 1949). The developmental stages of the reproductive organs were identified according to the guidelines of Bonnett (1948) and Cheng *et al.* (1983). The lengths of the embryonic tassel and ear were recorded each week. Tasseling commenced at nine weeks after emergence and each week the number of plants per plot with tassels and silks were recorded, up to thirteen weeks after emergence.

4.3.2 MICROSCOPY PROCEDURE

Scanning Electron Microscopy (SEM) procedure

Developing reproductive organs were fixed in 2.5% glutaraldehyde (in 0.075M phosphate buffer, pH 7.4). The samples were rinsed three times each in 0.075M phosphate buffer at ten minutes intervals. Another fixation was done for 1-2hours using 0.5% aqueous osmium tetroxide, and rinsed three times in distilled water.

Samples were consecutively dehydrated in 30%, 50%, 70%, 90% and 100% ethanol (100% X 3) for about 10 minutes in each concentration and critical point-dried with liquid CO_2. The specimens were mounted on stubs and sputtered with gold. The SEM observations were conducted using a JEOL JSM-840 scanning electron microscope.

Dissecting Microscopy Procedure

In addition, dissecting microscopy was used to monitor the different developmental stages of the reproductive organs. The main shoots and the axillary shoots were dissected, inspected and photographed under the dissecting microscope. The time of initiation and subsequent differentiation of the reproductive organs were recorded for each observation. This information was used to identify stages of tassel development and eight stages in the development of the ear in an effort to describe the rate of development of the floral organs.

4.3.3 YIELD COMPONENTS

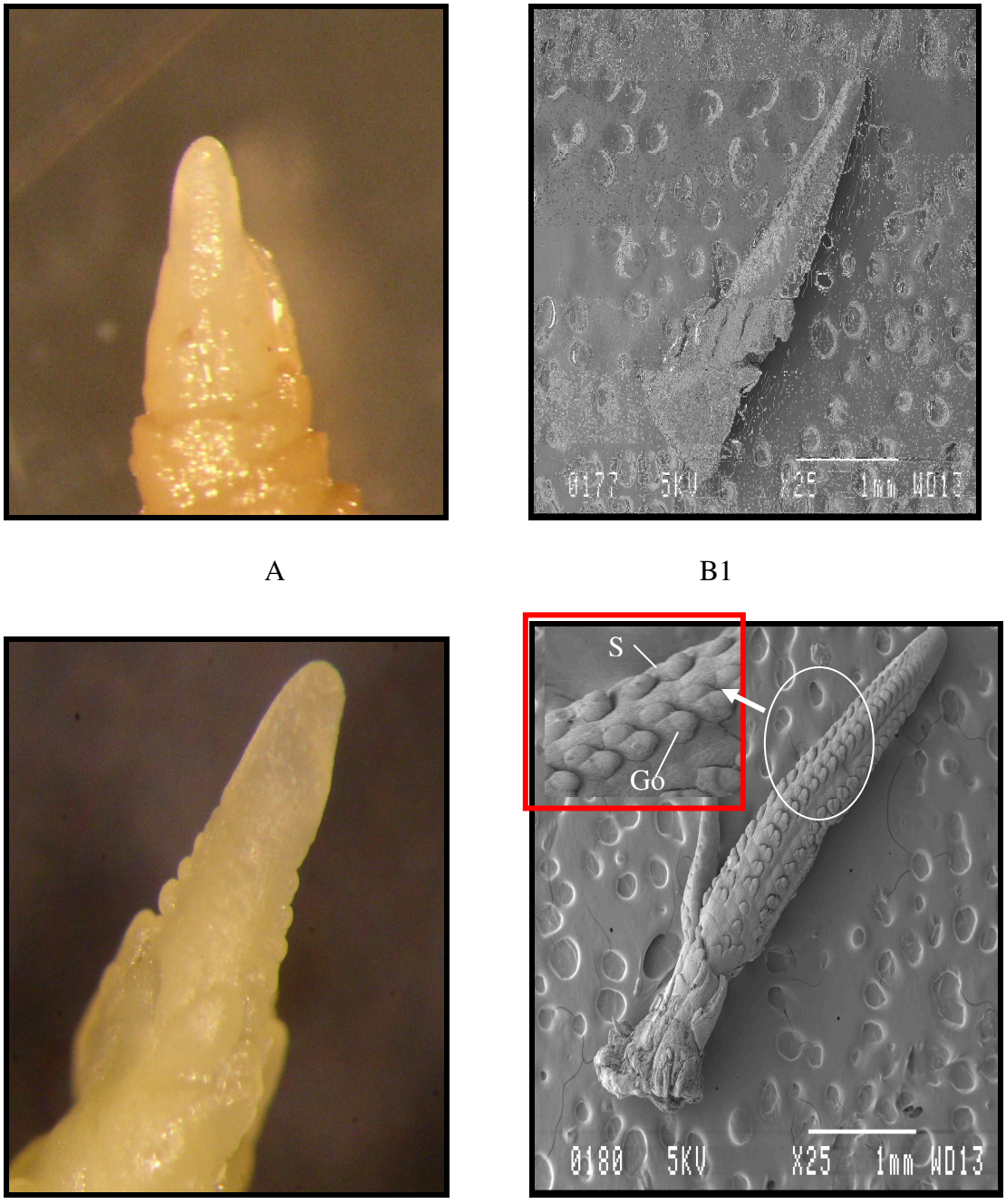
The aspect of yield components is dealt with in detail in Chapter 5. Here the yield components were monitored in an attempt to establish whether observed patterns in the development of the reproductive structures were reflected in the ultimate sink size. At maturity two plants per plot were harvested and oven dried at 40 ºC to constant mass to determine the total dry mass. Number of rows per cob and number of kernels per row were recorded to determine the potential kernel number per ear. Kernel number per row was determined for the row with the highest number of fully developed kernels on a cob. Actual number of kernels per cob and kernel mass was also determined.

4.4 RESULTS AND DISCUSSION

4.4.1 DEVELOPMENTAL STAGES OF REPRODUCTIVE STRUCTURES

Figures 4.1 and 4.2 illustrate the developmental phases of the embryonic tassel and ear identified during the investigation and based on the excellent descriptions of

Bonnett (1948) and Cheng *et al.* (1983). These stages were applied to quantify differences in the developmental rate of the reproductive organs.

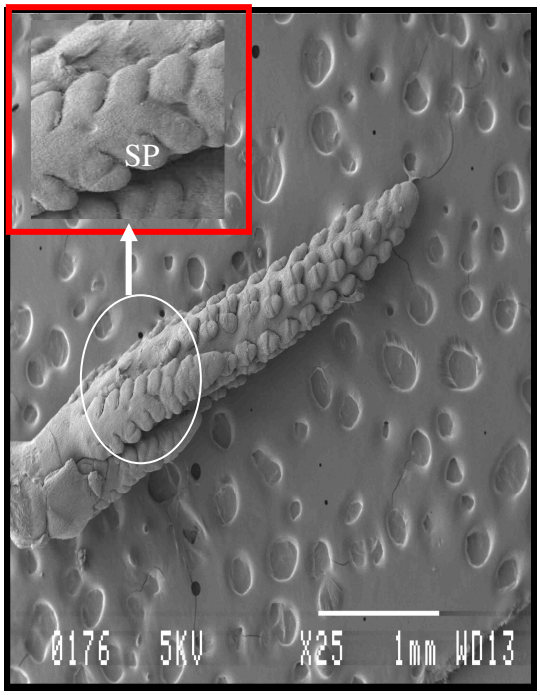


A B1

B2 C

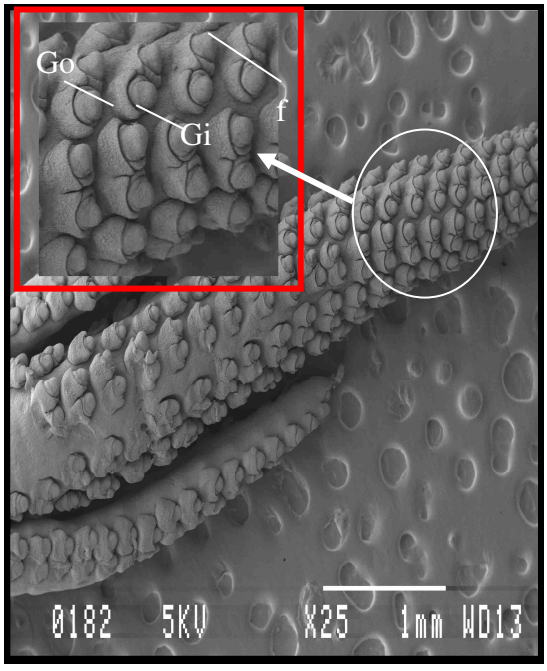
Figure 4.1: Different developmental stages of the maize tassel.

D1



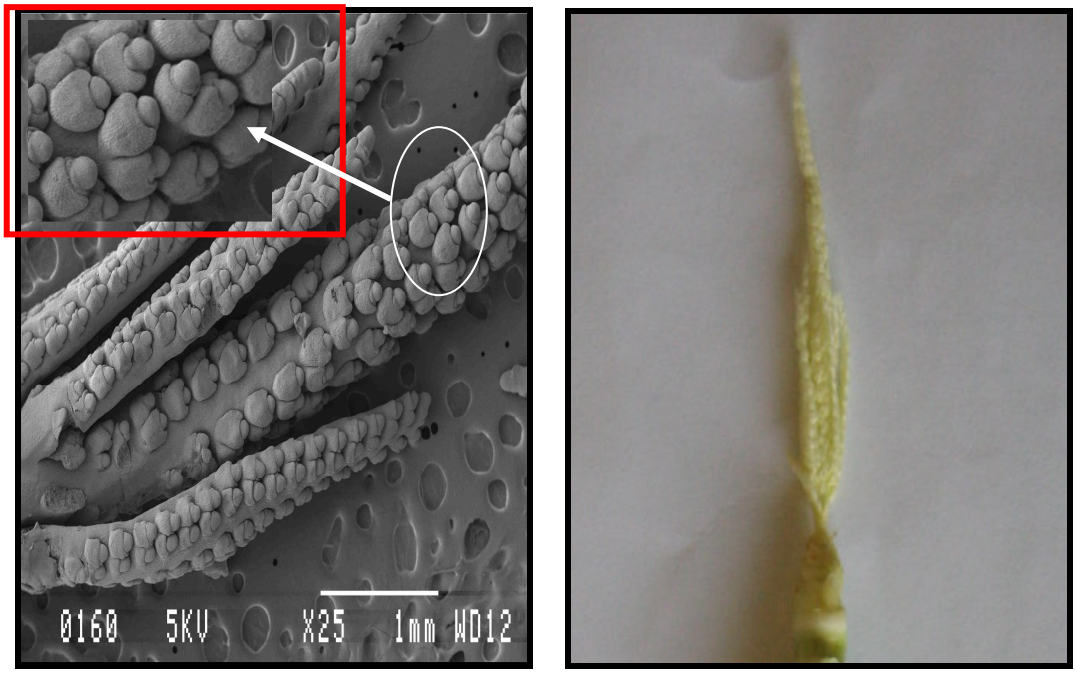
D2

E1



E2

Figure 4.1 continued: Different developmental stages of the maize tassel.



F G

Figure 4.1 continued: Different developmental stages of the maize tassel.

(A) Apical vegetative meristem.

(B) Beginning of the differentiation of the meristem before initiation of branch primordia. (B1=B2).

(C) Stages in spikelet development from spikelet-pair primordia.

(D) Spikelets primordia showing inner and outer glumes primordia, and branch primordium illustrating the initiation sequence of spikelet-pair development (D1=D2).

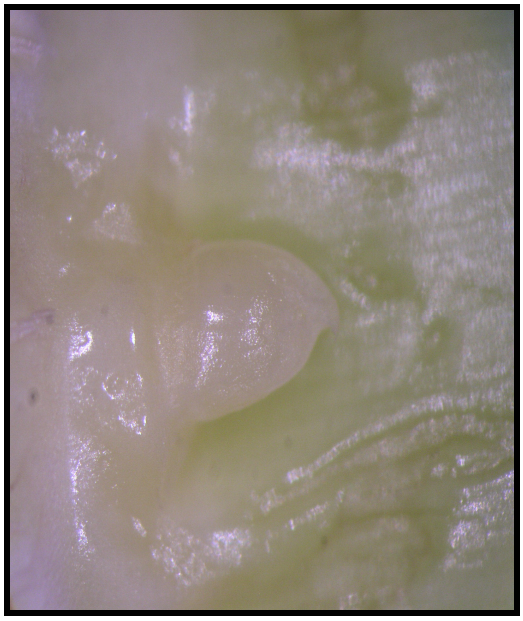
(E) Elongation of the basal branches of the tassel (E1). Spikelet differentiation on the central axis of the tassels initiation of first (upper) and second (lower) flowers in spikelet (second flower out of view) (E2).

(F) More advanced stage of differentiation of spikelets and empty glumes

(G) Fully developed tassel.

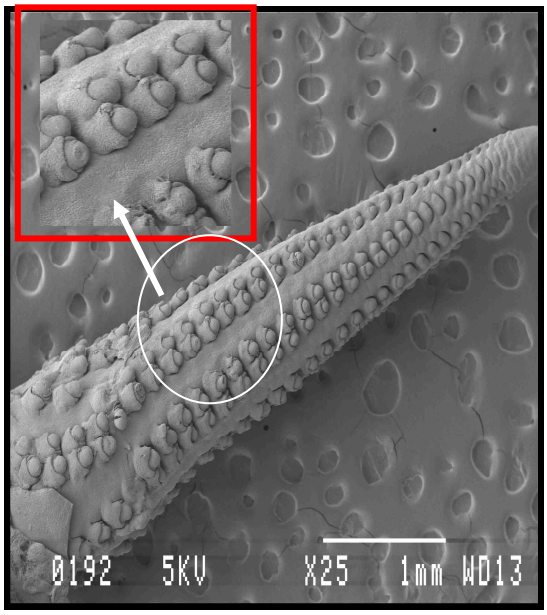
(f= first (upper) flower; Gi= inner glume; Go= outer glume; S= spikelet primordium; SP= spikelet-pair primordium).

A1



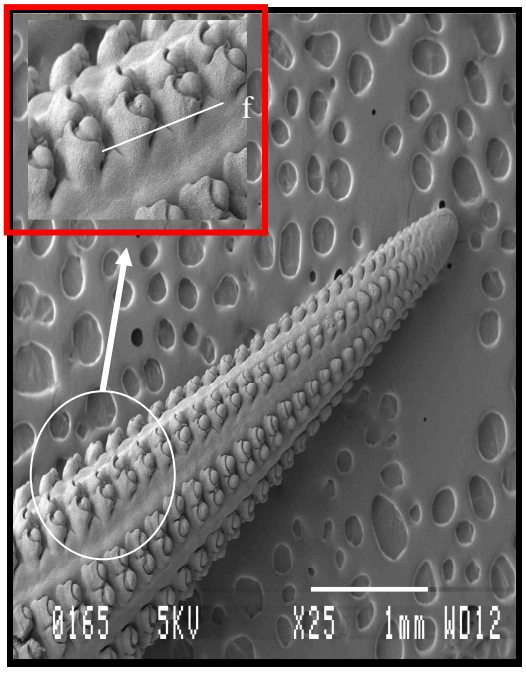
A2

B

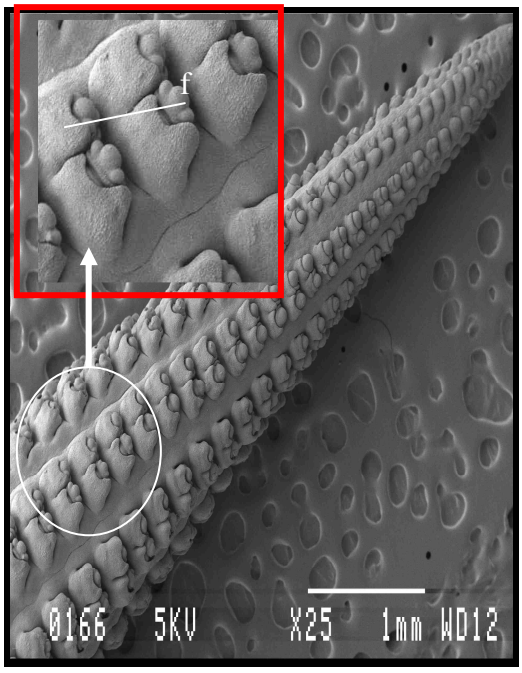


C

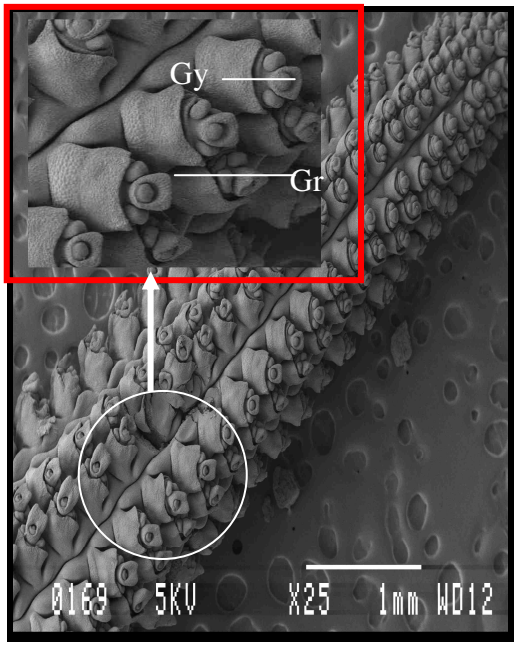
Figure 4.2: Developmental stages of the embryonic maize ear.



D



E



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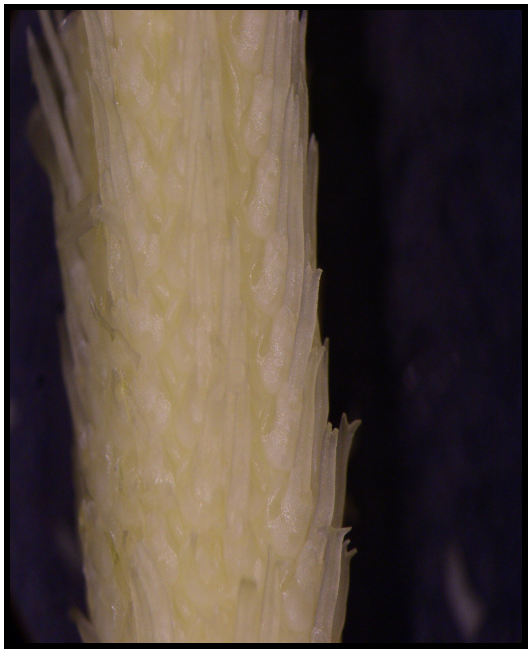

G

Figure 4.2 continued: Developmental stages of the embryonic maize ear.

H

Figure 4.2 continued: Developmental stages of the embryonic maize ear.

(A) Axillary shoot in which the ear develops; enclosed in the prophyllum (A1) and without the prophyllum (A2).
(B) Beginning of the differentiation of the ear.
(C) Initiation of rows of spikelet-pair primordia.
(D) Initiation of first and second flowers in spikelets.
(E) Stamen and palea initiation on first flower.
(F) Early stage of silk development from gynoecial ridge in the first flower.
(G) Well-developed silks
(H) Young ear of maize
(f= first (upper) flower; Gr = gynoecial ridge; Gy= gynoecium; S= spikelet primordium; SP= spikelet-pair primordium)

The developmental rate of the reproductive structures was affected by the soil nutrient status (Table 4.1). Tassel development was earlier in the WNPKM treatment; three weeks after emergence it was at stage F and four weeks after emergence it was at stage G, the last stage of development (Figure 4.1). Initiation of the embryonic tassel only occurred after the third week after emergence in the other treatments. Tassels of the PK and NP treatments completed their development between the fifth and the sixth week after emergence. The NK treatment resulted in the slowest rate of embryonic tassel development and completed development later than the seventh week after emergence. According to Kiesselbach (1949) and Galinat & Naylor (1951) the first indication of tassel differentiation is reached about two weeks after emergence under favourable conditions.

Embryonic ear development followed the same pattern. Ear initiation and differentiation started in the fourth week after emergence for the WNPKM treatment and later in all the other treatments (Table 4.1 and Figure 4.2). It is known that ear development only starts after tassel differentiation has commenced (Bonnett, 1954; Kiesselbach, 1949). The WNPKM treatment reached the final phase of ear development by the seventh week. At the eighth week, the PK treatment was at a more advanced stage of ear development than the NP and NPK treatments. Generally, ear initiation occurred by the time the embryonic tassels started to develop basal branches (Bonnett, 1954; Kiesselbach, 1949).

The effect of nutrient stress on the length of the embryonic tassels and cobs of maize are illustrated in Figures 4.3 and 4.4. Six weeks after emergence, the tassels in the WNPKM treatment were almost three times larger than those of the PK treatment. The NK treatment had the slowest rate of increase in tassel length. During the observation period ear development of plants from the WNPKM treatment was much more advanced than those of the other treatments, while the NK treatment maintained the shortest ear length. Jacobs & Pearson (1991) observed that development of the embryonic ear was delayed by nitrogen stress and defoliation.

Table 4.1: Effect of soil nutrient status on the development of maize reproductive structures

Treatments		Weeks after emergence					
		3	4	5	6	7	8
O	Tassel	A	B	E	F	G	G
	Ear	A	A	A	B	D	E
PK	Tassel	A	D	F	G	G	G
	Ear	A	A	C	E	F	G
NK	Tassel	A	B	D	F	F	G
	Ear	A	A	A	B	B	D
NP	Tassel	A	D	F	G	G	G
	Ear	A	A	A	D	E	F
NPK	Tassel	A	C	E	F	G	G
	Ear	A	A	A	C	D	F
WNPKM	Tassel	F	G	G	G	G	G
	Ear	A	C	E	G	H	H

The letters A-H refers to the developmental stages identified in Figures 4.1 and 4.2.

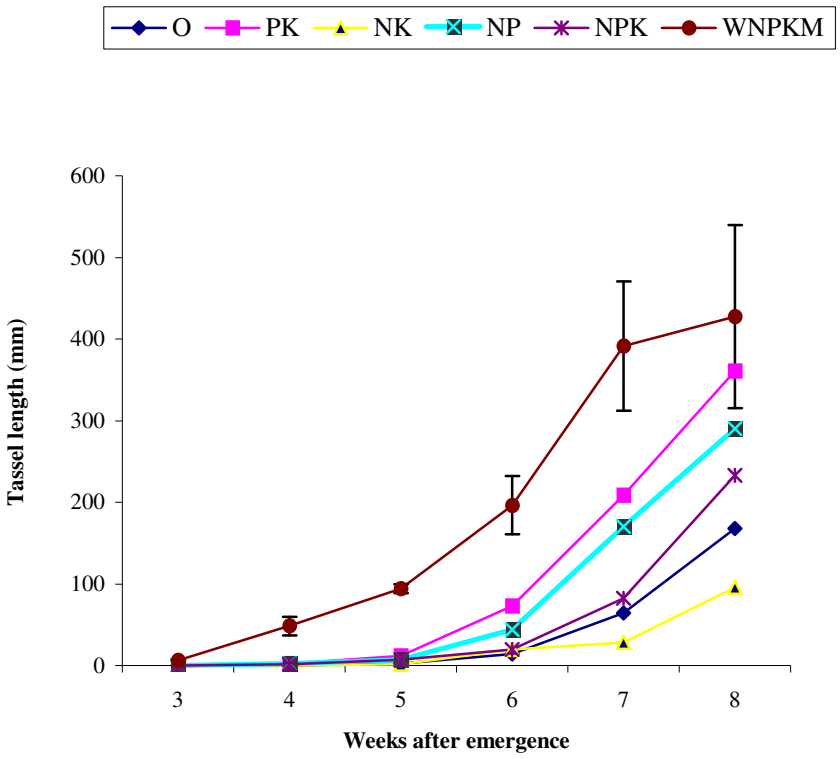

Figure 4.3: Effect of nutrient status on embryonic tassel growth (Treatment means in Appendix Table A4.4).

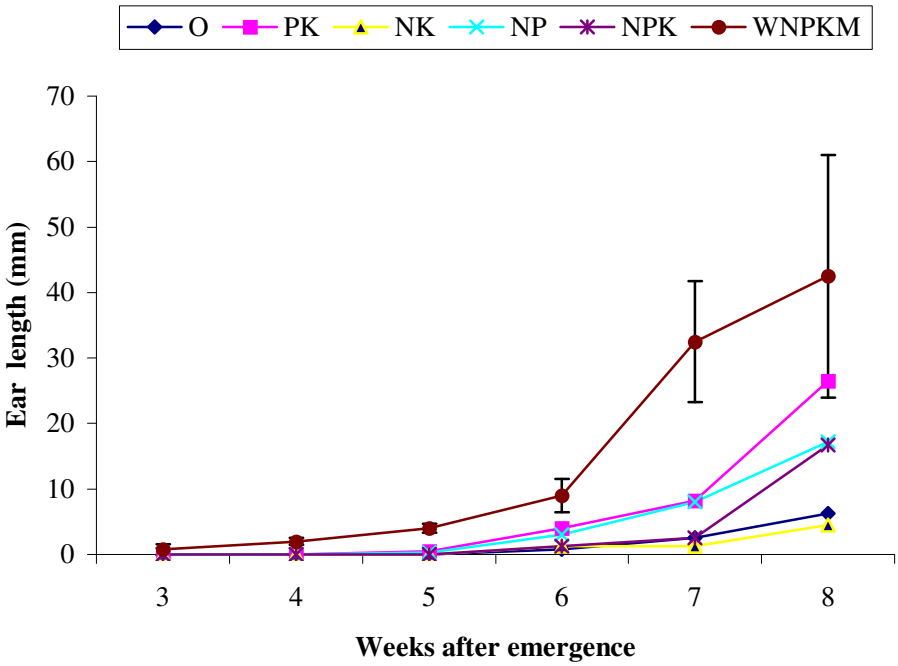

Figure 4.4: Effect of soil nutrient status on growth of the embryonic ear (Treatment means in Appendix Table A4.5).

During reproductive development the maize plant is extremely sensitive to stress, which may cause structural or functional abnormalities (Saini, 1997). Development of tassels were delayed in nutrient deficient treatments, and this phenomenon is often observed in farming situations. According to Coligado & Brown (1974) and Acker & Laubscher (1980) long day lengths delayed tassel initiation and differentiation in comparison to short day lengths, irrespective of temperature. Birch *et al.* (1998b) used leaf number of maize to predict time of tassel initiation and silking. Birch *et al*. (1998a) also observed that photoperiod extension prolonged the time to tassel initiation and increased the number of leaves, while Lejeune & Bernier (1996) found that chilling before tassel initiation causes ear abortion. An increase in temperature between 15 °C and 25 °C reduced time to tassel initiation (Coligado & Brown, 1974). Extension of the photoperiod increased total leaf number at tassel initiation (Birch *et al.,* 1998b). Water stress interferes with the development of male gametophyte preventing fertilization and inducing abortion (Westgate & Boyer 1986). Abrecht & Carberry (1993) demonstrated that water deficit delays tassel initiation and silking. According to Saini (1997) the arrest of male reproductive development leading to pollen sterility is common in cereals. Zinselmer *et al*. (2002) observed that abnormal floral development and impaired ear growth due to abiotic stress can occur during the reproductive phase in maize.

4.4.2 RELATIONSHIP BETWEEN LAI, DRY MASS AND SIZE OF REPRODUCTIVE STRUCTURES

The relationship between LAI 8 weeks after emergence (Chapter 3) and the size of the reproductive structures at that stage are illustrated in Figure 4.5 where the linear relationship between the LAI and the size of the reproductive structures can be observed. The WNPKM treatment had the highest LAI and resulted in the largest reproductive structures. Except in the case of the NK and O treatments, the tassel length increased with increase in the canopy size. The same trend occurred in the development of the embryonic ear. It implies that canopy size plays an important role in determining the size of the reproductive structures. Crops with fruit and seed as the economic yield require a large photosynthetic surface prior to fruiting in order to maximize potential sink size (Gardner *et al*., 1985).

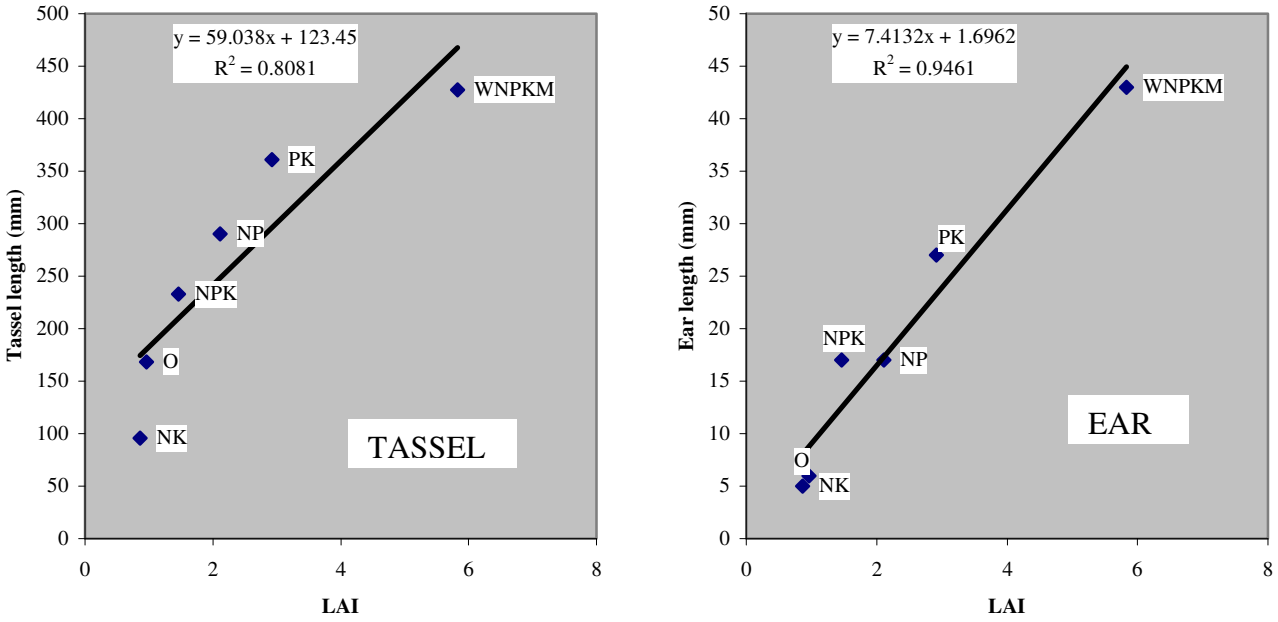

Figure 4. 5: Relationship between leaf area index and the size of the reproductive structures.

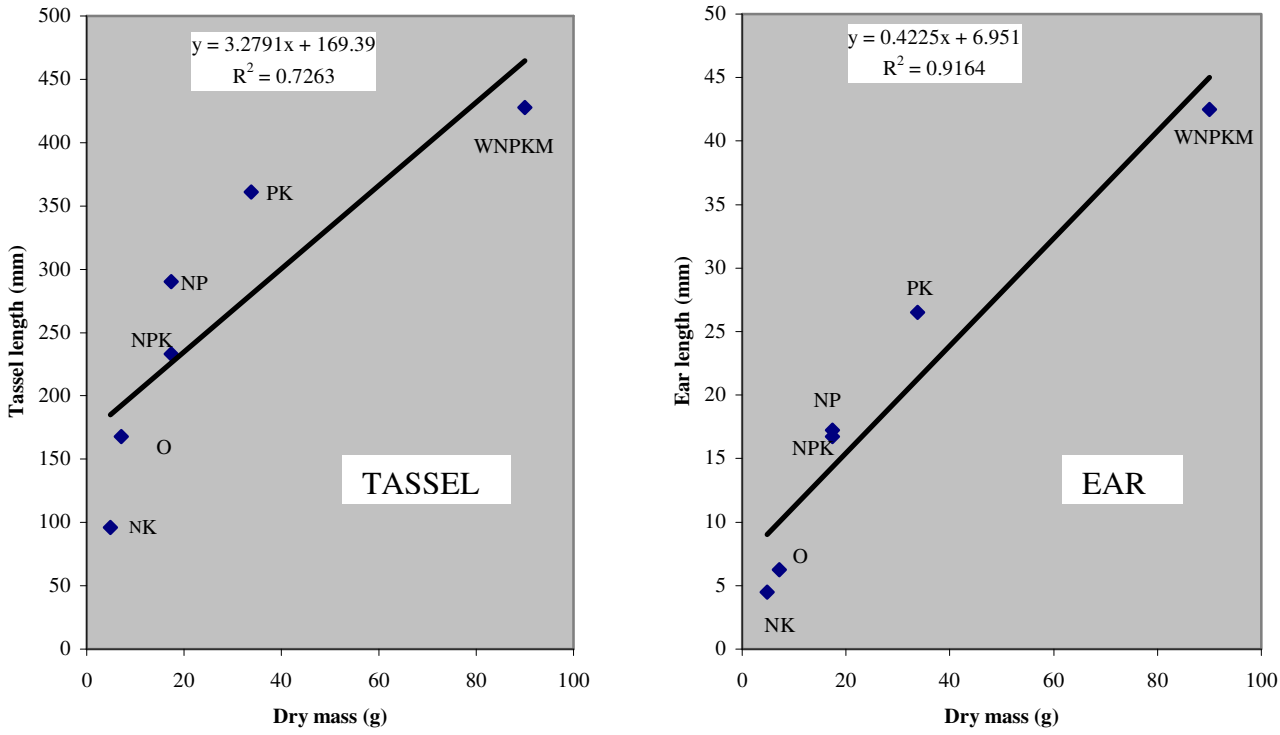

Figure 4.6: Relationship between total above ground dry mass and the size of the reproductive structures.

The linear relationship between dry mass and reproductive size is illustrated in Figure 4.6. The well-balanced nutrient treatment developed high dry mass with the largest reproductive structures, while nutrient deficient treatments NK and O, produced the lowest dry mass which was associated with the smallest reproductive structures. Reproductive growth is linearly related to the vegetative development of the crop. The larger the leaf area of a plant the better the development of the reproductive structures.

4.4.3 ANTHESIS

Soil fertility status dramatically affected the date of tasseling and silking. The WNPKM treatment reached anthesis earlier than the rest of the treatments. Nine weeks after emergence almost all the plants of the WNPKM treatment have tasseled, with the other treatments exhibiting between zero and 30% tasseling (Figure 4.7). By eleven weeks after emergence more than 90% of the plants of the NPK and PK treatments tasseled. The NK treatment still had less than 80% of the plants tasseling after twelve weeks. Figure 4.8 represents the percentage of silking plants as affected by soil nutrient status. Ten weeks after emergence all the plants of the WNPKM treatment had started silking. At the end of the twelfth week after emergence, the PK treatment had about 80% of its population silking. The O and NK treatments had less than 40% of plants silking at the twelfth week after emergence. Comparing Figures 4.7 and 4.8 it is clear that date of silking was even more delayed by nutrient imbalances than date of tasseling. In both instances the O and NK treatments delayed the appearance of reproductive organs the most. Synchronization of tasseling and silking is essential for effective pollination and the lack of enough and viable pollen grains by the time of silking in the imbalanced treatments possibly contribute to the low grain yields of these plots.

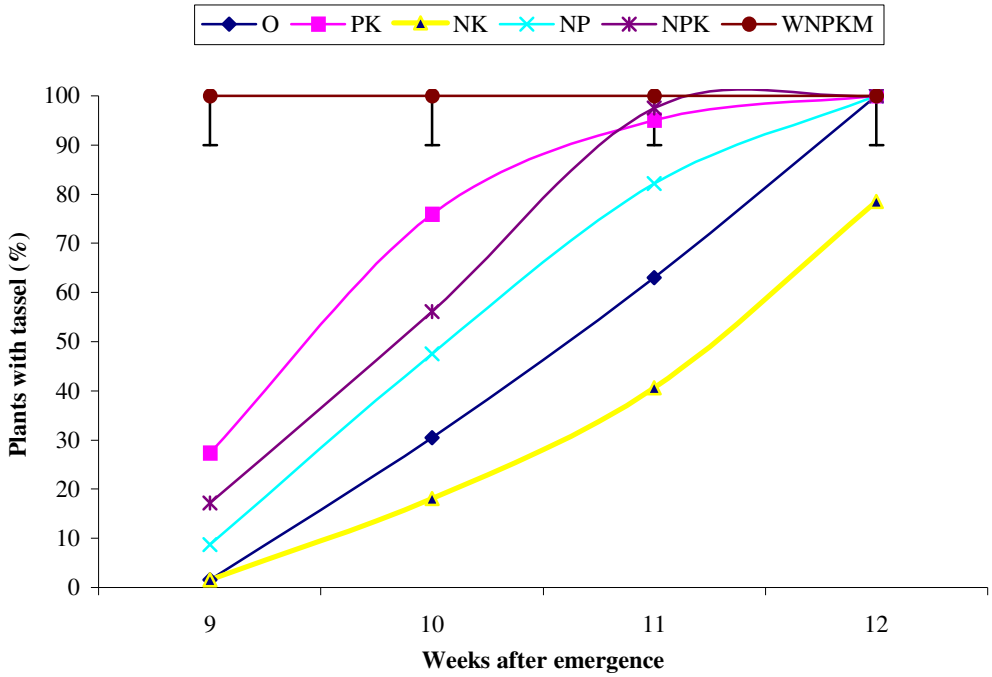

Figure 4.7: Tassel emergence rate as affected by soil nutrient status.

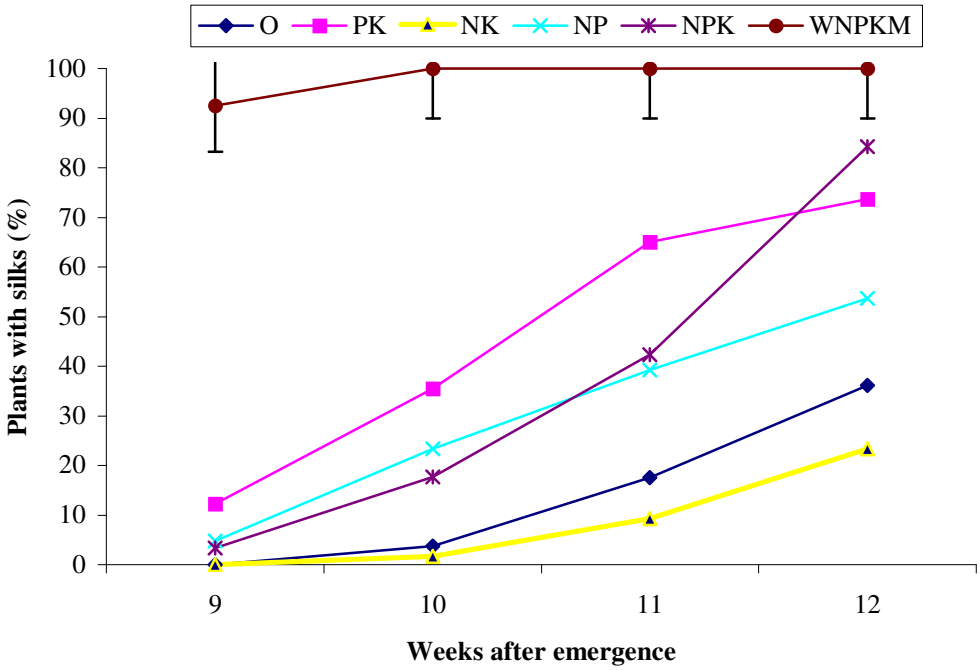

Figure 4.8: Silk emergence rate as affected by soil nutrient status.

Quantitative published information on the effect of soil nutrient status on tasseling dates is surprisingly scarce. According to Anderson *et al.* (1984) nitrogen supply influences synchronisation of flowering of maize and as a result also the grain yield.

Exposure of maize to water stress before tasseling alters the dynamics of flowering and reduces the number of viable pollen grains produced per plant (Hall *et al*., 1982). Water stress immediately before flowering can delay silking relative to pollen shedding, which will reduce yield due to poor synchronisation (Hall *et al*., 1981). Herrero & Johnson (1981) also observed that silking was more affected by water stress than tasseling. Photoperiod extension before tassel initiation reduces the duration of tassel initiation to tassel emergence (Ellis *et al*., 1992).

4.4.4 YIELD COMPONENTS

The effect of soil nutrient status on the yield components is discussed in more detail in Chapter 5. In this section the yield components associated with the differences in embryonic ear development are summarised to reflect the end result of ear differentiation. Differences in soil fertility did not affect row numbers significantly, but influenced the other yield components (Table 4.2). Plants of the WNPKM and PK treatments had the most kernels per row namely, 31, while the NK treatment resulted in the least number of kernels per row. Kernel numbers per cob of the WNPKM treatment (392 kernels) did not differ significantly from the NPK and PK treatments. The kernel number per cob of the NK treatment (99) was the lowest. The estimated potential kernel number per cob (no rows x no of kernels in the longest row) overestimated the actual number by more than 10%. The WNPKM treatment produced the largest kernels (0.34g) as well as the highest mass per cob (133.50g). The NK treatment had the smallest kernel mass (0.19g) and the lowest mass per cob.

Yield is the end product of reproductive development of maize. Any stress encountered during the reproductive development will be reflected in the yield. The more balanced nutrient treatments had the highest yield components and invariably the best yield. Grain number was reduced to a greater extent than the grain mass (kernel size) by nutrient deficiencies. Pandey *et al*. (2000) reported yield reduction associated with reduction in kernel numbers and to a lesser extent to kernel size. Hall *et al.* (1982) observed that kernel number per plant was reduced due to the exposure of the crop to water stress prior to flowering. In other studies, grain mass was more affected than grain numbers due to shading in sunflowers, soybeans and maize (Andrade & Ferreiro, 1996). Maddoni *et al.* (1998) reported smaller kernel mass

resulting from a reduction in assimilates and low partitioning to the grains due to low air temperature and less incident solar radiation.

Table 4.2: Yield components of maize as affected by soil nutrient status

Treatments	No of rows cob^{-1}	Kernel no row^{-1}	Kernels no cob^{-1}	*Potential kernel number cob^{-1}	Mass kernel^{-1} (g)	Mass of kernels cob^{-1} (g)
O	12.75^{a}	12.25^{b}	128.60^{bc}	158.25^{b}	0.17^{d}	21.32^{c}
PK	13.25^{a}	31.40^{a}	368.00^{a}	412.25^{a}	0.24^{b}	86.84^{b}
NK	12.00^{a}	10.75^{b}	99.75^{c}	136.00^{b}	0.19^{cd}	19.00^{c}
NP	12.75^{a}	15.70^{b}	186.75^{b}	199.00^{b}	0.17^{d}	33.14^{c}
NPK	13.75^{a}	27.25^{a}	341.10^{a}	372.00^{a}	0.22^{bc}	75.38^{b}
WNPKM	14.00^{a}	30.90^{a}	392.40^{a}	435.25^{a}	0.34^{a}	133.50^{a}
LSD (0.05)	1.82	4.99	61.82	76.34	0.03	15.67

*No of rows x no of kernels on the longest row of the cob

Means within the same column sharing the same letters are not significantly different ($p < 0.05$)

4.5 CONCLUSIONS

Soil fertility status affected reproductive development of maize. The well-balanced treatment (WNPKM) resulted in earlier development of larger reproductive structures and their emergence ahead of those of the nutrient deficient treatments. The timely completion of all the stages of reproductive development enables synchronization of tassel and silking. Of all the nutrient deficient treatments, the phosphorus deficient treatment (NK) resulted in the slowest development rate. This led to late emergence of inflorescences and dramatic decreases in the size of the different yield components.

Observations inferred that the impact of the nutrient status of the soil on the early development of the reproductive structures is reflected in the yield components and grain yield. Yield component data of the 2005/2006 season in Chapter 4 will be compared in Chapter 5 with the yield component data of a more typical production season, namely that of 2004/2005 in an effort to characterize yield components and grain yield reactions to soil fertility.

CHAPTER 5

EFFECT OF SOIL NUTRIENT STATUS ON YIELD COMPONENTS AND GRAIN YIELD OF MAIZE

5.1 ABSTRACT

Grain yield of maize is a function of the yield components. Various stresses, including nutrient deficiencies affect the individual yield components. A better understanding of the impact of nutrition on yield components presents opportunities for effective manipulation of the yield. During the 2004/2005 and 2005/2006 seasons two mature plants per plot were sampled from selected treatments of the Long-term Trial in order to quantify the yield components. The components determined were number of kernel rows per cob, kernel number per row, potential kernel number per cob, mass per kernel and kernel mass per cob. Row number per cob was not affected by soil nutrient status. Soil fertility affected the other yield components. During the two growing seasons the WNPKM treatment (with adequate macronutrients and organic manure applied) had the highest kernel number per row and consequently the highest number of kernels per cob. The NPK treatment was not significantly different. The NP treatment had the lowest kernel number per row and kernel number per cob, about 50% lower than the WNPKM treatment. Yield components of the zero fertilizer treatment, O, were not significantly different from the potassium deficient treatment. Plants of the WNPKM treated plots had the highest mass per kernel (35g/100 kernels) followed by NPK treated plants at 32g/100 kernels. Treatments NP, O and NK produced the lowest mass per kernel at 17g to 19g/100 kernels. Treatments NK (33.14g), O (21.32g) and NP (19g) produced the lowest kernel yield per cob. WNPKM (240g) and NPK (190g) produced the highest yields. Comparing yield data of the 2004/2005 season and the mean yield for the 1980-1990 decade as reported by Nel et al. (1996), the yields were in the same pattern but the mean yield for 1980-1990 is higher than the yield of 2004/2005 season.

5.2 INTRODUCTION

Analysing the grain yield of a cereal crop in terms of the applicable yield components presents the opportunity to understand variations in yield much better. Yield components of maize include row number per cob, kernel number per row, kernel number per cob, mass per kernel, kernel mass per cob, number of cobs per plant, yield per plant and number of plants per unit area. Row number per cob is strongly controlled by plant genetics and not affected by environmental conditions (Nielsen, 1995). When grain number is reduced due to stress, sink size and potential grain yield are reduced. Kernel number is strongly affected by environmental stress, which means ear length will vary dramatically as growing conditions vary (Nielsen, 1995).

Numerous investigations demonstrated the influence of stress on yield components. Water deficit imposed at different growth stages of maize reduced kernel number and kernel mass, and thus ear yield (Eck, 1984; Bolanos & Edmeades, 1996). Small kernels resulted from low temperature and low incident solar radiation due to reductions in biomass partitioning to the grains (Maddonni *et al*., 1998). Uhart & Andrade (1995) reported that nitrogen deficiency reduced dry matter partitioning to the reproductive sink thus reducing kernel numbers. In an experiment to investigate the influence of nitrogen and plant population on silk emergence and grain yield in maize, Lemcoff & Loomis (1994) observed low kernel numbers due to reduced emergence of silks. Kernel number and kernel mass were also affected by plant density and nitrogen availability. Kernel size is depressed in plants suffering from phosphorus deficiency, leading to poor grain yield (Mengel & Kirkby, 2001). Potassium deficiency severely reduces grain yield as a small ear, often underdeveloped at the tip, with kernels smaller than normal, is produced (Grundon, 1987).

Some physiological functions in plants have been related to yield components of maize. Otegui & Bonhomme (1998) established a linear relationship between kernel numbers per plant and the intercepted photosynthetic active radiation. Kiniry *et al*. (1997) reported a linear relationship between kernel number and plant growth rate to predict potential grain yield of maize. The relationship between kernel number per plant and plant growth rate is curvilinear. This accounted for kernel number per plant

when plant growth rate varies due to plant populations, radiation, night temperature, or years (Andrade *et al.,* 1999).

The yield components for the 2005/2006 crop were determined and recorded in an effort to correlate it with the early development of the reproductive organs in Chapter 4. However, the 2005/2006 crop was untypical, as the plots had to be replanted late in the season with a hybrid with a short growing season. Consequently, in this chapter data of the more representative 2004/2005 crop was utilized together with data of 2005/2006 to characterise the yield components. Grain yield for the more representative season (2004/2005) was compared with the average grain yield of the last decade as reported by Nel *et al.* (1996). The objectives of this chapter were to investigate the effect of soil nutrient status on yield components and grain yield of maize in the long-term trial.

5.3 MATERIALS AND METHODS

The study was conducted on the long-term fertilization trial on the Experimental Farm of the University of Pretoria. The general layout is discussed in Chapter 3. The O, PK, NP, NK, NPK and WNPKM treatments were selected for this investigation. During the 2004/2005 and 2005/2006 seasons, two plants per plot were sampled at maturity to determine the yield components. The cobs were dried at ± 40 ºC to constant mass. After drying the number of rows on a cob and kernel number per row were recorded. Kernel number per row was determined for the row with the highest number of fully developed kernels on that cob. Kernel numbers per cob were taken as the product of number of rows per cob and the kernel number per row. One hundred kernels from each sample were weighed to determine kernel mass. All the kernels of the two plants from each plot were weighed to determine yield per plant.

Statistical analyses were performed using SAS for Windows V8. The data was subjected to analyses of variance and comparisons were made between means of the treatments, using the Duncan Multiple Range tests or Tukey studentized range test.

5.4 RESULTS AND DISCUSSION

5.4.1 ROW NUMBER PER COB

Soil fertility did not affect row number per cob. There was no significant effect of nutrient stress on the row number per cob during the two seasons (Table 5.1). The highest mean row number was 14 for the WNPKM treatment and the lowest was 12 for NP. Row number is determined by genetic components of the maize rather than the environment (Nielsen, 1995). Regardless of growing conditions the row number for any hybrid will remain constant, and the tendency towards less rows per cob in the NP treatment reflected the presence of very small, malformed cobs in the K-deficient plots.

5.4.2 KERNEL NUMBER PER ROW

Kernel number per row was significantly affected by nutrient deficiencies (Table 5.1). In the 2004/2005 season, the WNPKM treatment produced the highest kernel number per row with an average of 42 while the lowest was 20 kernels in the NP treatment. Similar to the previous season, the WNPKM treatment produced the highest kernel per row (31 kernels) while the NP treatment had the least kernels per row (11 kernels) in 2005/2006. The kernel number per row for the 2005/2006 growing season was about 30% lower than the previous year, due to the late planting with a short season hybrid.

The number of kernels per row is strongly affected by environmental stresses as it is determined by the growth in the length of the ear shoot. Increase in length of the ear shoot allows more spikelet-forming branch primordia to form (Bonnett, 1954). The high number of kernels per row found in the WNPKM treatment reflected the vigorous growth and early cob initiation. Inadequate supply of nutrients limited the growth in other plots. Leaf area and the crop growth rate were affected, reducing photosynthate production and arresting elongation of the ear shoot. The NP and NK plots show the expression of phosphorus and potassium deficiencies on grain formation. The higher the kernel number per row the higher the kernel number per cob which will lead to increase in the grain yield (Bonnett, 1954; Nel *et al.,* 1996).

Svecnjak *et al.* (2006) reported an increase in kernel number per cob due to more kernels per row at low plant populations, where the plants were probably less exposed to stress due to interplant competition.

Table 5.1: Row number per cob, kernels per row, and potential kernels per cob as affected by soil nutrient status

Treatments	Row number cob^{-1}	Kernels number row^{-1}	Kernels number cob^{-1}	Mass kernel^{-1} (g)	Kernel mass cob^{-1} (g)
2004/2005 SEASON					
O	12.75^{a}	21.50^{cd}	274^{cd}	0.24^{cd}	50.00^{d}
PK	12.50^{a}	33.50^{abc}	419^{abc}	0.27^{bc}	92.50^{c}
NP	12.00^{a}	19.75^{d}	237^{cd}	0.23^{cd}	32.50^{d}
NK	12.75^{a}	26.75^{bcd}	341^{bcd}	0.27^{bc}	70.00^{cd}
NPK	13.00^{a}	38.00^{ab}	494^{ab}	0.32^{ab}	190.00^{b}
WNPKM	13.50^{a}	42.25^{a}	570^{a}	0.35^{a}	240.00^{a}
LSD (0.05)	5.04	13.50	203.64	0.06	40.00
2005/2006 SEASON					
O	12.75^{a}	12.25^{b}	156.19^{b}	0.17^{d}	21.32^{c}
PK	13.25^{a}	31.40^{a}	416.05^{a}	0.24^{b}	86.84^{b}
NP	12.00^{a}	10.75^{b}	129.00^{b}	0.19^{cd}	19.00^{c}
NK	12.75^{a}	15.70^{b}	200.18^{b}	0.17^{d}	33.14^{c}
NPK	13.75^{a}	27.25^{a}	374.69^{a}	0.22^{bc}	75.38^{b}
WNPKM	14.00^{a}	30.90^{a}	432.60^{a}	0.34^{a}	133.50^{a}
LSD (0.05)	1.82	4.99	76.34	0.03	15.66

Means within the same column sharing the same letters are not significantly different ($p < 0.05$)

5.4.3 KERNEL NUMBER PER COB

The effect of soil nutrient status on kernel number per cob is illustrated in Table 5.1. In the 2004/2005 season, the WNPKM treatment produced the highest number of kernels per cob (570 kernels) and the NP treatment the least number of kernels (237 kernels) with a similar pattern in 2005/2006. Comparing the highest yielding treatment (WNPKM) with the lowest yielding treatment (NP) the kernel numbers per cob declined by 58% in 2004/2005 and 70% in 2005/2006.

Accurate prediction of kernel number can be used to estimate grain yield. Grain yield is better correlated with kernels per ear than with other yield components (Bolanos & Edmeades, 1996). Result of the present study is consistent with the results of previous studies, which reported that stress drastically reduces kernel numbers (Kamara *et al.,* 2003). Svecnjak *et al.* (2006) recorded low kernel numbers per cob at high plant populations. Kamara *et al.* (2003) established that genotypes with reductions in the kernel number per ear due to water deficits recorded higher reductions in yield. Kernels per plant was the yield component most affected by plant population and defoliation (Tollenaar *et al.,* 1992). According to Jacobs & Pearson (1991) grain yield per plant decreases with increasing plant population, which is due to a decrease in kernel number per plant. The same study reported that an increase in yield due to increased nitrogen fertilizer was associated with increased kernel number per plant.

5.4.4 MASS PER KERNEL

The effect of soil nutrient status on mass per kernel during the 2004/2005 and 2005/2006 seasons is illustrated in Table 5.1. The WNPKM treatment had the highest mass per kernel for the two seasons at approximately 0.35g. The O, NP and NK treatments produced the smallest kernels. Comparing the highest yielding treatment (WNPKM) with the lowest yielding treatments (O and NK) the mass per kernel declined by 34% in 2004/2005 and 50% in 2005/2006.

Pandey *et al.* (2000) attributed reduction in yield to reduce kernel size due to high population, water and nitrogen stress. Both on the apical and subapical ears, high plant population reduced kernel size according to Svecnjak *et al.* (2006). Kamara *et*

al. (2003) reported that water deficit reduced kernel mass irrespective of the genotype. Kernel size increased with increase in nitrogen fertilization, which increased grain yield (Bruns & Ebelhar, 2006). Smaller kernel size resulted from reduced assimilation and low partitioning of assimilates to the grains due to low air temperature and less incident solar radiation (Maddoni *et al.,* 1998). However, many studies agree that reduction in grain yield is due mainly to kernel number that declines with stress rather than kernel mass (Classen & Shaw, 1970; Fischer & Palmer, 1984; NeSmith & Ritchie, 1992; Pandey *et al.,* 2000). Grain number is more closely related to yield than other yield components (Tollenaar, 1977).

5.4.5 KERNEL YIELD PER PLANT

Kernel yield per plant followed the same trend as kernel number per plant (Table5.1). The WNPKM treatment produced the highest grain yield per plant (240g) while the NP treatment resulted in the lowest mass (32.5g) in the 2004/2005 season. Kernel yield per plant of 2005/2006 was approximately 50% lower than that of 2004/2005 in all the treatments except for the PK treatment. Comparing the highest yielding treatment (WNPKM) with the lowest yielding treatment (NP) the kernel yield per plant declined by 86% in 2004/2005 and 85% in 2005/2006.

These results are consistent with previous observations that variations in maize grain yield are mainly related to changes in kernel number per plant (Tollenaar *et al.,* 1992). Kamara *et al.* (2003) reported that genotypes with higher numbers of kernels per cob produced higher grain yield than those with lower numbers of kernels per cob. The balanced nutrient treatment had the highest grain yield of 240g per plant, which is similar to grain yield often reported in literature (NeSmith & Ritchie, 1992). Bruns & Ebelhar (2006) and Kogbe & Adediran (2003) reported that grain yield per plant increases with the increase in nitrogen fertility rates.

5.4.6 GRAIN YIELD PER PLOT

It was observed that irrespective of cultivar and season differences, crop yields reacted similarly to the treatments in both seasons. In the 2004/2005 season, which was a better year both the actual and the estimated grain yield (Figure5.1) followed

the same trend as observed for the yield components. The grain yield estimated based on the yield components data overestimated the actual yields by 30% or more, indicating the potential limitations of sampling. The well-balanced nutrient treatments (WNPKM and NPK) produced the highest actual grain yields of 9.11 and 7.60 t ha^{-1} while the K-deficient treatment (NP) produced the lowest grain yield of 0.56 t ha^{-1}. The good yields obtained from the NPK (and WNPKM) plots after more than 60 years of continuous maize production and with the past 20 years without the benefit of a pea rotation crop illustrates the sustainability of the cropping system. During the 2004/2005 season plants in these plots were vigorous, with no signs of maize diseases or micronutrient deficiencies.

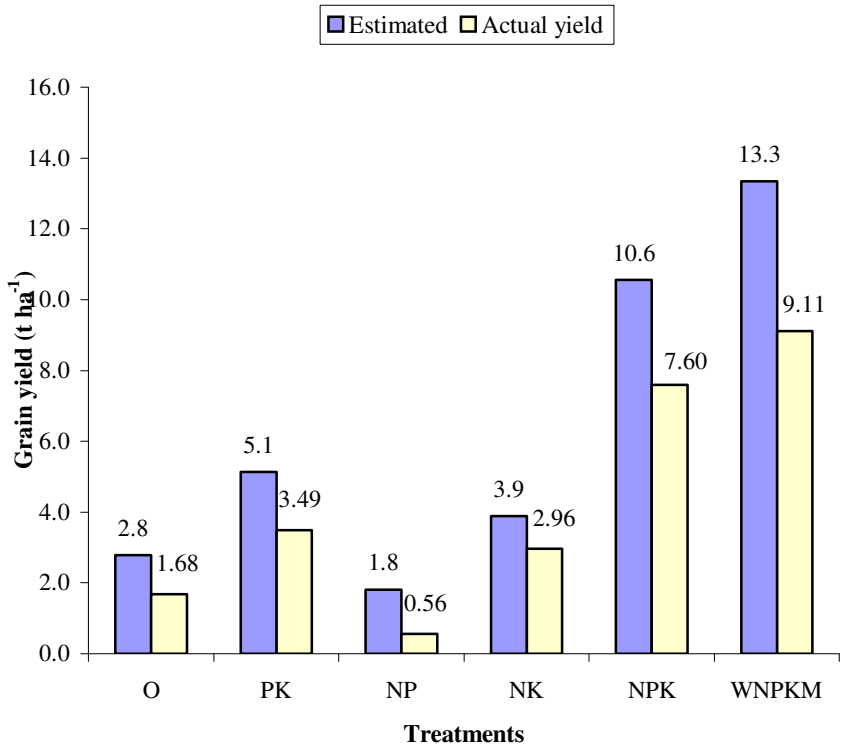

Figure 5.1: Actual and Estimated grain yields as affected by soil nutrient status (Treatment means in Appendix Table A5.2).

Yield trends for the 1980-1990 decade as reported by Nel *et al.* (1996) are illustrated in Figure 5.2 and compared to the 2004/2005 results. The treatment yields followed the same pattern but for all the treatments the yields for 1980-1990 were higher than the yields recorded in 2004/2005. The balanced nutrient treatments (WNPKM and NPK) produced the highest grain yield both in 2004/2005 and during the 1980-1990

decade. The yield of the WNPKM treatment is higher than that of the NPK treatment. Similarly, Jiang *et al.* (2006) reported that higher yield of wheat and maize was recorded in a long-term field trial where both inorganic NPK and manure were applied compared to only inorganic NPK application. The PK treatment followed balanced nutrient treatments in grain yield production. Initially, the rotation of maize with field peas contributed in sustaining relatively good yields in treatments not receiving nitrogen fertilization (Nel *et al.*, 1996). The O treatment, which was unfertilized for more than 60 years, still yielded 1.68 t ha^{-1} in 2004/2005. Similarly, wheat cropped for 150 years without fertilization still produced acceptable yields in the classical Rothamsted trial (Lewis, 1993).

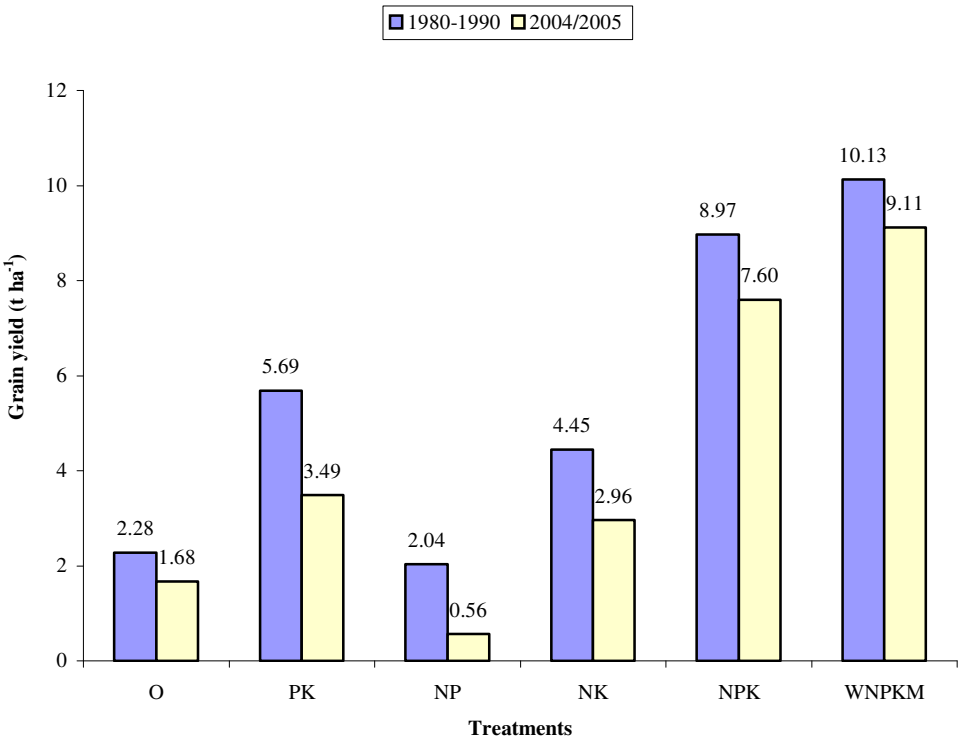

Figure 5.2: Grain yield trends as affected by soil nutrient status.

The grain yield of the unfertilized control (O) treatment tends to be higher than the NP treatment. This is most probably due to a severe potassium deficiency, which manifested during the 1980s` in the NP plots, due to previous decades of over exploiting inherent potassium reserves because of the high levels of N and P fertilization. Grain yields of maize and wheat were higher in plots that were fertilized for 22 years than those plots that were not for the same period (Fan *et al.*, 2005). The

absence of potassium affected wheat yield more than the maize in a long-term trial of 20 years (Jiang *et al.,* 2006). In a review of long-term experiments by Ellmer *et al.* (2000) potassium deficiency resulted in large yield depressions.

5.5 CONCLUSIONS

Nutrient stress decreased both kernel number and kernel mass, the determinants of the grain yield. The negative effect of a potassium deficiency on all the yield components as well as the final grain yield is clearly illustrated. After 66 years of continuous fertilization there was a slight decline in the yield of all treatments. The unfertilized control treatment still produced grain yield of 1-2 t ha^{-1}, while excellent yields of more than 7 t ha^{-1}were obtained from the balanced treatments.

CHAPTER 6

EFFECT OF SHADING ON GROWTH AND REPRODUCTIVE DEVELOPMENT OF MAIZE

6.1 ABSTRACT

The objective was to investigate whether variations in assimilate availability due to different shading levels affect initiation and differentiation of maize reproductive structures in a similar way as nutrient deficiencies. The study was carried out at the Experimental Farm, University of Pretoria. Treatments consisted of three shading levels (10%, 40% and 70% shade nets) and the treatments were replicated four times. Two maize seeds were planted per container of 11 litres in a coir and sand mixture. Each replicate of the shade structures contained forty pots. Plants were regularly sampled, dissected and microscopically inspected to record the stages of reproductive development. Leaf areas were measured and plant tissues were oven dried to constant mass to determine the dry mass. Nine weeks after emergence, plants exposed to 10% shading had a leaf area of 4170cm^2 per plant, at 40% shading it was 3956cm^2 per plant and at 70% shading it was 3349cm^2. The plant dry mass was 36g, 31g and 20g respectively at the ninth week after emergence. Initiation and differentiation of the reproductive structures started earlier in the 10% and 40% shading treatments compared to 70% shading treatment. In the 10% shading, the tassel and the embryonic ear developed at a faster rate than the other treatments. Respectively the lengths of the embryonic ear nine weeks after emergence were 14mm, 9mm and 5mm. The results indicate that low availability of radiation reduced growth and development. Exposure of plants to reduced radiation delayed the initiation of the reproductive structures and reduced the size of these organs. The effect of shading on the rate of differentiation and general morphology of the reproductive organs were similar to the field trial observations on the reaction to soil nutrient status. This suggests that development of the reproductive organs is primarily determined by availability of assimilates.

6.2 INTRODUCTION

The principal source of energy for biomass synthesis is solar radiation. Biomass accumulation by crops is a function of both light intercepted by leaves and the efficiency with which the intercepted light is used to produce dry matter. Many studies demonstrated that the dry matter produced by a crop is directly related to the amount of photosynthetically active radiation (PAR) intercepted by the canopy (Gardner *et al.,* 1985). Idinoba *et al*. (2002) stated that cumulative dry mass is linearly related to cumulative PAR intercepted by the maize crop. Growth rate and optimum leaf area index are radiation dependent (Black, 1963). Leaf area index and distribution of light affect the rate of light absorption of any plant. More radiation is intercepted with increasing canopy size.

Accurate measurement of crop growth and radiation use efficiency (RUE) under optimal growth conditions is required to predict plant dry matter accumulation and grain yield at the genetic growth potential (Lindquist *et al*., 2005). With a decrease in the level of incident radiation and an increase in the proportion of diffuse radiation, radiation use efficiency of maize, soybean and peanut increased (Sinclair *et al*., 1992; Hammer & Wright, 1994). However, radiation use efficiency of maize was higher than cowpea and groundnut (Idinoba *et al*., 2002).

Tollenaar (1977) concluded that the amount of radiation intercepted to produce photosynthate during flowering is the main factor determining final kernel number. The rate of dry matter production affects the amount of assimilates allocated to the developing inflorescences and the grain sink development. This is determined by the competition between various sinks (Johnson *et al.*, 1986; Mostut & Marais, 1982). Shading reduced the dry mass of ears, husk of the ear, tassels and grain yield in both temperate and tropical adapted cultivars of maize (Aluko & Fischer, 1987). Low levels of radiation reduced seed production of tropical pasture grasses (Humphreys, 1979; Oliveira & Humphreys, 1986).

Under favourable conditions, maize reproductive development may begin about two weeks after emergence (Kiesselbach, 1949; Galinat & Naylor, 1951). Ears develop from one or more of the upper axillary shoots of the stem after tassel differentiation

has commenced (Bonnett, 1948; Kiesselbach, 1949). The early stages of ear development are similar to the corresponding stages in the development of the tassel, except that there are no branches on normal ears (Kiesselbach, 1949). Little information exists on the effect of shading on the reproductive development of maize. The objective was to investigate whether variations in assimilate availability due to different shading levels affect initiation and differentiation of maize reproductive structures in a similar way as nutrient deficiencies. Therefore, this experiment was carried out to investigate how shading levels affect growth and time of initiation and differentiation of maize reproductive structures.

6.3 MATERIALS AND METHODS

The study was conducted in shade net structures on the Experimental Farm of the University of Pretoria (25°45′ N, 28°16′ E). Treatments consisted of three shading levels of 10%, 40% and 70% light exclusion, with four replications in a randomized complete block design. Shade nets were made of black synthetic cloth of different mesh. Each shade net structure covered an area of 55m^2. Two maize seeds were planted per container of 11 litres in a coir and sand mixture. Fertigation was done by the drip method, four times per day for 15 minutes. A standard nutrient solution was applied at a rate of 500ml per 15 minutes resulting in vigorous growth of the plants.

Radiation was measured with a Sunfleck Ceptometer at midday. The average percentages of full sunlight available at noon in the shade net structures of 10%, 40% and 70% shadings were 87%, 56% and 28% respectively. Starting three weeks after emergence, two plants per treatment were sampled weekly to determine leaf area, dry mass and reproductive development. Leaf area was measured with a Li-Cor LAI 3000 leaf area meter. The plants were oven dried to constant mass to determine total dry mass. The apical meristems of the main shoots were dissected and inspected with a dissecting microscope every week to monitor the stage of tassel development. The two topmost axillary shoots were dissected to monitor ear development. Developmental stages of the reproductive structures identified in Chapter 4 were used to quantify differences in the developmental rate.

Statistical analyses were performed using SAS program for Windows V8. The data were subjected to analyses of variance and comparisons were made between means of the treatments, using the least significant difference (LSDs) test at a probability level of 5%.

6.4 RESULTS AND DISCUSSION

6.4.1 LEAF AREA PER PLANT

The leaf area was significantly affected by shading (Figure 6.1). Nine weeks after emergence plants exposed to the shading level of 10% light exclusion had the highest leaf area of 4170cm^2 per plant while in the shading level of 70% light exclusion the leaf area per plant was 3349cm^2.

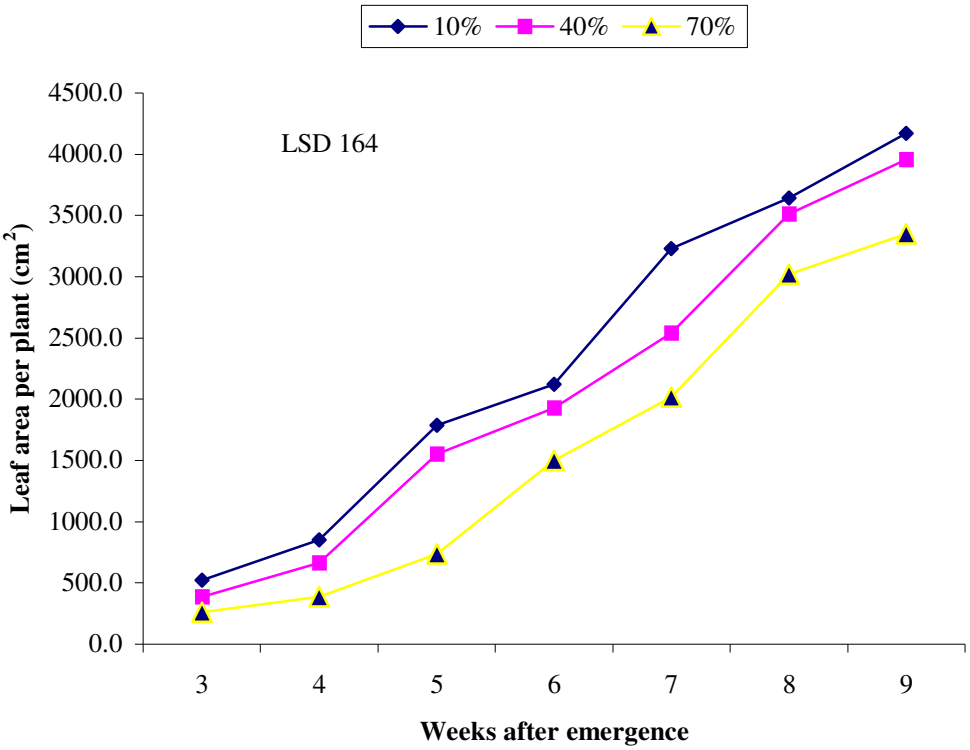

Figure 6.1: Leaf area per plant as affected by different shading levels (Treatment means in Appendix Table A6.2).

Light stress is detrimental to canopy formation. Figure 6.1 illustrates that increased light availability increased leaf area. The capacity of a crop to intercept solar radiation is expressed as leaf area index, which is a function of leaf area per unit land

area. Black (1963) also reported that increased radiation increased leaf area index (LAI). Healey *et al.* (1998) demonstrated that the leaf area index was higher in the full sun than under different shade structures and a linear relationship between radiation level and the leaf area index was established.

6.4.2 TOTAL DRY MASS

Total plant dry mass till nine weeks after emergence are illustrated in Figure 6.2. Dry mass was significantly affected by radiation level. Dry mass increased linearly over time for each treatment but differed between the treatments. Five weeks after emergence the total dry mass for plants in 10% light exclusion shade net was 17.1g while it was 5.2g for plants in the 70% light exclusion treatment.

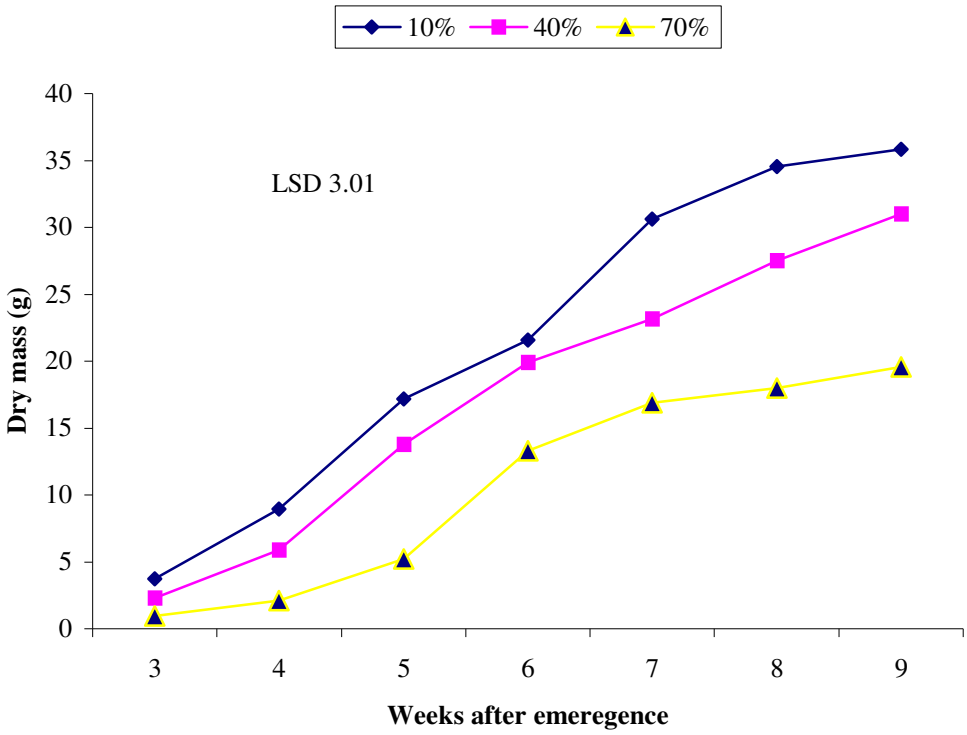

Figure 6.2: Effects of different shading levels on plant dry mass (Treatment means in Appendix Table A6.4).

The results are in agreement with the study carried out by Aluko & Fischer (1987) indicating that shading reduces the total dry mass of maize while enhanced radiation increases it. Total dry matter yield is a result of crop canopy efficiency in intercepting and utilizing the solar radiation available (Gardner *et al.*, 1985) and dry mass of plants increase with the available light (Black, 1963).

6.4.3 REPRODUCTIVE DEVELOPMENT

Table 6.1 demonstrates the influence of different shading levels on the developmental rate of the reproductive structures. Differentiation of the reproductive structures started earlier in 10% and 40% levels of shading compared to 70% shading. Nine weeks after emergence development of the tassel and the embryonic ear were in a more advanced stage in the 10% shading level than the rest of the treatments.

Table 6.1: Developmental stages of maize reproductive structures as affected by different levels of shading

Treatments		Weeks after emergence						
		3	4	5	6	7	8	9
10%	Tassel	A	B	B	C	D	E	F
	Ear	A	A	A	B	C	D	E
40%	Tassel	A	B	B	C	C	D	D
	Ear	A	A	A	B	B	C	C
70%	Tassel	A	A	B	B	C	C	C
	Ear	A	A	A	A	B	B	B

Developmental stages A-F as illustrated in Figures 4.1 and 4.2

The increase in size of the reproductive structures are illustrated in (Figure 6.3 & Figure 6.4). Nine weeks after emergence the tassel length in the 10% shading treatment was 315mm compared to 110mm and 70mm of 40% and 70% shading treatments respectively. The size of the embryonic ear of 10%, 40% and 70% levels of shading at the ninth week after emergence were 14mm, 9mm and 5mm respectively.

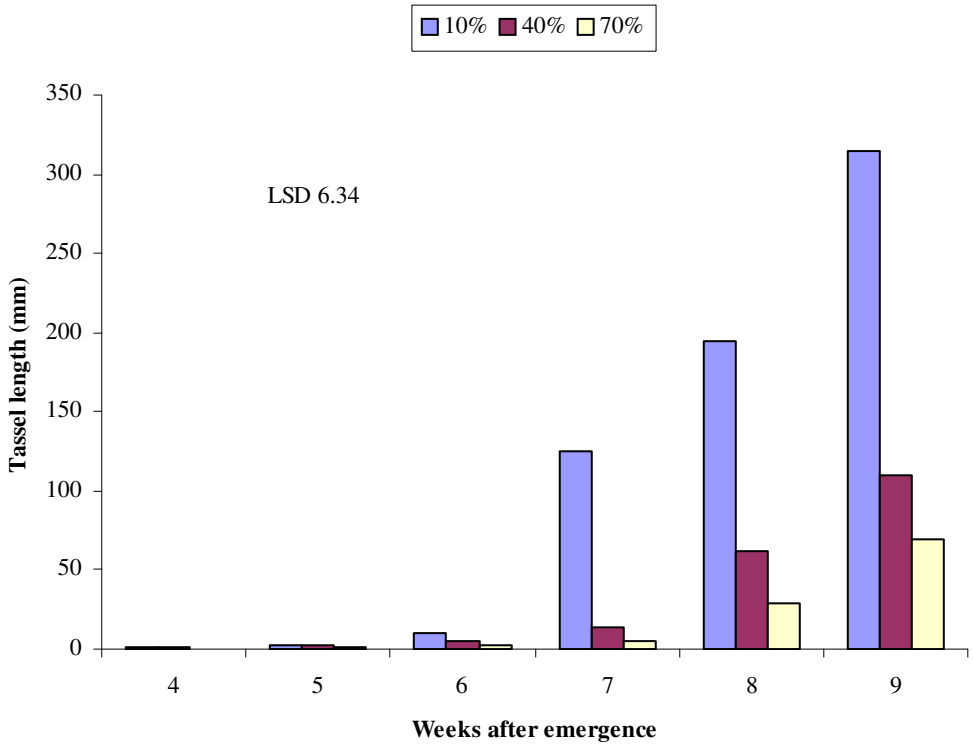

Figure 6.3: Effect of different shading levels on tassel development (Treatment means in Appendix Table A6.5).

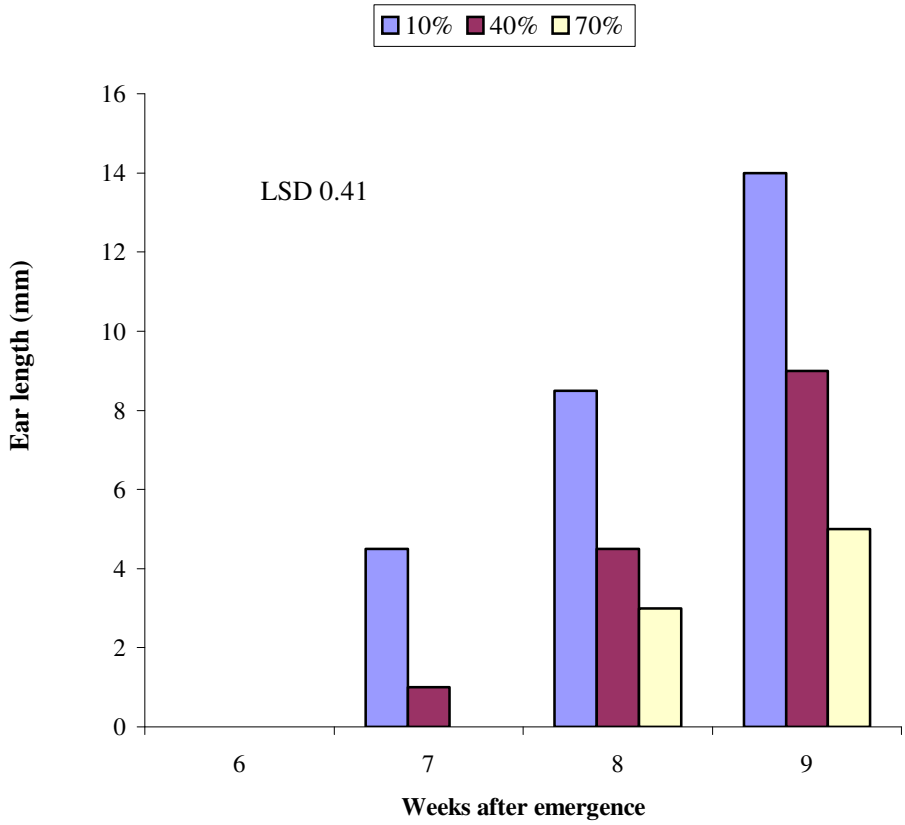

Figure 6.4: Effect of different shading levels on embryonic ear development (Treatment means in Appendix Table A6.6).

Information is scarce on the effect of continuous shading on the initiation and development of reproductive structures. Many studies were carried out on the effect of light stress on yield rather than reproductive development. These experiments often involved shading at a particular stage of the crop development. Maize exhibited higher sensitivity towards light stress imposed after silking rather than before silking (Gerakis & Papkosta-Tasopoulou, 1980). Aluko & Fischer (1987) reported that reduction in radiation during the early stage of grain development reduced grain yield may be due to reduction in assimilates for grain filling. Shading at the reproductive stage reduced yield of soybean cultivars (Egli, 1997). Hay & Walker (1989) concluded that shading reduces both tiller survival and floret formation, resulting in fewer ears and grains per ear in wheat. Shading reduced yield and yield components of *Panicum maximum* (Oliveira & Humphreys, 1986).

6.5 CONCLUSIONS

Shade reduced the leaf area, limiting the canopy size for radiation interception and thus decreased biomass. The initiation of the reproductive structures was delayed by reduced radiation and the size of the embryonic reproductive organs were reduced. Decreased availability of assimilates due to shading delayed the development of the reproductive organs in a similar manner than the decreased biomass production observed in the unbalanced fertilization treatments in the field trial. This may be an indication that the development of the reproductive organs in maize is closely correlated with biomass production (i.e. availability of assimilates).

CHAPTER 7

GENERAL DISCUSSION AND CONCLSUIONS

Long-term experiments are valuable sources of information for understanding factors influencing soil fertility and sustainable production. A long-term fertilization trial was established in 1939 on the experimental farm of the University of Pretoria, and over decades dramatic differences in the soil nutrient status of the 32 treatment combinations developed. This is directly reflected in the yield response of the maize, as reported by Nel *et al.* (1996). The long term trial offered a unique opportunity towards a better understanding of how differences in nutrition affects early growth and development and consequently yield, aspects which have received little attention in the specific trial. Clearly, yield differences must emanate from differences in early growth that should be quantifiable by means of standard growth analyses and differences in early reproductive development, both probably affecting the yield components in one way or another.

It is not clear whether the potential size of maize cobs is actually determined soon after initiation, or whether the supply of assimilates and other growth substrates later in the pre-anthesis stage are key factors. Thus, this study was carried out to quantify the effect of soil nutrient status of the selected treatments in the long-term trial on the growth and development of maize, the development of the reproductive organs, yield components and grain yield. In a shading trial the development of the reproductive organs at different light intensities were monitored to establish whether assimilate availability may explain the differences in the differentiation of the reproductive structures.

In **Chapter 3** the effect of soil nutrient status on growth was examined by means of classical growth analyses. Unacceptably large variations in the net assimilation rate (NAR), relative growth rate (RGR) and crop growth rate (CGR) occurred probably due to the small samples (two plants per plot) and problems regarding representative sampling. Differences in canopy development (LAI) were prominent as early as three weeks after emergence. At eight weeks after emergence the WNPKM plots had a LAI

of 5.4 while the NK and O treatments had leaf area indices less than 1. Serrano *et al.* (1995) also observed that balanced nutrition encourages adequate development of the photosynthetic factory in crops. Canopy size directly related to biomass during early growth conditions (soil nutrient status) better than with growth rate estimates (NAR, RGR, CGR).

In **Chapter 4** the effect of soil fertility status on the initiation and differentiation of reproductive organs and how it affects the yield components were investigated. The well-balanced nutrient treatments promoted early tassel and embryonic ear development, while nutrient deficiencies slowed the development and limited the size of the reproductive structures, especially in the phosphorus deficient (NK) treatment. Development of tassels and ears were delayed by temperature stress (Coligado & Brown, 1974), nutrient deficiency (Jacobs & Pearson, 1991), water stress (Abrecht & Carberry, 1993), and photoperiod extension (Acker & Laubscher, 1980; Lejeune & Bernier, 1996). The linear relationship between the leaf area index (LAI), dry mass and the size of the reproductive organs emphasizes the importance of vegetative development in reproductive growth of maize. The larger the leaf area or the dry mass the larger the size of the reproductive structures during the entire growing period. Early in the growing period, larger reproductive organs were also at more advanced stages of development.

Reproductive structures were timely developed in the well-balanced nutrient treatment, which enabled synchronization of tasseling and silking. Silking in the phosphorus deficient treatment (NK) was very late and will probably result in poor pollination. Higher kernel numbers and larger kernel mass were recorded in the well-balanced nutrient treatments, while the potassium and phosphorus deficient treatments produced the lowest kernel number and the smallest kernel mass. Of all the yield components, kernel number was most affected by the soil nutrient status.

In **Chapter 5** the effect of soil nutrient status on yield components and grain yield was investigated. Nutrient stress decreased kernel number and kernel mass, which are the major determinants of the grain yield. The well-balanced nutrient treatments produced more than 400 kernels per cob and kernel mass of over 30 g/100seeds. The nutrient deficient treatments especially potassium deficient treatment produced less

than 300 kernels per cob and kernel mass of less than 25 g/100seeds. Consequently, the well-balanced nutrient treatments produced the highest grain yields, which ranged between 7 and 9 t ha^{-1} while the K-deficient treatment produced the lowest grain yield of 0.56 t ha^{-1}. Grain yield for the 2004/2005 season was compared with the grain yield of the last decade as reported by Nel *et al.* (1996). The same yield trend was maintained throughout the treatments after continuous fertilization for more than 60 years. The well-balanced nutrient treatments still produced more than 7 t ha^{-1} while the control treatment, which was unfertilized for more than 60 years still produced close to 2 t ha^{-1}. The better performance of unfertilized control treatment than the potassium deficient treatment indicated the negative effect of potassium deficiency on grain yield.

In **Chapter 6** the effect of shading on the growth and time of initiation and differentiation of maize reproductive organs was investigated. This is to know whether variations in assimilate availability due to different shading levels affect initiation and differentiation of maize reproductive structures in a similar way as nutrient deficiencies. Intensive shading reduced plant mass and delayed initiation and differentiation of the reproductive organs. This may be an indication that the development of the reproductive organs in maize is closely correlated with biomass production (i.e. availability of assimilates), and that nutrient deficiencies do not affect reproductive development in a more direct way.

Aspects deserving future research include:

- Investigate if and when the effect of nutrient stress on the reproductive structures can be corrected during the growing season.
- Determine whether the potential number of kernels per cob can be estimated at an early embryonic stage in the development of the reproductive organs.
- Investigate effect of nutrient deficiencies on viability of pollens and pollination of maize.
- The pivitol role of organic compounds in the soil on either the physiology of the plant or the availability of inorganic nutrients to the plant or both.

SUMMARY

The objectives of this research were to:

(1) Investigate the effect of soil nutrient status on growth and development of the reproductive structures of maize.
(2) Quantify how the effect of soil fertility will be reflected in the yield components at maturity.
(3) Determine the effect of soil nutrient status on grain yield.
(4) Determine the influence of shading on reproductive development of maize.

Treatments selected from a long-term trial for this study were the O (unfertilized), PK (nitrogen), NK (phosphorus), NP (potassium), NPK, and WNPKM treatments. Plants were regularly sampled, dissected and microscopically inspected to carry out growth analyses and to monitor the stage of reproductive development. Rate of tasseling and silking was monitored. At maturity yield components were determined both in 2004/2005 and 2005/2006. In a shading trial, the treatments consisted of three shading levels (10%, 40% and 70% light exclusion) in shade net structures. Leaf areas and plant dry mass were recorded. Plants were regularly sampled, dissected and microscopically inspected to record the stages of reproductive development

Three weeks after emergence the LAI of WNPKM plots was already about five times higher than the LAI of the other treatments. At the end of the eighth week, the WNPKM treatment had the highest total dry mass of 90g per plant, while NK had the lowest at 4.9g. There tended to be a gradual decline in net assimilation rate (NAR) for most of the treatment combinations as the season progressed. The WNPKM treatment exhibited the highest crop growth rate (CGR) of 233g m^{-2} $week^{-1}$, while the NK and O treatments had the lowest crop growth rates of 19 and 17.7g m^{-2} $week^{-1}$ respectively. The variability of results indicates possible limitation of growth analyses to explain treatment effects.

Tassel development was earlier in the WNPKM treatment and the final phase of ear development was reached during the seventh week after emergence. The NK treatment had the slowest rate of embryonic tassel development and completed

development later than the seventh week after emergence, while the ear differentiation was still in the early phases of development.

A linear relationship was observed between the LAI and the size of the reproductive structures. The WNPKM treatment had the highest LAI and resulted in the largest reproductive structures. Generally, the size of reproductive organs increased with increase in the canopy size. The well-balanced nutrient treatment (WNPKM) resulted in the highest biomass with the largest reproductive structures, while nutrient deficient treatments NK and O, produced the lowest dry mass which was associated with the smallest reproductive structures. Nine weeks after emergence all the plants of the WNPKM treatment have tasselled while more than 90% have reached silking. In the same week the other treatments exhibited between zero and 30% tasseling. Twelve weeks after emergence the PK treatment had about 80% of its population silking while the O and NK treatments had less than 40% of plants silking.

There was no significant effect of nutrient stress on the row number per cob. The WNPKM treatment produced the highest kernel number per row while the lowest was found in the NP treatment in both seasons. The WNPKM treatment produced the highest number of kernels per cob (570 kernels) while the NP treatment produced the least number of kernels (237 kernels). In the 2004/2005 season, the WNPKM treatment produced the highest grain yield per plant (240g) while the NP treatment had the lowest mass (32.5g). Yield data for the 2004/2005 season was compared to the mean yield for the 1980-1990 decade as reported by Nel *et al*. (1996). The yields followed the same pattern but the mean yield for 1980-1990 was higher than the yield in 2004/2005. The balanced nutrient treatments (WNPKM and NPK) produced the highest grain yield both in 2004/2005 and 1980-1990 decade. The O (control) treatment, which was unfertilized for more than 60years, still yielded 1.68t ha^{-1} in 2004/2005.

Nine weeks after emergence, plants exposed to 10%, 40% and 70% shading had leaf areas of 4170cm^2 per plant, 3956cm^2 per plant and 3349cm^2 per plant respectively. The dry mass was 36g, 31g and 20g at the ninth week after emergence. Initiation and differentiation of the reproductive structures started earlier in the 10% shading and 40% shading treatments compare to 70% shading treatment. In the 10% shading, the

differentiation of embryonic reproductive organs was in a more advanced stage of development than the other treatments. Linear relationship between the canopy size, dry mass and the size of the reproductive organs shows that the results from the long-term trial are similar to that of the shade trial.

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APPENDIX

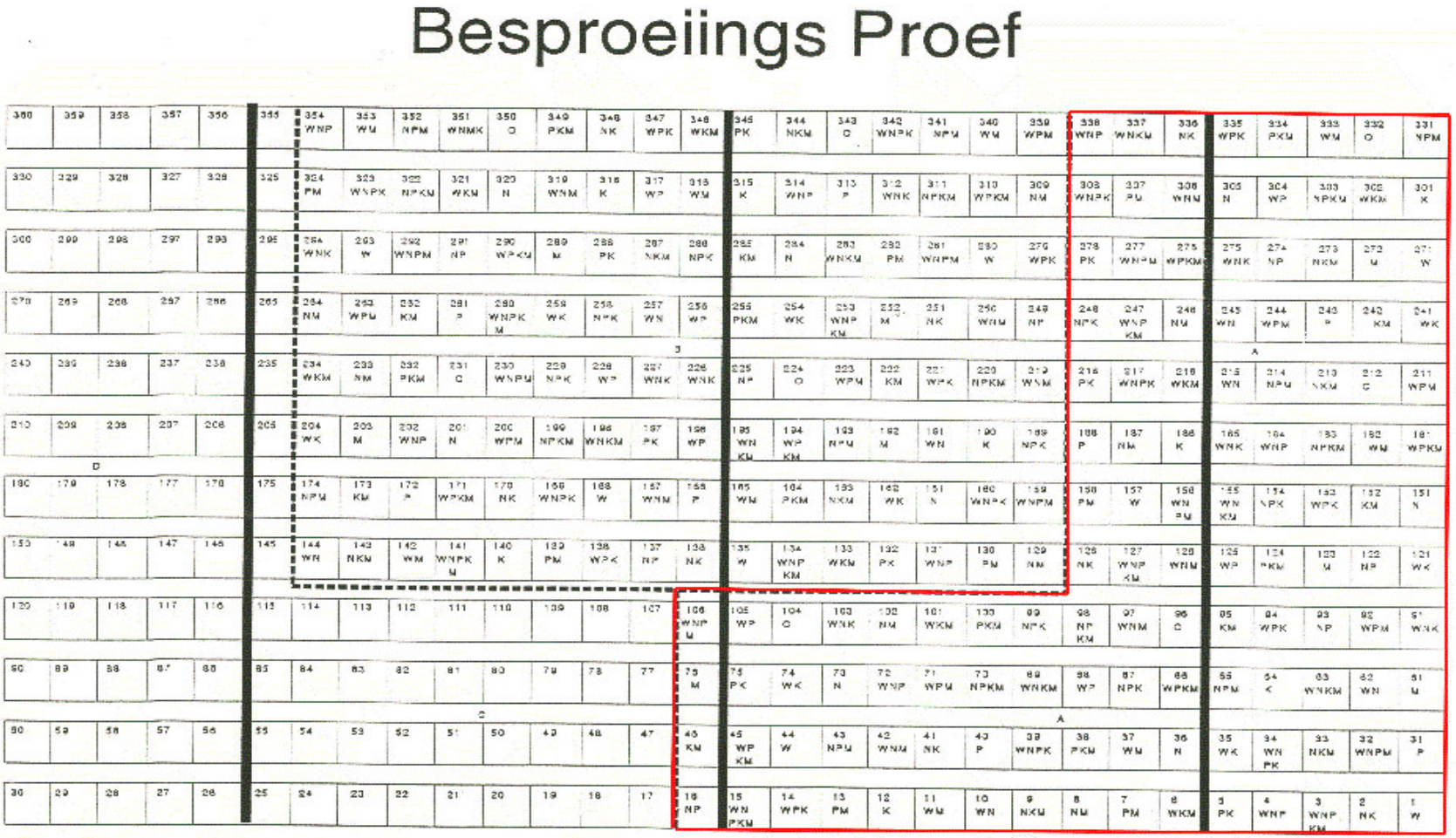

Figure A1: Experimental layout of the long-term fertilization trial, Experimental farm, University of Pretoria (Red line indicates experimental plots).

*, ** = Significantly different at 5% and 1% level of probability respectively
ns = not significant
DF = degree of freedom

Table A3.1: Summary of analyses of variance for leaf area, leaf area index, leaf area duration, dry mass, net assimilation rate, crop growth rate, and relative growth rate.

		Leaf area		Leaf area index		Leaf area duration		Dry mass		Net assimilation rate		Crop growth rate		Relative growth rate	
Source	DF	MS	F	MS	F	MS	F	MS	F	MS	F	MS	F	MS	F
Treatments	5	0.10005	127.13**	1.388306	137.47**	15.06452	454.37**	44.66226	61.72**	0.129345	4.72*	0.035734	0.63ns	0.041094	0.82ns
Block	3	0.008719	11.08**	0.135165	13.38**	0.476923	14.38**	6.482272	8.96**	0.050518	1.84ns	0.098807	1.74ns	0.096041	1.92ns
Weeks	5	0.039072	49.65**	0.600899	59.5**	16.76367	505.62**	31.96001	44.17**	0.217811	7.95**	0.018779	0.33ns	0.282455	5.64ns
Trt*Week	25	0.003797	4.82**	0.044905	4.45**	1.493429	45.04**	3.018972	4.17**	603933.1	3.5**	0.072658	1.28ns	0.064521	1.29ns
Error	93	0.000787		0.010099		0.033155		0.723631		0.027407		0.056842		0.050076	
C.V		3.55		9.45		19.55		28.89		7.79		10.12		7.12	
R^2		0.93		0.93		0.98		0.89		0.61		0.30		0.43	

Table A3.2: Summary of analyses of variance for Leaf area weekly.

		Weeks after emergence											
		3		4		5		6		7		8	
Source	DF	MS	F	MS	F	MS	F	MS	F	MS	F	MS	F
Treatments	5	0.000585	355.93**	0.0248	254.57**	0.072585	136.2**	0.097409	25.61**	0.140485	48.71**	0.090363	24.07**
Block	3	5.2E-07	0.32ns	0.000492	5.05*	0.000465	0.87ns	0.006377	1.68ns	0.011201	3.88*	0.023268	6.2**
Error	15	1.64E-06		9.74E-05		0.000533		0.003803		0.002884		0.003755	
C.V		7.84		16.87		20.55		40.79		29.63		27.98	
R^2		0.99		0.99		0.98		0.90		0.94		0.90	

Table A3.3: Summary of analyses of variance for LAI weekly.

		Weeks after emergence											
		3		4		5		6		7		8	
Source	DF	MS	F	MS	F	MS	F	MS	F	MS	F	MS	F
Treatments	5	0.018063	355.93**	0.76543	254.57**	2.240289	136.2**	3.006458	25.61**	4.335961	48.71**	2.788975	24.07**
Block	3	1.62E-05	0.32ns	0.015175	5.05*	0.01435	0.87ns	0.196818	1.68ns	0.345704	3.88*	0.718153	6.2**
Error	15	5.08E-05		0.003007		0.016449		0.117383		0.089019		0.115892	
C.V		7.84		16.87		20.55		40.79		29.63		27.98	
R^2		0.99		0.99		0.98		0.90		0.94		0.90	

Table A3.4: Summary of analyses of variance for LAD weekly.

		Weeks after emergence											
		3		4		5		6		7		8	
Source	DF	MS	F	MS	F	MS	F	MS	F	MS	F	MS	F
Treatments	5	18.75	225**	0.287697	367.26**	1.399193	246.1**	2.602054	66.76**	3.629033	62.69**	3.482841	75.91**
Block	3	0.083333	1**	0.0076	9.7**	0.01341	2.36ns	0.069817	1.79ns	0.234595	4.05*	0.439655	9.58**
Error	15	0.083333		0.000783		0.005685		0.038977		0.057885		0.045879	
C.V		23.09		13.06		15.89		26.97		26.06		19.27	
R^2		0.99		0.99		0.99		0.96		0.96		0.96	

Table A3.5: Summary of analyses of variance for dry mass weekly.

		Weeks after emergence											
		3		4		5		6		7		8	
Source	DF	MS	F	MS	F	MS	F	MS	F	MS	F	MS	F
Treatments	5	2.787628	58.2*	31.28825	71.16**	198.9103	90.01**	737.4131	22.97**	2982.321	24.58**	4064.001	6.75**
Block	3	0.033075	0.69 ns	3.424849	7.79*	3.058582	1.38 ns	46.78904	1.46 ns	169.3311	1.40 ns	1336.178	2.22 ns
Error	15	0.047895		0.439665		2.209979		32.1083		121.3087		601.7412	
C.V		23.06		24.58		22.10		48.09		55.35		36.31	
R^2		0.98		0.96		0.97		0.89		0.89		0.73	

Table A3.6: Summary of analyses of variance for NAR weekly.

		Weeks after emergence									
		4		5		6		7		8	
Source	DF	MS	F	MS	F	MS	F	MS	F	MS	F
Treatments	5	792.3764	2.95*	2316.835	3.93*	974.6841	2.23 ns	3910.648	3.05*	2450.168	0.37 ns
Block	3	359.2743	1.34 ns	407.21	0.69 ns	215.9705	0.49 ns	553.9931	0.43 ns	10966.54	1.68 ns
Error	15	268.7122		589.9582		436.4813		1283.344		6534.506	
C.V		32.24		49.54		16.95		12.92		20.93	
R^2		0.56		0.59		0.46		0.52		0.32	

Table A3.7: Summary of analyses of variance for RGR weekly.

		Weeks after emergence									
		4		5		6		7		8	
Source	DF	MS	F	MS	F	MS	F	MS	F	MS	F
Treatments	5	209010.5	2.14 ns	484907.6	2.94*	224103.2	2.52ns	492811.8	2.59ns	186139.6	0.48ns
Block	3	114896.1	1.18ns	101683.8	0.62ns	32345.46	0.36ns	49512.47	0.26ns	773115.8	1.99ns
Error	15	97599.2		164672.9		88939.92		189982.8		388062.9	
C.V		32.70		49.66		59.52		13.91		16.48	
R^2		0.49		0.52		0.48		0.48		0.36	

Table A3.8: Summary of analyses of variance for CGR weekly.

		Weeks after emergence									
		4		5		6		7		8	
Source	DF	MS	F	MS	F	MS	F	MS	F	MS	F
Treatments	5	1216.958	24.93**	4328.481	16.5**	7338.974	5.54**	32466.87	4.85**	11222.07	0.39ns
Block	3	182.0949	3.73*	39.46868	0.15ns	1532.742	1.16ns	5661.602	0.85ns	43129.33	1.51ns
Error	15	48.81223		262.3662		1324.109		6697.299		28581.37	
C.V		44.66		49.79		15.19		49.28		25.12	
R^2		0.90		0.85		0.68		0.64		0.30	

Table A3.9: Mean leaf area (m^2) of selected treatments for six weeks.

	Weeks after emergence					
Treatments	3	4	5	6	7	8
O	0.052815	0.015513	0.026826	0.040144	0.06544	0.096094
PK	0.015423	0.03773	0.113396	0.16696	0.208429	0.292286
NK	0.009405	0.0198	0.026185	0.05736	0.038643	0.086056
NP	0.011141	0.033468	0.067658	0.119467	0.170319	0.210592
NPK	0.011463	0.026254	0.060514	0.067883	0.065943	0.14643
WNPKM	0.054748	0.218364	0.379384	0.455215	0.538606	0.482563
LSD (0.05)	0.0033	0.0149	0.0348	0.0929	0.0809	0.0924

Table A3.10: Mean leaf area index of selected treatments for six weeks.

	Weeks after emergence					
Treatments	3	4	5	6	7	8
O	0.1	0.16	0.27	0.4	0.65	0.96
PK	0.15	0.38	1.13	1.67	2.08	2.92
NK	0.09	0.2	0.26	0.57	0.76	0.86
NP	0.11	0.33	0.68	1.19	1.7	2.11
NPK	0.11	0.26	0.61	0.68	0.96	1.46
WNPKM	0.52	0.97	1.83	4.55	5.39	4.83
LSD (0.05)	0.02	0.08	0.19	0.52	0.45	0.51

Table A3.11: Mean leaf area duration (weeks) of selected treatments for six Weeks.

Treatments	Weeks after emergence					
	4	5	6	7	8	Total
O	0.13	0.21	0.33	0.53	0.81	2.01
PK	0.27	0.76	1.40	1.88	2.50	6.80
NK	0.15	0.23	0.42	0.67	0.81	2.27
NP	0.22	0.51	0.94	1.45	1.90	5.02
NPK	0.19	0.43	0.64	0.82	1.21	3.30
WNPKM	0.75	1.40	3.19	4.97	5.11	15.41
LSD (0.05)	0.04	0.11	0.30	0.36	0.32	

Table A3.12: Mean dry mass (g) of selected treatments for six weeks.

	Weeks after emergence					
Treatments	3	4	5	6	7	8
O	0.43	0.87	1.61	2.93	4.65	7.09
PK	0.76	2.13	8.22	11.9	19.49	33.77
NK	0.48	1.12	1.61	4.04	4.52	4.85
NP	0.55	2.09	4.6	8.51	13.75	17.39
NPK	0.58	1.67	4.09	4.68	7.74	17.39
WNPKM	3.71	10.07	18.87	38.66	74.05	90.04
LSD (0.05)	0.56	1.00	2.24	8.54	16.60	36.97

Table A3.13: Mean net assimilation rate (g m^{-2} $week^{-1}$) of selected treatments for six weeks.

	Weeks after emergence				
Treatments	4	5	6	7	8
O	33.82	31.64	36.94	37.57	22.39
PK	54.19	89.88	24.83	36.56	61.06
NK	42.99	21.18	52.56	-17.27	28.12
NP	71.86	54.03	41.22	34.85	23.28
NPK	60.75	56.60	8.19	3.38	79.66
WNPKM	41.47	40.85	41.94	72.96	22.18
LSD (0.05)	24.71	36.61	31.49	53.99	121.83

Table A3.14: Mean relative growth rate (mg $g^{-1}week^{-1}$) of selected treatments for six weeks.

	Weeks after emergence				
Treatments	4	5	6	7	8
O	659.6405	548.24	570.6831	579.69	289.6119
PK	1019.587	1375.77	342.8594	435.3024	618.9502
NK	795.736	359.2052	784.6443	-254.26	401.9651
NP	1313.067	833.7743	595.8206	458.0823	290.5105
NPK	1060.691	882.5664	112.3846	49.17908	606.13
WNPKM	883.533	903.7343	599.9843	656.302	51.58421
LSD (0.05)	470.85	611.61	449.48	656.93	938.88

Table A3.15: Mean crop growth rate (g m^{-2} $week^{-1}$) of selected treatments for six weeks.

	Weeks after emergence				
Treatments	4	5	6	7	8
O	3.333742	5.832351	8.885201	13.16814	17.70148
PK	11.61204	58.53691	25.63974	50.62821	96.81436
NK	5.20838	3.117774	20.29095	-5.4631	19.15666
NP	14.43608	20.08135	28.65836	34.96731	23.868
NPK	8.996637	21.44996	4.221792	1.90758	129.5791
WNPKM	50.26841	86.18317	119.8602	233.7145	118.429
LSD (0.05)	10.53	24.41	54.84	123.34	254.80

Table A3.16: Summary of regression equation fitted for NAR data.

Treatments	Fitted regression equation	R^2
O	y=-2.1908x2 + 24.597x - 31.864	0.64
PK	y=3.8855x2 - 50.585x + 209.16	0.15
NK	y=2.3703x2 - 35.262x + 147.01	0.19
NP	y=1.353x2 - 27.871x + 160.86	0.99
NPK	y=14.604x2 - 176.79x + 547.51	0.65
WNPKM	y=-5.0287x2 + 59.697x - 123.21	0.27

Table A3.17: Summary of regression equation fitted for RGR data

Treatments	Fitted regression equation	R^2
O	y=-8.8869x2 + 28.567x + 633.72	0.77
PK	y = 10.318x2 - 263.33x + 1416.8	0.59
NK	y = 48.932x2 - 435.24x + 1183.9	0.32
NP	y=34.903x2 - 461.57x + 1692.3	0.98
NPK	y= 85.931x2 - 731.59x + 1763.9	0.67
WNPKM	y = -6.8782x2 - 115.86x + 1064.9	0.79

Table A4.1: Summary of analyses of variance for tassel and embryonic ear lengths.

		Tassel length		Ear length	
Source	DF	MS	F	MS	F
Treatments	5	77074.18	39.23**	544.0429	15.04**
Block	3	11653.65	5.93ns	85.95	2.38ns
Weeks	5	239910.9	122.13**	1248.407	34.51**
Trt*Week	25	11884.2	6.05**	143.1485	3.96**
Error	93	1964.447		36.17366	
C.V		47.65		51.91	
R^2		0.92		0.80	

Table A4.2: Summary of analyses of variance for tassel length weekly.

		Weeks after emergence											
		3		4		5		6		7		8	
Source	DF	MS	F	MS	F	MS	F	MS	F	MS	F	MS	F
Treatments	5	6.75	81**	1472.875	25.48**	5249.675	395.46**	19489.34	34.55**	70706.74	25.62**	60164.97	10.86**
Block	3	0.083333	1ns	54.375	0.94ns	24.375	1.84ns	1702.042	3.02ns	6866.931	2.49ns	19241.06	3.47*
Error	15	0.083333		57.80833		13.275		564.1417		2759.564		5537.722	
C.V		38.49		33.32		17.45		38.91		33.34		28.34	
R^2		0.99		0.90		0.99		0.92		0.90		0.81	

Table A4.3: Summary of analyses of variance for embryonic ear length weekly

		Weeks after emergence											
		3		4		5		6		7		8	
Source	DF	MS	F	MS	F	MS	F	MS	F	MS	F	MS	F
Treatments	5	0.083333	1 ns	2.666667	24**	10.04167	45.76**	38.34167	13.44**	561.275	14.99**	791.5417	5.24**
Block	3	0.083333	1 ns	0.111111	1ns	0.152778	0.7 ns	7.152778	2.51 ns	45.48611	1.21 ns	195.7083	1.3 ns
Error	15	0.083333		0.111111		0.219444		2.852778		37.45278		151.075	
C.V		34.41		10.00		59.17		52.64		17.07		16.83	
R^2		0.55		0.89		0.94		0.83		0.84		0.67	

Table A4.4: Average tassel lengths (mm) of selected treatments for six weeks.

	Weeks after emergence					
Treatments	3	4	5	6	7	8
O	0	0.25	2.5	14.5	64.25	168
PK	0	2	11.75	73	208.75	361
NK	0	0.25	1.5	19.5	28.5	96
NP	0	2.5	7	43.75	170	290
NPK	0	1.5	6.75	19.25	82.5	233
WNPKM	6	48.25	94.5	196.25	391.25	427.5
LSD (0.05)	0.74	11.46	5.49	35.80	79.17	112.16

Table 4.5: Average ear lengths (mm) of selected treatments for six weeks.

	Weeks after emergence					
Treatments	3	4	5	6	7	8
O	0	0	0	1	3	6
PK	0	0	1	4	8	27
NK	0	0	0	1	1	5
NP	0	0	0	3	8	17
NPK	0	0	0	1	3	17
WNPKM	1	2	4	9	33	43
LSD (0.05)	0.74	0.50	0.71	2.55	9.22	18.53

Table A4.6: Summary of analyses of variance for time of tasseling.

		Weeks after emergence							
		9		10		11		12	
Source	DF	MS	F	MS	F	MS	F	MS	F
Treatments	5	49423.58	69.62**	31390.28	7.81**	19156.37	12.83**	2709.375	1.9 ns
Block	3	2075.486	2.92 ns	7115.153	1.77 ns	3167.833	2.12 ns	1424.486	1 ns
Error	15	709.8861		4019.586		1492.967		1424.486	
C.V		34.55		39.17		16.33		13.23	
R^2		0.96		0.75		0.82		0.45	

Table A4.7: Summary of analyses of variance for silking time.

		Weeks after emergence							
		9		10		11		12	
Source	DF	MS	F	MS	F	MS	F	MS	F
Treatments	5	46366.87	73.15**	46362.6	18.02**	38703.18	7.98**	30184.84	10.14**
Block	3	1350.444	2.13 ns	9964.5	3.87*	11048.38	2.28 ns	10662.04	3.58*
Error	15	633.8444		2572.4		4850.442		2977.242	
C.V		25.23		26.51		31.73		29.81	
R^2		0.96		0.87		0.76		0.80	

Table A4.8: Summary of analyses of variance for Harvest index.

Source	DF	MS	F
Treatments	5	270.0442	6.07**
Block	3	130.0353	2.92
Error	15	44.47634	
C.V		18.22956	
R^2		0.722886	

Table A4.9: Summary of analyses of variance for number of rows, kernels per row, kernels per cob, kernel size, mass per cob and potential kernel number.

		Number of rows		Kernels per row		Kernels per cob		Kernel size		Mass per cob		Potential kernel number	
Source	DF	MS	F	MS	F	MS	F	MS	F	MS	F	MS	F
Treatments	5	4.33	1.35ns	726.37	30.03**	134015.8	36.13**	0.0342	54.96**	16390.64	68.79**	147196.7	26.02**
Block	7	3.33	1.04	52.64	2.18	7731.43	2.08	0.0034	5.51	944.62	3.96	9353.51	1.65
Error	35	3.22		24.19		3709.08		0.0006		238.26		5656.8	
C.V		13.71		23.03		24.09		11.29		25.09		26.35	
R^2		0.75		0.83		0.85		0.90		0.91		0.80	

Table A4.10: Mean yield components of selected treatments.

Treatments	Number of rows	Kernels per row	Kernels per cob	Mass per cob (g)	Kernel size (g)	Potential kernel number
O	12.75	12.25	128.60	21.32	0.17	158.25
PK	13.25	31.40	368	86.84	0.24	412.25
NK	12	10.75	99.75	19	0.19	136
NP	12.75	15.63	186.75	33.14	0.17	199
NPK	13.75	27.25	341.10	75.38	0.22	372
WNPKM	14	30.90	392.40	133.50	0.34	435.25
LSD (0.05)	1.82	4.99	61.82	15.67	0.03	76.34

Table A5.1: Summary of analyses of variance for number of rows, kernels per row, potential kernel number, kernel size and mass per cob.

		Number of rows		Kernels per row		Potential kernel number		Kernel size		Mass per cob	
Source	DF	MS	F	MS	F	MS	F	MS	F	MS	F
Treatments	8	1.86	0.42ns	325.74	10.32**	62721.24	8.74**	0.009	4.69**	21302.78	28.23**
Block	3	10.89	2.48	92.93	2.95	33565.67	4.68	0.0004	0.2	862.96	1.14
Error	24	4.39		31.55		7179.04		0.002		754.63	
C.V		16.83		20.76		24.48		16.43		29.61	
R^2		0.31		0.79		0.78		0.61		0.91	

Table A5.2: Means of the 2004/2005 season grain yield of selected treatments.

Treatments	Actual yield (t/ha)	Estimated yield (t/ha)	% Reduction
O	1.68	2.78	39.69
PK	3.49	5.14	32.14
NP	0.56	1.81	68.78
NK	2.96	3.89	23.83
NPK	7.60	10.56	28.02
WNPKM	9.11	13.33	31.64

Table A6.1: Summary of analyses of variance for tassel length, ear length, leaf area per plant, and dry mass.

		Tassel length		Ear length		Leaf area		Dry mass	
Source	DF	MS	F	MS	F	MS	F	MS	F
Treatments	2	24137.81	373.20**	29.17	106.52**	0.019	43.21**	426.62	29.22**
Block	3	325.93	5.04	0.024	0.09	0.000004	0.01	4.12	0.28
Weeks	6	24313.1	375.91**	89.71	327.62**	0.11	242.47**	646.64	44.29**
Trt*Week	12	5809.3651	89.82**	8.0277778	29.32**	0.00065817	1.52ns	14.861238	1.02ns
Error	60	2218.94		3.18		0.0005		14.7	
C.V		10.33		21.45		11.33		22.87	
R^2		0.73		0.85		0.98		0.91	
LSD		6.34		0.41		164		3.01	

Table A6.2: Average leaf area per plant (cm^2) for three different levels of shading treatments for seven weeks.

	Weeks after emergence						
	3	4	5	6	7	8	9
10%	524.95	849.56	1790.01	2122.99	3230.30	3643.40	4170.00
40%	387.02	662.68	1551.80	1929.68	2538.39	3509.60	3956.30
70%	261.91	388.42	737.36	1499.44	2019.97	3023.45	3349.35

Table A6.3: Average leaf area indices (LAI) for three different levels of shading treatments for seven weeks.

	Weeks after emergence						
	3	4	5	6	7	8	9
10%	0.29	0.47	0.99	1.18	1.79	2.02	2.32
40%	0.22	0.37	0.86	1.07	1.41	1.95	2.20
70%	0.15	0.22	0.41	0.83	1.12	1.68	1.86

Table A6.4: Average dry mass (g) for three different levels of shading treatments for seven weeks.

	Weeks after emergence						
	3	4	5	6	7	8	9
10%	3.71	8.97	17.165	21.58	30.635	34.56	35.86
40%	2.275	5.9	13.77	19.92	23.14	27.51	31
70%	0.97	2.09	5.21	13.29	16.89	17.97	19.58

Table A6.5: Average tassel lengths (mm) for three different levels of shading for seven weeks.

	Weeks after emergence						
	3	4	5	6	7	8	9
10%	0	1	3	9.5	125	195	315
40%	0	1	3	5	14	62.5	110
70%	0	0	1	2	5	28.5	70

Table A6.6: Average embryonic ear lengths (mm) for three different levels of shading for seven weeks.

	Weeks after emergence						
	3	4	5	6	7	8	9
10%	0	0	0	0	4.5	8.5	14
40%	0	0	0	0	1	4.5	9
70%	0	0	0	0	0	3	5