EVALUATING HYBRID-MAIZE SIMULATION MODEL FOR GRAIN YIELD ESTIMATION IN HYBRID SEED MAIZE PRODUCTION

BY

LENNIN MUSUNDIRE

A thesis submitted in partial fulfilment of the requirements for the degree of
MASTER OF SCIENCE (MSc.) IN CROP SCIENCE (Plant Breeding)
Submitted to the

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Supervisors:

Dr A. B Mashingaidze

Dr J. MacRobert

Mrs. S. Dari

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Approved by:

Supervisors,	Dr A. B Mashingaidze	………………….
	Dr J. MacRobert	………………….
	Mrs. S. Dari	………………….
Head of Department	Dr. P. Jowah	………………….
Course Coordinator	Dr. C. Nyakanda	………………….

ABSTRACT

The study was carried out to determine the effect of Male Planting Date (MPD) and Female Plant Population (FPP) on the Grain Yield (GY), yield components and flowering of a three-way hybrid. The study also evaluated Hybrid-Maize simulation model for grain yield (GY) estimation in hybrid seed maize production. Seed grading of harvested three-way hybrid seed was also carried out to determine the seed grades based on the principle of length and thickness of the seed according to the Zimbabwe screen sizes. A CIMMYT three-way hybrid, with pedigree of (CML395/CML444//CML443) was used in this research. The experiment was laid out in (5 x 3) two-way factorial arrangement in a Randomized Complete Block Design (RCBD) at CIMMYT-Harare research station. Fifteen treatment combinations of five MPD as a deviation from the female planting date and three FPP replicated three times were used. The Hybrid-Maize simulation model programme was used to forecast the possible GY outcomes for the fifteen treatments of the experiment using estimated parameters and weather data for the 2006/7 season. The field experiment produced significant ($P<0.005$) main effects but non-significant interaction effects for grain yield, yield components and ASI. Female seed yield was affected by time of male pollen shed relative to female silking (Anthesis-Silking Interval, ASI), with highest yields associated with close synchrony (ASI= +/-3 days). ASI had a significant effect on the number of Kernels Per Ear, KPE, with the greatest KPE (318) associated with an ASI of +/-3 days. FPP effects on yield are typical for maize, showing a curvilinear response from low to high density. The optimum population density for grain yield was 5.4 plants m^{-2}. Simulation output from the Hybrid-Maize model showed an overestimation of GY compare to the observed yield. Furthermore, the model was unable to predict yields for the low FPP of 2.7 plants m^{-2}. This model would need to be modified for estimating seed yield of a three-way hybrid through the inclusion of male and female components. Seed grading data produced significant ($P<0.005$) difference for main effect FPP for medium size kernel weight but non-significant effects for the other FPP grades, MPD and interaction effects.

DECLARATION

The thesis study was carried out at the International Maize and Wheat Improvement Centre (CIMMYT-Zimbabwe) in collaboration with the University of Zimbabwe and University of Nebraska-Lincoln under the supervision of Dr J MacRobert, Dr A.B Mashingaidze, Mrs S. Dari and Dr Yang.

Research presented in this thesis represents original work by the author and has never been submitted in any form for degree or diploma to any University. Where use has been made of the work of others it is duly acknowledged in the text.

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DEDICATION

To my caring parents Nicholas and Leadmore Musundire.

CONTENTS

LIST OF ABBREVIATIONS

Abbreviation	
ASI	Anthesis-Silking Interval
^{o}C	Degrees Celsius
ANOVA	Analysis of Variance
CERES-Maize	Crop Environmental Resource Synthesis
CIMMYT	International Maize And Wheat Improvement Centre
Df	Degrees freedom
DA	Days to Anthesis
DS	Days to Silking
ED	Ear density
EPP	Ears Per Plant
Ex	Extra
F	Flat
FPD	Female Planting Date
FPP	Female Plant Population
GYP	Grain Yield Per Plant
HD	Harvest Density
Hum	Humidity
IPAR	Intercepted Photosynthetically Active Radiation
K	Extinction coeffients
KNP	Kernels Per Plant
KPE	Kernels Per Ear
KS	Percent Kernel Set
KWP	Kernel Weight Per Plant
L	Large
LAI	Leaf Area Index
M	Medium
mm	millimetres
MPD	Male Planting Date
P	Total seasonal amount of pollen produced by male population
PD	Plant density
Plants ha^{-1}	Plants per hectar
PR	Daily rate of pollen shed
R^2	Correlation value
R	Round
Rel	Relative
RCBD	Randomised Complete Block Design
RI	Radiation Interception
S	Small
T	Thick
Temp	Temperature
TKW	Thousand-Kernel Weight
t	Current day pollen shed
tx	Day of maximum pollen shed
W	Width of the pollen-shed curve measured at half the maximum pollen shed rate
WP	Wettable Powder

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Chapter 1

INTRODUCTION

Maize Hybrid Seed is a source of subsistence, an embodiment of technological change and vital input for commercial maize agricultural production (Tripp, 2001). It is the outcome of careful planning and selection, which has a growth pattern that follows predictable patterns of nature but is also affected by intervention of human management. The main aim of intervention through human management is the need to attain maximum yield per unit land area to meet national requirements for both the commercial and seed maize. A response to the expected rise in demand for maize is inevitable according to a report by Rosegrant, Agcaoli-Sombilla and Perez (1995). World demand in 2020 is predicated to rise to about 138 percent of 1995 demand. Hence, Africa's food production demands urgent attention of scientists and policy makers. Given the limited opportunities for augmenting maize area in most countries, future output growth must come from intensifying production on current maize land.

Of major concern with regards to efforts currently underway to increase maize production is the shortage of hybrid seed maize (Havazvidi and Tatterfied 2006), particularly in Zimbabwe, where traditional seed producers were displaced during the fast track land reform programme that started in 2002. For example, National Tested Seeds, which based its production on three farms, had lost two of them by the end of 2002. The country also experienced a low level of crop production since 2000 due to on farm production constraints namely, poor fertilizer availability and erratic supplies of diesel and electricity due to load shedding (especially for winter seed crops). Reduced production of seed due to acquisition of seed producing farms meant most of this demand had to be satisfied by export bans. For example, hybrid seed maize production was 35 000 tonnes in 1991, increasing to 60 000 tonnes in 2001, but declined to about 33 000 tonnes in 2004 (Zimbabwe Seed Traders' Association, 2006). In addition, whilst maize seed requirements for the 2003/04 season were estimated at 87 599 tonnes, the seed available for the season was only 31 495 tonnes, leaving a shortfall of 56 005 tonnes (Utete, 2003). Despite the shortfall, increases in seed sales have however been noted. Both Government and the Non-Governmental

Institutes/Organizations have attributed this to high seed demand for the drought recovery programmes and increase in the numbers of farmers due to the resettlement programme.

Seed production and distribution is currently associated with reduced production base, poor seed quality, increased marketing outlets and increased marketing costs. Therefore there is the need to have increased yield per unit land area to sustain the market as well as offset costs. In maize hybrid seed production, grain yield is closely associated with kernel number at harvest (Andrade, Uhart, Cirilo, Cantarero and Valentinuz, 1999). Kernel number per plant is the most important aspect of grain yield in seed production because it determines the volume of hybrid seed maize that is produced per unit land area. Therefore, understanding the mechanisms that determine the volume of hybrid seed maize is important to maize physiologists, modelers and breeders in the development of production systems and models that aim to increase hybrid seed maize production. Accurate simulation models provide an important vehicle of estimating kernel number per plant in hybrid maize seed production.

According to Yang, Dobemann, Lindiquist and Walters (2006) forecasting of grain yields is important for several reasons. Firstly, seed producers use such predictions for evaluating drought risks, helping to guide in-season adjustments to crop management, and to provide additional information to crop marketing decisions. Secondly, major grain producers utilize yield forecasts to refine seed purchasing plans. Thirdly, politicians, insurance agencies and financial institutions may wish to predict farm income. Simulation models can be used to integrate the interaction of various physiological and abiotic factors that affect kernel number in maize and therefore are useful for predicting seed maize grain yields. These models can therefore be used along with other sources of information, common sense and experience to guide management and decisions in addressing the persistent shortfalls that are experienced in hybrid seed maize demand.

Model predictions of grain yield per plant are generally based on empirical relationships between final kernel number and carbohydrate supplies or plant growth at silking, plant density and the radiation intercepted by the crop during the critical period bracketing flowering (Lizaso; Westgate; Batchelor and Fonseca, 2003). In addition, final kernel production per hectare can also be simulated fairly accurately under pollen-limited conditions from simple measures of pollen shed and silking dynamics (Fonseca, Lizaso, Westgate, Grass, and Dornbos, 2004). This model assumes that pollination, which is followed by fertilization and kernel formation, is the limiting stage in kernel set and kernel production under optimum conditions. This assumption might apply to typical commercial maize production in some cases, but the number of fertilized ovules can limit kernel yield in a wide array of circumstances.

However, according to Carcova, Uribelarrea, Borras, Otegui and Westgate (2002) pollination has been found not to limit kernel set under commercial hybrid maize production. The amount of pollen produced per plant could become a limiting factor for kernel number. In hybrid seed production pollen production could be particularly important in certain specific production systems, where only a small proportion of plants (usually less than 20 percent) are used as pollinators (male lines). In these situations, knowledge of pollen production dynamics becomes essential for assessing the proportion of pollinating plants in the population needed for maximum kernel set. A short anthesis-silking interval (ASI = anthesis date minus silking date) is key trait for obtaining high grain yield in maize seed production. A short ASI appears to result in a synchronous pollination among ovaries within and between ears. This has been reported to increase grain yields (Sarquis, Gonalez and Dunlap, 1998; Carcova *et al*., 2002) of different maize genotypes cropped at contrasting plant densities in different environments.

In contrast, plant density has been recognized as a major factor determining grain yield per plant (Andrade, Calvino, Cirilo and Barbieri, 2002). Reduction in grain yield may be the result of lower numbers of ears (barrenness), lower kernel weight or a combination of these components. In dense populations, most of the ears may not develop. This occurs in some genotypes due to poor pollination resulting from delayed silking compared to tassel emergence and or due to limitation in assimilate supply that causes kernel and ear abortion. Crop models such as CERES-Maize (Jones and Kiniry, 1986) and Hybrid-Maize (Yang, Dobermann, Cassman and Walters, 2006) have been used to predict seed number; they can dynamically evaluate optimum planting densities with different soils, different rainfall conditions and different maize hybrids.

Similarly, when water and nutrients are not limiting growth, grain yield per plant can be calculated using the models based on intercepted photosynthetically active radiation per plant (IPAR) (Andrade *et al*., 2002). Radiation is the focal point in limiting grain yield per plant at the critical period bracketing (Otegui and Bonhomme, 1998) or close to silking (Kiniry and Knivel, 1995). These studies have clearly indicated that a simple linear relationship would be suitable to explain kernel set response to IPAR during the critical period with kernel set reaching a different plateau depending on the potential seed number of each hybrid. However data from Andrade, Uhart, and Frugone, (1993) suggested that the response function of kernel set is curvilinear.

This research will attempt to establish whether Hybrid-Maize simulation model could be used in hybrid seed maize production, mainly to estimate grain yield by using a male inbred line and a female single cross so as to provide specific parameters for use in the models and optimization of management practices in seed production to maximize yields in hybrid seed maize production. This will be achieved through accumulating weather data, male and female flowering dynamics, and female plant density data during the critical period of maize growth for the evaluation of the Hybrid-Maize simulation model in estimating grain yield in hybrid seed maize production. Comparison of the estimated grain yield from the simulation model and the actual yield was then carried out so as to determine the accuracy of the model.

The objectives of the study were:

1. To determine the effects of maize plant density and male and female planting dates on Anthesis Silking Interval (ASI), seed size grades and maize grain yield in maize seed production using a male inbred line and a female single cross.

2. To simulate maize grain yield production for hybrid seed production using the Hybrid–Maize simulation model using the parameters; ASI, population density, planting dates and weather data so as to compare predicted yield and actual grain yield.

3. To evaluate the potential of modelling for optimising management practices in hybrid seed maize production.

4. To parameterise the Hybrid-Maize simulating model used in commercial maize production for hybrid seed production.

Hypotheses tested were:

1. Maize grain yield will decrease with late planting and increased plant density as a result of reduced IPAR and asynchrony between pollen shed and silking.

2. Hybrid-Maize simulating model can be used to predict grain yield in hybrid seed maize production.

3. Hybrid-Maize simulating model has the potential for optimising management practices in hybrid maize seed production.

4. Appropriate parameters for the Hybrid-Maize simulation model may be determined for the male and female components of a seed field.

Chapter 2

LITERATURE REVIEW

2.1 Maize grain yield.

In maize, grain yield is closely associated with kernel number. Therefore understanding the mechanisms of kernel number determination is of great importance to physiologists, modelers and breeders. Maize grain yield is a product of kernel number per plant (KNP) and kernel weight per plant (KWP) at harvest. In most cases, however, maize yield is more closely associated with KNP than with KWP. Consequently, GYP is mainly related to KNP (Echarte, Luque, Andrade, Sandras, Cirilo, Otegui and Vega, 2000), while KW contributes to GYP variations only in some hybrids (Otegui, Nicolini, Ruiz and Dodds, 1995). According to Westgate and Boote (1999), KNP is generally related to assimilate supply as set by solar irradiance, nitrogen supply, fertility and water supply. For simulation purposes, the developmental events that determine KNP can be divided into three consecutive processes (Lizaso *et al.,* 2003). In the first stage, male (tassels) and female (ears) reproductive structures are initiated and differentiated. The second stage involves functional maturation of flowers and pollination. Synchrony in floral development is critical to ensure pollination of exposed silks. During the third stage, pollination is followed by fertilization and kernel formation.

In relation to the three developmental processes that determine KNP, current models for simulating hybrid seed maize do not consider the quantitative dynamic nature of the first two stages. Most efforts to simulate kernel formation in hybrid seed maize have attempted to associate the final kernel number per plant with the current supply of photosynthates or related characteristics such as light interception or plant growth rate around the time of silking (Edmeades and Daynard, 1979; Andrade *et al*., 1999; Andrade *et al.,* 1993; Kiniry and Knivel, 1995; Otegui 1997; Andrade *et al.,* 2002). These implicitly assume that neither flower initiation, differentiation, nor pollination limit kernel set. These assumptions might apply to typical commercial maize production in some cases, but the number of fertilized ovules can limit kernel yield in seed production where limited number of male pollinating plants that have small tassels (inbreds) are available to pollinate female single cross.

KNP as determined by the three developmental stages is also a function of pollen timing, which has shown a dependence on dry weight increase per plant during the flowering period. Genetic variation for the Anthesis-silking interval may indicate differences in this relationship hence differences in partioning of currently formed assimilates to the ear at flowering. KNP is determined during the critical period ranging from approximately ten days before until fifteen days after anthesis (Tollenaer, 1977). When maize is exposed to stress at flowering there is an increase in the interval between pollen shedding and silk emergence, (ASI). This is referred to as silk delay, loss of synchrony, protandrous flowering. However, genetic variation for ASI also exists in maize. This difference in this relationship results in differences in partioning of currently formed assimilates to the ear at flowering. Observation of ASI is done on individual plant basis but at plot level it is measured as the date when fifty percent of the plants have visible silks minus the date when fifty percent of plants first extrude anthers.

2.2 Floral dynamics in male and female plants

Although the maize plant has traditionally been considered an overabundant producer of pollen relative to the number of ovaries available for pollination, such genetic, management, and environment influences on pollen production and viability provide numerous opportunities for the timing and density of pollen shed to limit kernel production under field conditions (Westgate, Lizaso, and Batchelor, 2003). This seems particularly clear for hybrid seed production since pollination could be less than desired for several reasons. First, pollen shed density is much less than in commercial maize field since inbreds typically produce less pollen than do their hybrid counterparts. Second, Fonseca, Westgate, Doyle, (2002) further reported that, only a fraction of the field population is permitted to shed pollen from the male inbred parent. Actually, the major goal in hybrid seed production is to reduce the area dedicated to male rows as much as possible without decreasing the number of kernels harvested per area. Third, the level of pollen viability could be less than required for optimum pollination of receptive silks (Schneider, 2003). Fourth, pollen shed and silk extension on spatially separated plants increase the probability that floral asynchrony can lead to poor kernel set. These biological and physical factors create conditions in which primarily the number of pollinated flowers could limit KNP. This potential for pollination depends directly on the dynamics of male and female flowering within the seed field.

Westgate *et al.* (2003) developed quantitative descriptions for the daily progress of pollen shed and silk emergence under field conditions on the basis of simple measures of male and female flowering. When coupled mathematically to the pollination efficiency curve generated by Bassetti and Westgate (1994), these estimates of male and female flowering can be translated into daily values for kernel set. Lizaso *et al.* (2003) showed that this mathematical approach was highly accurate at simulating kernel production for maize hybrids across a wide range of pollen shed densities. The procedure for simulating kernel production begins with developing data for pollen shed for the male population and profile of silk extension for the female population. These floral dynamics can then be translated into daily values of kernel production by female inbred lines using the procedures described by Lizaso *et al*. (2003), which rely on the quantitative relationship between daily pollen shed density (grains per cm^2) and percent kernel set published by Bassetti and Westgate (1994). In this calculation the assumptions is that pollen density is distributed homogeneously among the female population.

Contrary to this assumption, Westgate *et al*. (2003) reported that for maize plant populations there are three stages, in terms of pollen density distribution recorded, namely Beginning Shed, Maximum Shed and End Shed. Beginning shed is recorded as the proportion of plants that have exerted anthers on the main tassel branch. Maximum shed represents plants that have exerted anthers on the main tassel branch and side branches. Tassels with no new anthers on any tassel branch are recorded as having completed pollen shed (End shed) (Westgate *et al*. 2003). The progress of each population through Beginning shed, Maximum shed and End shed can readily be described by a common set of sigmoid logistic functions separated in time by one to five days. The area between these curves provides a daily index of pollen shed for the population. Typically, the same group of plants is used to record the proportion of plants at Beginning shed, Maximum shed and End shed to generate the population index curve. The actual rate of pollen shed (grains $cm^{-2}d^{-1}$) is calculated by multiplying this index values by the average pollen production per plant and the male population density. Lizaso *et al.* (2003) showed that the seasonal pattern of pollen shed followed a Gauss curve according to Equation

$$\mathbf{PR = P/ [W * \sqrt{(\pi/ 2)}] \quad * e^{-2 [t-tx] 2 / w2}} \qquad \textbf{(1)}$$

Where: PR is the daily rate of pollen shed (grains cm^{-2} d^{-1}).

P is the total seasonal amount of pollen produced by the male population (Grains cm^{-2}),

W is the width of the pollen-shed curve measured at half the maximum pollen Shed rate (d), and

t and tx are the current day and day of maximum pollen shed, respectively.

The average pollen produced per plant and the plant population density defines the total seasonal amount of pollen, P. The day of maximum pollen shed curve, W, is determined empirically for each field by forcing the Gauss curve to start pollen shed at Beginning shed = 0% and End pollen shed = 100% + 5d. Addition of five-days was done according to prior studies (Westgate *et al*., 2003; Lizaso *et al*., 2003) indicating that the interval between Beginning shed and End shed for an individual tassel is typically five-days. This interval should coincide with the silking period when fifty percent of silks have been exerted for maximum kernel set. A short ASI typically considered optimum for kernel set in hybrid seed production.

2.2.1 Anthesis silking interval in maize flowering

A plant is considered to have reached anthesis or silking if at least an extruded anther or one silk is visible, respectively. An experimental maize plot is considered to have reached anthesis or silking when at least fifty percent of the plants have reached anthesis [Days to anthesis (DA)] or fifty percent have produced silks [Days to silking (DS)], respectively. Anthesis-silking interval is calculated as DS-DA (Edmeades, Banziger, and Ribaut 2000). According to Westgate, and Boote, (2000) when maize is stressed at flowering because of deficits of water, light, and or nutrients, and sometimes by long photoperiods and lack of thermal adaptation, ear growth slows down in relation to tassel growth and the anthesis-silking interval (ASI) increases. A short ASI typically is considered optimum for kernel set in hybrid seed maize. A delay in silking relative to pollen shed increases ASI and has a large impact on potential kernel production, especially when pollen amount is limiting. However, perfect synchrony (ASI=0 silking and anthesis on the same day) may not correspond to optimum potential kernel production (Bolanos and Edmeades, 1993; Edmeades *et al*., 2000). Maximum kernel yield is usually obtained by delaying anthesis for the male inbred population by about four days, relative to silking.

Delaying pollen shed to maximize kernel yield could expose the seed to increase potential for out-crossing the early emerging silks (Westgate *et al.,* 2003). On the other hand, greater coverage of late-emerging silks by delaying pollen shed dramatically increases kernel yield thereby decreasing the potential for out-crossing for the late silkers in the female production. Hence the best approach to manage floral synchrony will depend on the specific risk of foreign pollen entry during silking. Common practice in seed production fields to delay pollen shed and expand pollen-shed duration is through flaming, staggering of planting dates and clipping of apical leaves at the vegetative stage of development. There is potential to improve kernel yield by carefully managing the anthesis interval between pollen sources to increase pollen shed duration. The number of sources, the timing between them and the proportion of plants assigned to each source are management options that can be tested and optimized by a simulation model in hybrid seed production (Lizaso *et al*., 2003)

The simulation models should focus on the timing of silking by the female population in terms of silking as it has an impact on potential grain yield. Decreasing uniformity of silking on individual ears has direct negative impact on kernel number (Bassetti and Westgate, 1993a). It has been further reported that female inbred lines that are capable of producing ninety-five percent of the silks within four days would increase potential kernel production by about seventeen percent. A female requiring nine days to produce ninety-five percent of the silks would produce fifteen percent fewer kernels and leave more than fifty percent of the exposed silks unpollinated. The dynamic characterization of ASI in relation to the daily pollen shed density can be used to simulate grain yield per plant in hybrid seed fields from the flowering dynamics of the parent lines.

2.2.2 Relationship between kernel set and daily pollen shed density.

Exposed silks will be pollinated at a rate determined by two consecutive linear functions on the basis of the pollination efficiency curve of Bassetti and Westgate (1994). Their pollination efficiency curve is generated by means of receptive florets in the middle of the rachis for which no abortion occurred. Therefore, this efficiency curve provides the expected percentage of Kernel Set (KS) when receptive silks are exposed to a known density of pollen shed for one-day. The limits of pollen-shed density for each equation are

$$KS = 0.96 \times p \qquad 0 < pr \leq 100 \qquad (\mathbf{2})$$

and

$$KS = 96 \qquad pr > 100 \qquad (\mathbf{3})$$

Where KS is the percent kernel set

pr is the daily rate of pollen shed (grains $cm^{-2}\ d^{-1}$).

These equations indicate that per-cent kernel set is linearly related to daily pollen shed density up to 100 grains $cm^{-2}\ d^{-1}$ with an efficiency of ninety-six percent (i.e. at fifty grains $cm^{-2}\ d^{-1}$, forty-eight percent of exposed silks will be pollinated). At pollen densities greater than one hundred percent grains $cm^{-2}\ d^{-1}$, ninety-six percent of the expose silks are pollinated. The remaining unpollinated silks are added to the next day’s pool available for pollination. Exposed unpollinated silks will be considered to remain receptive to pollen for five additional days. Silks that will not be pollinated by the sixth day will be assumed to have lost receptivity and no longer contribute to kernel set (Bassetti and Westgate, 1993b). The female plant density can also alter pollen density that reaches each plant in relation to the distance moved from the source of pollen.

2.3 Female plant density in seed production

As reported by Sangoi, Gracietti, Rampazzo, and Biancheti (2002), female plant density has been recognized as a major factor determining the degree of competition between plants. Grain yield per plant decreases as the density per unit land area increases. Reduction in grain yield may be the result of lower number of ears (barrenness), lower kernel weight or a combination of these components. In dense populations, many grains may not develop. This occurs in some genotypes due to poor pollination resulting from delayed compared to tassel emergence and or due to limitation in assimilate supply that causes kernel and ear abortion.

Similarly, Edmeades and Daynard (1979), Tetiokago and Gardner (1988) reported that maize is one of the most sensitive grass species to intra-specific competition. When plant population density is increased; both plant biomass and grain yield per plant (GYP) declines. Considering GYP components, i.e., kernel number per plant (KNP) and kernel weight per plant (KW), the former is always reduced when stand density is increased (Edmeades and Daynard, 1979a;Tetiokago and Gardner, 1988; Echarte *et al.,* 2000; Sangoi *et al.,* 2002). Consequently, GYP is mainly related to KNP (Echarte *et al.,* 2002), while KW contributes to GYP variations only in some hybrids (Otegui *et al.,* 1995; Echarte *et al.,* 2000). Grain yield per unit land area, however shows a curvilinear response to plant population, producing a maximum value at the optimum plant density. Below this stand density, KNP increase is not compensated by the reduction in the number of plants per area, while substantial barrenness occurs above the optimum density (Tetiokago and Gardner, 1988).

Plant density can be used as an efficient management tool for maximizing grain yield by increasing the capture of solar radiation within the canopy. Efficiency of conversion of intercepted solar radiation into economic yield is, however limited by mutual shading and competition of plants (Bullock, Nielsen and Nyquist, 1988). An association has been reported between ASI and yield under high plant population density (Edmeades, Bolanos, Hernandez, and Bello, 1993). In an early review of the effects of plant density on maize yields Dungan, Lang and Pendelton (1958) reported an increase in ASI of around 0.4 day^{-1} plants m^{-2} increasing in planting rate. The critical period when plant density has a major effect on the incidence of the barrenness was identified through selective thinning by Prine (1971) as a period 10 days before silking until 10 days after silking. The general relationship between grain yield and ASI in individual plants grown at different plant densities resembles that for drought.

When the number of individuals per unit area is increased beyond the optimum plant density, there is a series of consequences that are detrimental to ear entogeny and results in barrenness. Firstly, ear differentiation is delayed in relation to tassel differentiation; later–initiated ear shoots have a reduced growth rate resulting in fewer spikelets primordia transformed into functional florets by the time of flowering. Functional florets extrude silks slowly, decreasing the number of fertilized spikelets due to lack of synchrony between anthesis and silking.

2.4 Intercepted radiation per plant in maize fields

When water and nutrients are not limiting, kernel number per plant (KNP) can be calculated for maize using linear models based on intercepted photosynthetically active radiation per plant (IPARP) (Andrade, Otegui and Vega, 1998). In main studies conducted to analyze kernel set in maize, IPARP at a period bracketing (Oteigui and Bonhome, 1998) or close to (Kiniry and Knievel, 1995) silking is used as a determinant variable. These studies indicate that a single linear relationship would be suitable to explain kernel set response to IPARP per plant during the critical period, with kernel set reaching a different plateau depending on the potential; seed number of each hybrid. In a study carried out by Otegui and Bonhome (1998) modeled and measured intercepted photosynthetically active radiation (IPAR) during a 327-degree day period bracketing flowering (when ear elongation occurs) to kernel number. In a linear regression analysis, a relatively high correlation coefficient (R^2 =0.70) was obtained between total IPAR and KNP. The linear regressions for all treatments and time of IPAR evaluation resulted in a positive intercept, but no kernels developed when the total IPAR for the 327-degree day period was less than a critical threshold value (about 12MJ per plant).

Kiniry, Xie and Gerik (2002) also reported the aspect of optimizing plant density to ensure maximum interception of solar radiation. Understanding the mechanism of seed set in hybrid seed maize in this study was critical in balancing the increase in light by the crop against the decreased number of seeds per plant, in optimizing plant density. Data obtained in this study was used for the crop model CERES-Maize to accurately predict seed number and to also dynamically evaluate optimum planting densities with different soils, different rainfall conditions and different maize hybrids.

Andrade *et al.* (2002) also reported the response of grain yield to narrow rows in terms of the effect of radiation intercepted by the crops. In this study decreasing row spacing at equal plant densities produces a more equidistant plant distribution. These distributions decrease plant-to-plant competition not only for light and increases radiation interception (RI) but also available water and nutrients. Similar results were also reported by Shibles and Weber (1996) Bullock *et al.* (1988). Decreasing row spacing also reduces the leaf area index required to intercept 95 percent of the incident radiation due to an increase in the light extinction coefficient. However, the benefits of more equidistant spacing for crops grown without important water and nutrient deficiencies are variable. Some researchers reported grain yield increases (Hunter, Daynard, Hume, Tanner, Curtis, and Kannenberg, 1970; Olson and Sanders, 1988; Ethredge, Ashley, and Woodruff, 1989; Board, Kamal, and Harville, 1992), but others have not (Balmey and Zollinger, 1997). Crop growth rate is directly related to the amount of radiation intercepted by the crop (Gardner, Pearce, and Mitchell, 1985). Therefore the response of grain yield to narrow rows can be analyzed in terms of the effect on the amount of Radiation incident at the critical periods for kernel set.

Anda and Lonke (2005) in their report brought up the concept of the variation in the architecture of maize hybrid crops during the course of development. Not only the architecture of the stand between varieties, but also within the same variety, leading to differences in the distribution of radiation within the stand which in turn may be responsible for differences in productivity indices per unit area. Among the indices related to radiation utilization, the easiest to measure, and thus the most frequently cited is the albedo, the loss of radiation directly by reflection from the top of stand. Non-reflected radiation penetrates into the stands and acts as a source of energy-demanding processes, while a remnant reaches the soil surface. The attenuation of the radiation, which is decisively affected by the architecture of the stand, is often characterized by the empirically determined extinction coefficient (K) despite serious doubts as to whether the conditions required for the approximation (random distribution of foliage in a horizontally homogenous canopy) can ever be fulfilled in plant stands. This index is generally quoted as being between 0.40 and 0.66 in fully developed maize stands in temperate zone when the sun is high in the sky (Fernando, Otegui and Vega, 2000; Tsubo and Walker 2002; Birch, Vos and Van der Putten, 2003; Lizaso *et al.*, 2003). However, lower values are also to be found in literature. Pommel and Bonhomme, (1998) for example quote a value of 0.34. The higher the value of K, the greater the radiation absorption (Oker-Blom and Kellomaki, 1983). Current simulation models for hybrid seed maize do not consider the quantitative dynamic nature of the response of grain yield to the amount of radiation incident at critical periods for kernel set.

2.5 Current Simulation models

A model is a simplified representation of a system, while simulation is the building of a mathematical model and study of their behavior in reference to that of the system they represent (Rabbinge and de Wit, 1989). Hence, crop simulation models are mathematical representations of plant growth processes as influenced by interactions among genotype, environment and crop management. Models have become an indispensable tool for supporting scientific research crop management and policy analysis (Hammer, Kropff, Sinclair and Porter, 2002). Simulation models serve different purposes, and the intended purposes influences the level of detail needed for mechanistic description of key processes, sensitivity to environment and management, data requirement and model outputs. The accuracy of simulating the outcome of these processes across a wide range of environments depends on basic understanding of the key ecophysiological processes and incorporating this knowledge in the mathematical formulations that constitute the model. These models integrate the interdisciplinary knowledge gained through experimentation and technological innovations in fields of biological, physical and chemical sciences relating to agricultural production systems.

Therefore, these models can increase understanding and management of agricultural systems in a holistic way.
According to Saseendran, Hubbard, Singh, Mendratta, Rathole, and Singh, (2005) to accurately simulate crop growth and development of a particular maize hybrid at a particular location, process-oriented models like CERES-Maize (Crop Environmental Resource Synthesis) need calibration of their crop-specific parameters that are not easy to quantify in the field. In CERES-Maize, genetic coefficients need to be calibrated separately and in a study carried out by Boote (1999) information on silking date, maturity date, grain yield and LAI were used to calibrate the genetic coeffients. With correctly calibrated genetic coeffients, there is also the need to have an improved understanding of crop responses to temperature and photoperiod so as to have a more reliable simulation of crop yield. Many field and simulation studies have been conducted to determine the developmental pattern of various crops in relation to temperature and photoperiod.

Secondly, there is the Hybrid-Maize model, its purpose is to accurately predict yield of maize determined by solar radiation, temperature, phenology and canopy architecture, when grown under favourable conditions that minimizes stress and allow yields to approach yield potential levels (Yang, Dobermann, Lindiquist, Walters, Akerbauer and Cassam, 2003). Hybrid-Maize model is available as Windows-based PC software with full text and graphical display that allows export of simulation results. The software converts climate data from the High Plains Regional Climate Center into the format required by the model. It also provides users access to all key model parameters for viewing or editing, as well as the possibility of restoring the original default values of that parameter. The model can be run in single season mode as well as for long-term simulations using multi-year climate data at a given site.

According to Yang *et al.* (2006), running the Hybrid-Maize model in current season prediction mode allows real-time, in season simulation of maize growth up to the date of the simulation run, and forecasting of the possible outcomes in final yield based on historical weather data for the remaining crop growth period. When the option include yield trend is included, yield forecasts will be made for each specified interval since emergence until the last day of the current season in the weather file. Knowing predicted yield trends for the current season helps adjusting water and fertilizer management. The model can be used to assess the overall site yield potential and its variability based on historical weather data; evaluate changes in attainable yield using different combinations of planting date, hybrid maturity, and plant density; analyze yield in relation to silking and maturity in a specific year.

In relation to this study, Hybrid-Maize model will be used to estimate grain yield in hybrid seed maize production. Weather data, planting dates, plant population density, male and female flowering dynamics and maturity dates are the parameters that will be computed into the model.

Chapter 3

GENERAL MATERIALS AND METHODS

Experiment 1

A component parent of a CIMMYT three-way experimental hybrid (CML395/CML444//CML443) was used in this research. The experiment was laid out according to a (5 X 3) two-way factorial arrangement in a Randomised Complete Block Design (RCBD). Treatments consisted of fifteen treatment combinations of First Factor, five Male Planting Dates (MPD) as a deviation from the Female Planting Date (FPD) and Second Factor, three Female Plant Populations as given in Table 3.1 and 3.2 respectively. The treatments were assigned randomly within blocks, each treatment once per block. The number of blocks was used as replications in which three replicates were used to produce forty-five plots for the experiment (Appendix 1). Any treatment in this experiment was adjacent to any other treatment, but not to the same treatment within the block.

Table 3.1: First Factor - Male planting date relative to the female planting date.

Date	Male Inbred line	Female Single Cross	Deviation
13/10/06	Male line planted 10 days earlier than the female single cross.	Female single cross not planted	-10 days
18/10/06	Male line planted 5 days earlier than the female single cross.	Female single cross not planted	-5 days
23/10/06	Male line planted on the same day as female single cross.	All female lines planted	0 days
28/10/06	Male line planted 5 days after the female single cross.	Female single cross not planted	+5 days
02/11/06	Male line planted 10 days after female single cross.	Female single cross not planted	+10 days

Table 3.2: Second Factor – Female Plant Population

Description	Code	Female Plant Population Plants ha^{-1}	Replications
Low	1	26 666	3
Medium	2	53 333	3
High	3	80 000	3

A combination of factors as illustrated in Appendix 1 was obtained to produce fifteen treatments that were randomly assigned within each block. Three replications were used hence a total of forty-five plots were laid out in the field for the trial (Fig 3.1). A female: male planting ratio of 3: 1, which is commonly used in seed production, was used in this trial. Each plot occupied sixty-six square meters with border rows surrounding the block and border plots separating plots as illustrated in Fig 3.1 (Field layout) to minimize cross pollination across the block and within the plots respectively. In addition, the experiment was isolated by distance and time to ensure that there was no cross pollination with adjacent fields. Detasselling of female single cross was also carried out. The tassels on the female single cross were removed before they started shedding pollen, that is when the top 3-4 cm of the tassel were visible above the whorl and this continued on a daily basis until complete. Shoot begging of the female single cross ears was also carried out. Shoot begs were only removed on plots where the male lines were shedding pollen to ensure that the pollen was coming from the specific male inbred line within a plot. The ears were covered back with the shoot bags as soon as the male line had reached complete anthesis stage per plot. Therefore, the source of pollen was only the specific male line within a given plot. Shoot begs were eventually removed after the silks had dried off and the ears were allowed to reach field maturity before harvesting commenced.

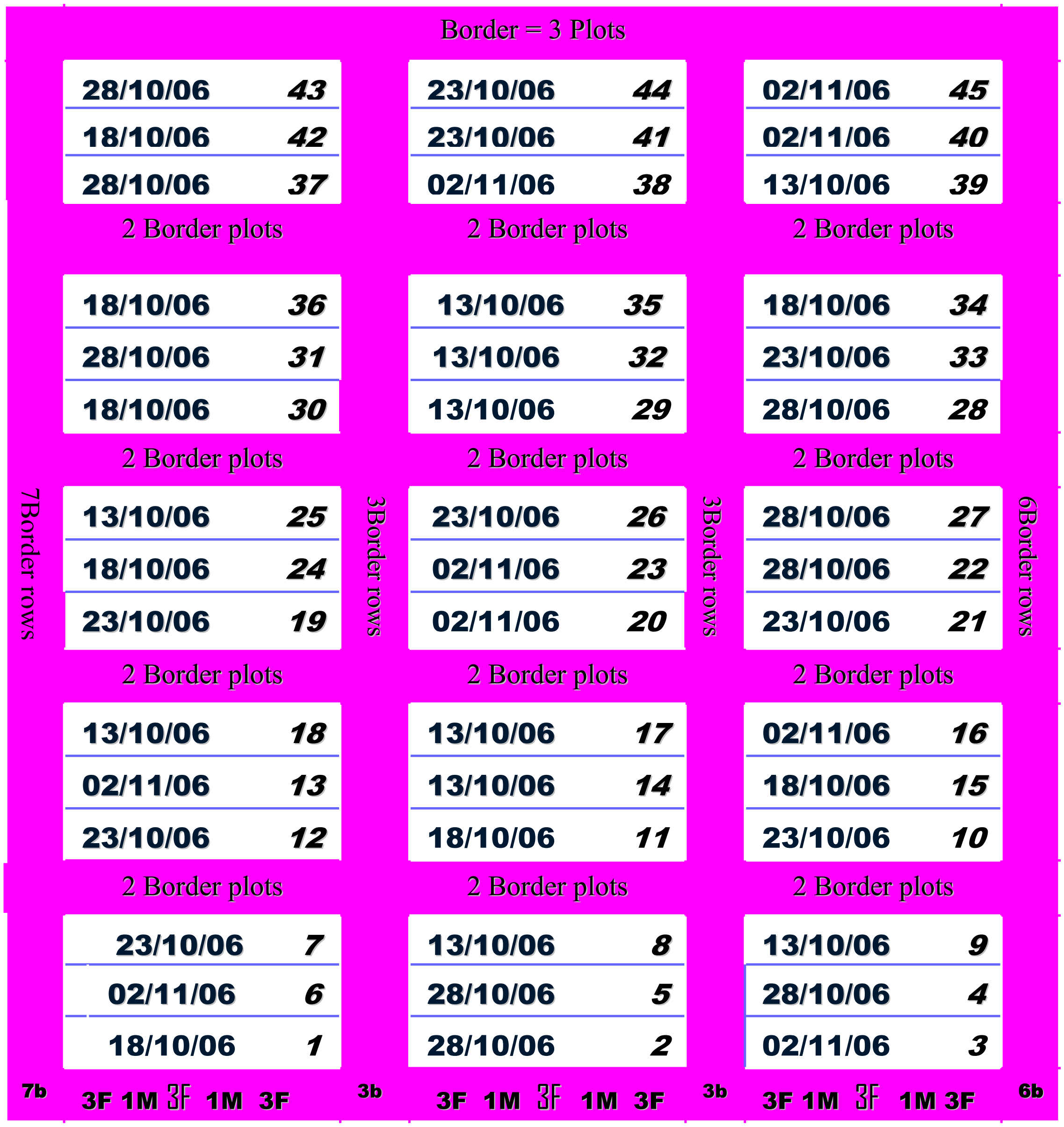


Figure 3.1 Field layout

Date	- MPD as a deviation from the FPD.
Italicized number	- Plot number.
3F	-Three Female rows (Net plot).
1M	- Male row.
b	- Border rows

3.1 Field Management.

3.1.1 Land Preparation and Planting.

Ploughing was carried out using a tractor-drawn heavy disc plough in September 2006 at CIMMYT-Harare Research Station. A premarked wire was used to mark planting stations at spacing of 0.75m between rows and 0.25m within rows 4m in length. Two seeds were sown by hand per planting hill and seedlings were thinned per planting hill four weeks after planting to achieve the three plant densities of 2.7 plants per m^2 (26 666 plants per hectare), 5.3 plants per m^2 (53 333 plants per hectare) and 8.0 plants per m^2 (80 000 plants per hectare). Appendix 1 illustrates the thinning ratio that was used for each planting date to achieve the desired female plant densities. Hand pulling was used during thinning.

3.1.2 Fertilizer Application and Water Management.

A basal fertilizer application of 400 kg/ha of Compound D fertilizer (8 percent N: 14 percent P_2O_5: 7 percent K_2O) was broadcast and disc-incorporated by a tractor. Topdressing was split applied using ammonium nitrate (34.5 percent N): first application of 200kg/ha was done at four weeks after crop emergence soon after thinning and the second, also of 200Kg/ha was done six weeks after crop emergence.

The trial was mainly rain-fed, however, irrigation water was applied when necessary, for example, under dry planting to facilitate germination and in the case of a long dry spell. Irrigation scheduling was determined by the stage of development of the plants and temperature. In general, an irrigation of seven mm/hr for six hours was applied just after planting to facilitate germination and thereafter irrigation interval ranged from 9 to 15 days depending on crop stage of development and temperature.

3.1.3 Weed Management.

It is an established fact that weed competition during the first four weeks of a crop's life is detrimental to yield. Also, small weeds are much easier to control than larger weeds. Thus, timely weeding when the crop and weeds were small was effective and beneficial. The trial was kept weed free throughout the season. Weeds were controlled using a mixture of Atrazine (Atrazine WP), dual (Metachlor) and Gramoxine (Paraquat) at 4.5, 1.8 and 1.0 L/ha respectively as a pre-emergence control. Herbicides were applied using 20-L Knapsack sprayers. Three weeks after crop emergence, Basagran, at 3.0-L /ha was applied to control broad-leaf weeds. At four weeks after crop emergence Bantazon was applied to control all weeds. From eight weeks onwards, weeds were controlled by hand weeding.

3.1.4 Pest and Disease Management.

Soon after crop emergence, scouting for the cutworm (*Agrotis ipsilon*) and maize stalk borer (*Busseola fusca*) was done. Endosulfan one percent granules were placed in the maize funnel at six weeks to control maize stalk borer at a rate of 2 kg/ha in a mixture of two parts sand and one part chemical. Maize streak virus disease was controlled by applying carbofuran (Curators) at a ratio of three parts chemical to four parts sand in the planting hole to kill Cicadulina leafhoppers that are the vectors of the disease.

3.1.5 Measurements of variables from net plot.

Measurements of variables were carried out in the net plot, three central female rows as shown in Fig 3.1. The measurements were carried out at various stages of development and the resultant data was used in the Hybrid-Maize simulation model as input data and also for general Analysis of Variance (ANOVA) as shown in Table 3.4 for estimating potential yield and assessing the actual data, respectively.

Table 3.4: Variables of the trial and measuring procedure at Vegetative stage

Variable	Procedure of measurement	Use of variable
Plant population density	Number of plants per hectare	-Input in Hybrid-Maize simulation model.
Planting dates of male line and female single cross	Record the planting dates.	-Input in Hybrid-Maize simulation model.

Variables of the trial and measuring procedure at Flowering Stage

Variable	Procedure of measurement	Use of variable
Days to Anthesis (DA)	At (5, 50, 95)% of the plot	-Determine anthesis range. -Determine ASI. -General analysis of variance.
Days to Silking (DS)	AT (5, 50, 95)% of the plot	-Determine silking range. -Determine ASI. -General analysis of variance

Variables of the trial and measuring procedure at Physiological maturity stage

Variable	Procedure of measurement	Use of variable
Grain yield components	-Count plants per row -Ear number per plant. -Field weight of cobs -Thousand kernel weight -Moisture of grain using moisture meter -Seed grading using sieve trays.	-General analysis of variance -Comparison with model data.
Root lodging	-Per-cent count per plot. -Per-cent count per plot	-General analysis of variance.

3.2 Hybrid–Maize simulation model

Running the Hybrid-Maize simulation model in Yield forecasting mode allowed real-time, in-season simulation of maize growth up to the date of simulation run, and forecasting of the possible outcome in final yield based on the up-to-date weather data of the current growing season, supplemented by the previously collected historical weather data for the University of Zimbabwe Farm. Yield forecasts were made until the last day of the 2006-7 seasons in the weather file. To use the yield-forecasting mode, a weather data file containing 17 years of reliable historical weather data was used, in addition to weather data for 2006-7 seasons as illustrated in Table 3.5.

Table 3.5: Weather daily data

Year	Day	Solar MJ m^{-2}	Temp-High °C	Temp-Low °C	Rel. Hum %	Rain mm

Hybrid-Maize simulation model could not separate difference in male and female planting dates. Hence, female planting dates (FPD) were used to run the programme. Model inputs for yield forecasting of the three-way hybrid variety at University of Zimbabwe farm is shown in Fig 3.2.

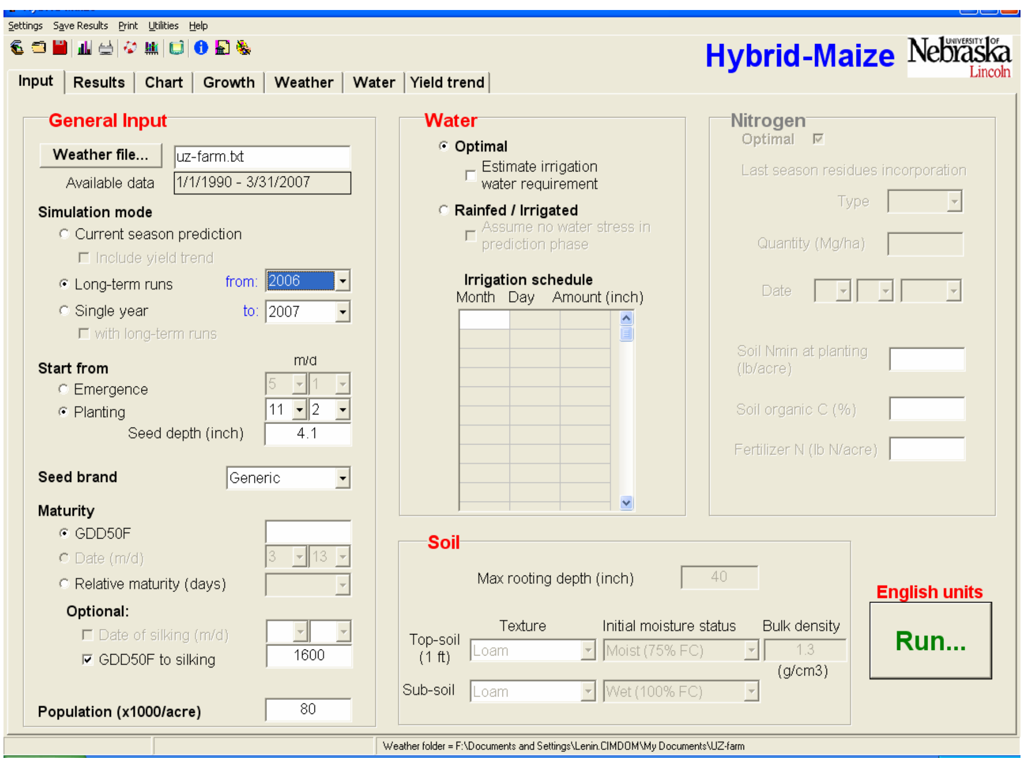


Fig 3.2 Model simulation inputs for yield forecasting

3.3 Statistical analyses

Analysis of data was conducted for grain yield, cobs per row, field weight, ear height for males, ears per plant, grain yield, moisture content of grain, plant height for females and males, plants per row, root lodging for males and females, stem lodging for males and females, a thousand-kernel weight, flowering data and seed grading data on individual row data and plot data analysis using Agro-base GII Statistical Package (Agronomix software Inc, 2007). The general linear model used for analyses of variance is shown in equation 4

Equation 4: $Y_{ijk} = \mu + \rho_i + \alpha_j + \beta_k + (\alpha\beta)_{jk} + \in_{ijk}$ where

Y_{ijk} = yield of the jth level of Factor A, kth level of Factor B in the ith Block

μ = the overall mean of all observations

ρ_I = effect of the ith block

α_j = added effect of the jth level of factor A

β_k = added effect of the kth level of factor B

$(\alpha\beta)_{jk}$ = added effect of the combination of the jth level of factor A and the kth level of factor B

$\in_{ijk}$ = a random error associated with the unit of the jth observation in the ith block

Experiment 2

Harvested hybrid seed maize grain from the net plot was graded based on the principle of length and thickness of the seed according to the Zimbabwe screen sizes (MacRobert, 2006).

3.4 Seed Size Grading

Seed size grading is a component of seed processing which is a process that involves:

- The separation of desired, good, healthy seed from inferior seed and impurities (extraneous matter and weed seeds) to achieve a specified standard of seed purity.
- Dividing good seeds into uniform grades of size and shape.
- Treating seed chemical protectants, colourants and or growth promoters.
- Packaging the pure, healthy seed into identified pack sizes.

3.4.1 Sequence of Seed Size Grading

Seed size grading was carried out based on the principle of length and thickness of the seed according to the Zimbabwe screen sizes (MacRobert, 2006). The widths of the seeds were classed into either Large, Medium or Small grades (Fig 3.2) differentiated by round-holed screens of various diameters. The thickness of a seed was classed into either Round, Thick or Flat grades (Fig 3.2) differentiated by slotted screens of various width. Five hundred kernels of seed maize per plot were counted from the harvested hybrid seed grain. Sieving of the sample kernels was carried out in stacked width sieve trays and then in stacked thickness sieve trays.

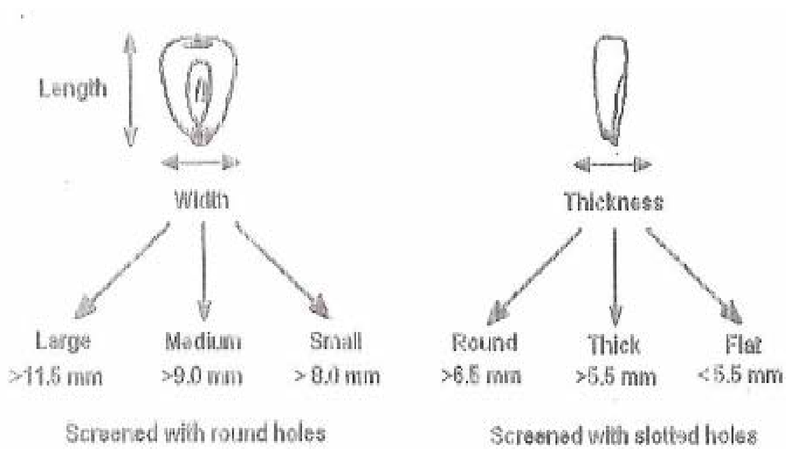
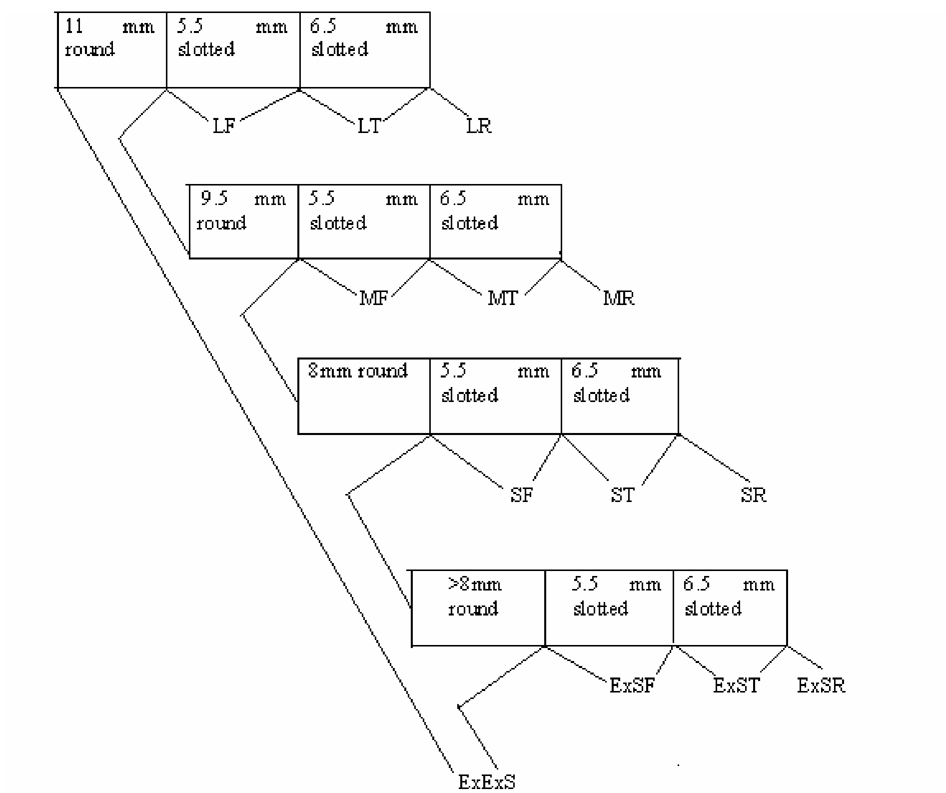


Fig 3.2 Definition of maize seed grading according the Zimbabwean screen sizes.

For the width grading, the first screen was (11.5 mm) round-holed. Seed that failed to pass through the screen was classed as large seed. Medium-sized seed passed through the 11.5 mm screen but failed to pass through the 9.0 mm round-holed screen. The small-sized seed passed through the 9.0 mm round-holed screen but failed to pass through the 8.0 mm round-holed screen. Seed that passed through the 8.0 mm screen was classed as extra-small. Counting and weighing of seed in each width class was carried out. Once the width classes of the seed had been screened, seed of each width class was passed onto slotted screens for thickness screening. Seed that failed to pass through a 6.5mm slotted screen was classed as round seed. Seed that passed through the 6.5 mm slotted screen but failed to pass through a 5.5 mm slotted screen was classed as thick seed. Flat seed was seed that passed through the 5.5 mm slotted screen. Counting and weighing of the seed in each thickness class was also carried out. Thus, there were a total of thirteen seed grades for the three-way hybrid variety as shown in Fig 3.3.



Key L-large: M-Medium: S-Small: F-Flat: T-Thick; R-Round: Ex-Extra.

Fig 3.3 Sequence of the seed grading process and the seed grades for the three-way hybrid maize seed variety adapted from Small Seed Business Management publication (2006).

Data obtained from counting and weighing of the hybrid seed for the thirteen seed grades for the three-way hybrid was analysed using Agro-base GII Statistical Package (Agronomix software Inc, 2007). The general linear model used for analysis of variance is shown in Equation 5:

$Y_{ijk} = \mu + \rho_i + \alpha_j + \beta_k + (\alpha\beta)_{jk} + \in_{ijk}$ where

Y_{ijk} = counting/weighing grade of the jth level of Factor A, kth level of Factor B in the ith Block

μ = the overall mean of all observations

ρ_I = effect of the ith block

α_j = added effect of the jth level of factor A

β_k = added effect of the kth level of factor B

$(\alpha\beta)_{jk}$ = added effect of the combination of the jth level of factor A and the kth level of factor B

$\in_{ijk}$ = a random error associated with the unit of the jth observation in the ith block

Chapter 4

RESULTS

4.1 Analysis Of Variance For The Actual Quantitative Traits Measured.

An analysis of variance of the main effects of Male Planting Date (MPD) and Female Plant Population (FPP), and the interaction of MPD and FPP for the following traits: Days to silking (DS), Days to anthesis (DA), Anthesis Silking Interval (ASI), Ears Per Plant (EPP), Plant Density (PD), Harvest Density (HD), Ear Density (ED), Kernels Per Ear (KPE), Thousand Kernel Weight (TKW), Grain Yield (GY) and Seed grading data is presented (Table 4.1) The raw data and individual summary means tables are provided in Appendices 2 and 3 while ANOVA table and means of the main factors MPD and FPP is presented in Table 4.1 and 4.2.

4.1.1 Days to Silking

There was no significant effect of Male Planting Date (MPD), Female Plant Population (FPP) and the interaction between MPD and FPP on the number of days from sowing of the female plants to silking (DS) (Table 4.1).

4.1.2 Days to Anthesis

There was a significant difference ($P<0.05$) for number of days from sowing to Anthesis of the male plants for Male Planting Date (MPD) (Table 4.1). However, there was no significant difference for FPP and the interaction between Male Planting Date (MPD) and Female Plant Population (FPP). A delay in the MPD was accompanied by an increase in the number of days from sowing to Anthesis of the male plants.

4.1.3 Anthesis Silking Interval

Data of DA and DS was used to calculate the Anthesis-Silking Interval (ASI). ASI was calculated as Days to silking minus Days to anthesis (DS-DA). There was highly significant difference ($P<0.001$) for ASI for Male Planting Date (Table 4.1). Anthesis-Silking Interval ranged from 7 to -15 days for MPD (Table 4.2). Close synchrony between pollen shed of male inbred lines and silking of the female single cross (ASI= -3 days) for MPD when male and female were sown on the same day was observed. There was no close synchrony between pollen shed of male inbred lines and silking of the female single cross (ASI= > 3 days or < 3 days) for all the other Male Planting dates. There were no significant differences for FPP and the Interaction. Hence, FPP and the interaction of MPD and FPP had no observable effect on the ASI for parental components used.

Table 4.1 Mean square Values of main effects of Yield and Yield Components of the Female of a Three-way Hybrid Seed Production

Source of variation	Df	Mean Squares									
		DS	DA	ASI	PD	HD	ED	EPP	KPE	TKW	GY
		days	days	days	m^{-2}	m^{-2}	m^{-2}			g	t ha^{-1}
Block	2	32744*	1022ns	17.24ns	0.973ns	0.829ns	2.188n	0.017ns	4004.252ns	36630.305***	18.161***
MPD	4	4.644ns	51.565*	781.60***	0.088ns	0.278ns	0.284ns	0.005ns	129321.602ns	5731.57ns	47.695***
FPP	2	4.642ns	24.503ns	20.36ns	40.649***	42.197***	27.702***	0.103*	9532.41ns	5125.302ns	18.667**
MPD * FPP	8	5.755ns	11.54ns	14.10ns	0.146ns	0.327ns	0.391ns	0.021ns	6434.618ns	3405.040ns	3.309ns
Error	28	7198	14.591	20.148	0.35	0.325	0.709	0.021	7257.753	2507.921	3.08

*, **, *** = Mean square values significant at 0.05, 0.01 and 0.001 significance levels.

ns = Mean square values not significant

Table 4.2 Summary of Means of Main Effects of Yield and Yield Components of the Female of Three-way Hybrid Seed Production.

Factors		ASI	PD	HD	ED	EPP	KPE	TKW	GY	Yield Mean	Rank
		days	m^{-2}	m^{-2}	m^{-2}			g	$t\ ha^{-1}$	%	
MPD	-10 days (13/10/06)	7	4.9	4.64	4.44	1.00	202	507	4.33	97	3
	-5 days (18/10/06)	2	4.8	4.33	4.45	1.02	343	454	6.76	151	2
	0 days (23/10/06)	-3	4.8	4.72	4.87	1.05	313	451	6.81	152	1
	5 days (28/10/06)	-12	5.0	4.66	4.65	1.00	120	456	2.61	58	4
	10 days (02/11/06)	-15	4.8	4.79	4.53	0.99	81	444	1.83	40	5
FPP	Low	3	3.1	2.86	3.17	1.11	214	482	3.20	72	3
	Medium	4	5.0	4.81	4.71	0.98	241	458	5.30	119	2
	High	5	6.4	6.20	5.88	0.96	181	446	4.90	183	1
	Grand Mean	4.2	4.85	4.654	4.604	1.010	211.8	462.2	4.466	100	
	LSD $_{(0.05)}$	4	0.57	0.53	0.82	0.14	81	48	1.70		
	CV	10.5	12.1	11.8	18.4	14.5	39.6	10.8	39.3		

MPD = Male Planting date (Factor A), FPP = Female Plant Population (Factor B), ASI = Anthesis Silking Interval (days), EPP = Ears Per Plant, PD = Plant density per square metre, HD = Harvest density per square metre, ED = Ear density per square metre, KPE = Kernel Per Ear, TKW = Thousand Kernel Weight, GY = Grain Yield (t/ha), %Mean yield = % of overall mean yield.

4.1.4 Female Plant Density

Female Plant density (PD) at emergence was highly significant ($P < 0.001$) for FPP, as expected (Table 4.1). Female Plant Density ranged from 3.1 plants m^{-2} for low FPP, 5.0 plants m^{-2} for medium FPP and 6.4 plants m^{-2} for High FPP (Table 4.2). There was no significant difference for MPD and the interaction between the two factors. There was variation between actual PD (Table 4.1) and the planned plant density. Planned population was 2.7 to 8.0 plants m^{-2} but field populations 3.1 to 6.4 plants m^{-2} were achieved. Reduction in plant density may be accounted for by destruction of plants during hoe weeding and disease infections. The higher plant density in the low FPD treatment may be accounted for by over planting and ineffective thinning out that was done.

4.1.5 Ear density

There was no significant difference for the MPD for ear density at harvest and the interaction between the main effects MPD and FPP (Table 4.1). However, as expected, ear density was highly significant ($P < 0.001$) for FPP. The highest ear density (5.88 ears m^{-2}) was noted on medium FPP (5.3 plants m^{-2}) and the lowest ear density (3.17 ears m^{-2}) was obtained with the low FPP (8.0 plants m^{-2}) (Table 4.2).

4.1.6 Harvest Density

MPD and the interaction between MPD and FPP main effects were not significant for HD (Table 4.1). However, the FPP were highly significant ($P<0.001$) with a range of 2.86 to 6.2 plants m^{-2} (Table 4.2), as expected. The low population density (2.7 plants ha^{-1}) had the lowest harvest density (2.86 plants m^{-2}), optimum harvest density (4.81 plants m^{-2}) was obtained from the medium FPP while the highest FPP (8.0 plants m^{-2}) had the highest harvest density (6.20 plants m^{-2}).

4.1.7 Ear Density

FPP had a highly significant ($P<0.001$) effect on ED of the female plants of the three-way hybrid (Table 4.1). The ED ranged from 3.17 to 5.88 ears m^{-2} for the Female Plant Population of the three-way hybrid (Table 4.2). The highest ED for the FPP was obtained on high FPP (5.88 t ha^{-1}) with the lowest (3.17) being obtained on low FPP.

There were no significant differences between MPD main effects for ED and there was no significant interaction between FPP and MPD for ED

4.1.8 Ears Per Plant

FPP had a significant ($P<0.05$) effect on the number of ears per plant (EPP) of the female plants of the three-way hybrid (Table 4.1). The number of EPP ranged from 0.96 to 1.11 for the Female Plant Population of the three-way hybrid (Table 4.2), with the high female population density (8.0 plant m^{-2}) having the lowest average EPP (0.96) and the lowest female population density (2.7 plants m^{-2}) having the highest average EPP (1.11). There were no significant differences between MPD main effects for EPP and there was no significant interaction between FPP and MPD for EPP. Consequently, this data indicates that EPP is mainly a function of plant density.

4.1.9 Kernels Per Ear

There was no significant difference for kernels per ear for MPD (Table 4.1). The main effect of FPP was also not significant for KPE. However, the highest KPE (241 kernels) was noted for medium FPP while the lowest number of kernels was noted for high FPP (Table 4.2).

4.1.10 Thousand Kernel Weight

Thousand kernel weight data was not significant for all the factors and the interaction between the two factors (Table 4.1). The high significant difference ($P<0.001$) for blocking indicated the efficiency of blocking in controlling error for the experiment.

4.1.11 Grain Yield

The grain yield was highly significant ($P<0.001$) for MPP (Table 4.1), with yields ranging from 1.83 to 6.81 t ha^{-1} (Table 4.2). Female Plant Population was significant ($P<0.01$) for GY with the highest yield (5.30 t ha^{-1}) being obtained for medium FPP (5.3 plants m^{-2}) and the lowest yield (3.20 t ha^{-1}) for low FPP (2.7 plants m^{-2}).

However, the interaction for the two factors was not significant (P= 0.05) for grain yield.

4.2 Relationship between Grain Yield and Other Traits and Treatments of Main Effects

ASI affected the Grain Yield (GY) of the female of the three-way hybrid as a result of varying MPD. Likewise, grain yield was also affected by FPP. This section presents the relationship observed between number of Days to Silking (DS), number of Days to Anthesis (DA), Anthesis-silking interval (ASI), Grain Yield (GY), Female Plant Population (FPP) and Harvest Density (HD).

4.2.1 Relationship between Days to Anthesis and Days to Silking

The cumulative emergence of silks on the female and the cumulative proportion of plants shedding pollen for each MPD treatment are shown in Fig 4.1. A short ASI is considered optimum for kernel set in hybrid seed maize production. Ideally, the male plants should begin shedding pollen when the first female silks begin appearing. There was a significant difference ($P<0.05$) of MPD for DA (Table 4.1). However, there was no significant difference of FPP and the interaction between MPD and FPP. In addition, there was also no significant difference for number of days to silking (DS) data. The time to fifty percent silking of the female plants occurred seventy-five days after planting and the time to fifty percent pollen shedding of male plants ranged from sixty-seven days to ninety days after planting of the male. Resultant data for DA and DS showed that ASI ranged from 7 days to -15 days. An almost perfect nick was obtained at MPD day zero where ASI=-1.

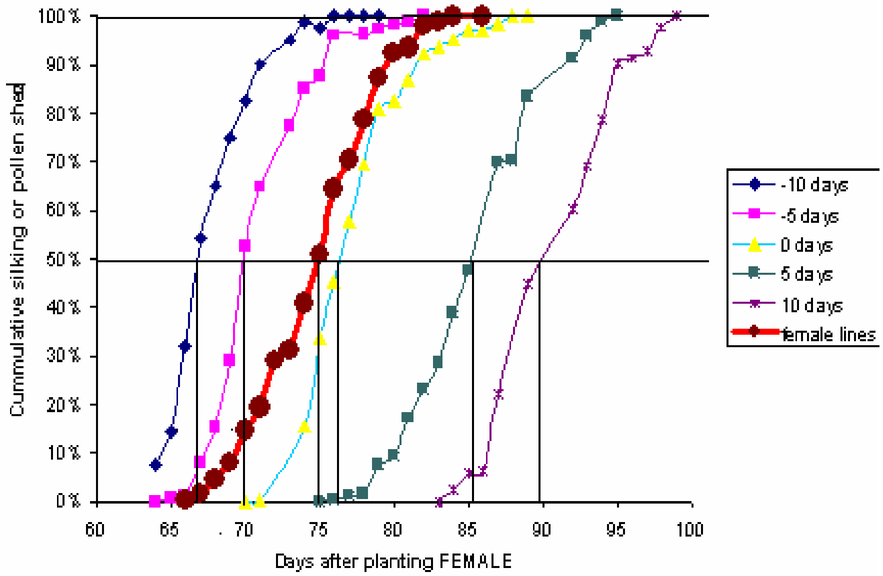


Figure 4.1 Relationship between Cumulative Silking or Pollen shed and Days after planting females

4.2.2 Relationship between Yield and ASI.

The relationship between grain yield (GY) and ASI showed that GY was greatest (6.81 t ha^{-1}) where there was close synchrony between pollen shed of male plants and silking of the female single cross (ASI= +/-3 days) (Fig 4.2). GY was less when ASI was either less than three days or greater than three days. A significant curvilinear regression was obtained between GY and ASI (R^2 =0.94).

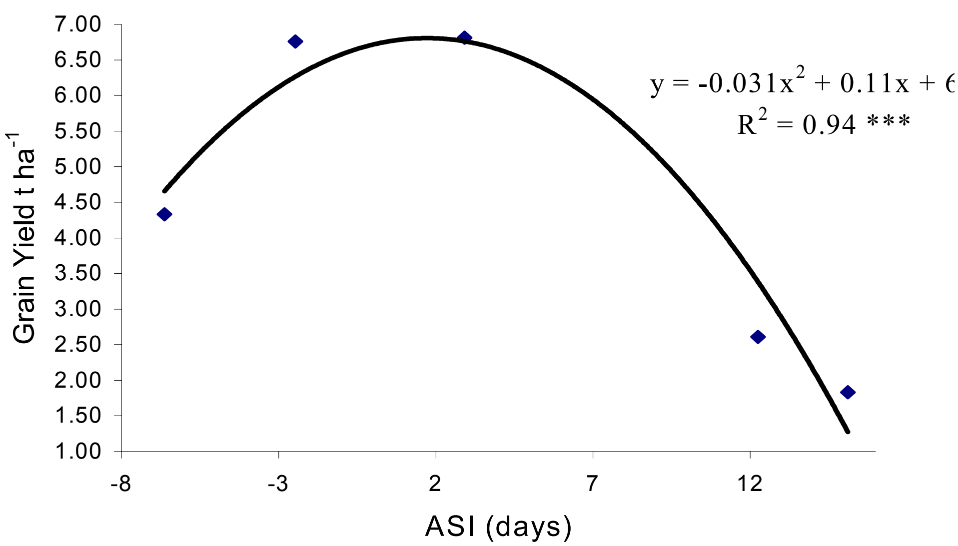


Figure 4.2 Relationship between ASI and Grain Yield

4.2.3 Relationship between Grain Yield and Female Plant Density

The relationship between Grain Yield (GY) and Female Plant Density (FPD) is presented (Fig 4.3) and a quadratic equation was fitted to the data. As plant density increased from a low FPP of 3.1 plants m^{-2} to a medium FPP of 5.0 plants m^{-2} there was a corresponding increase in GY from 3.20 t ha^{-1} to 5.30 t ha^{-1}. Yield declined from the medium FPP to the high FPP of 6.4 plants m^{-2}. Based on the curvilinear relationship the estimated maximum GY was obtained at a FPP of 5.4 plants m^{-2}.

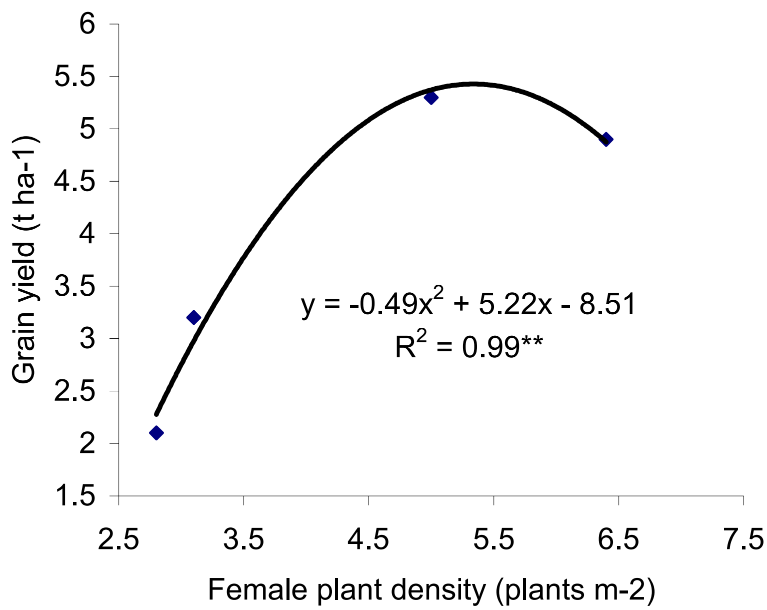


Figure 4.3 Relationship between Grain Yield and Female Plant Density

4.2.4 Relationship between Grain Yield and Harvest Density

The relationship between Grain Yield and Female Harvest density is presented in (Fig 4.4). Lowest grain yields were noted for low HD (3 plants m^{-2}) for all MPD with the exception of MPD +10 days in which the highest HD (6 plants m^{-2}) had the lowest yield of (0.9 t ha^{-1}). Increased HD from low to medium HD resulted in a corresponding increase in GY. A General decline in GY was noted with further increase in HD from medium to high HD (6 plants m^{-2}) with the exception of MPD of –5 and +5 days where there was a continuous increased GY of 8.07 and 3.70 respectively being noted.

Harvest density may also be related to the linear relationship between PD at emergence and ED at harvest (Fig 4.5). This explains the general relationship of GY and HD. A positive correlation ($R^2 = 0.97$) between PD at emergence and Plant or ED at harvest was noted. At low FPP, ED was greater than HD, while at High FPP, ED was less than HD.

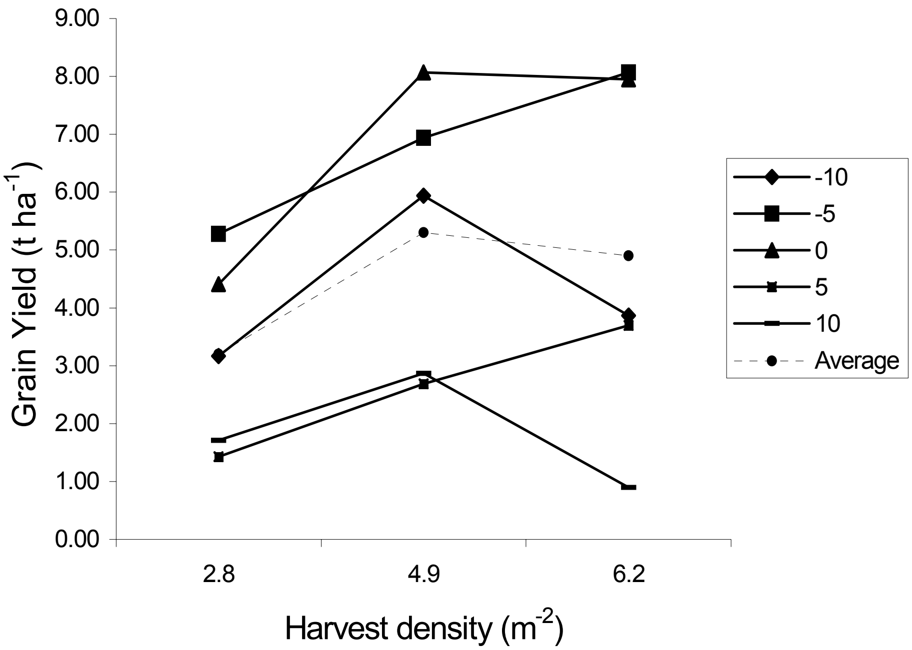


Figure 4.4 Relationship between Harvest density and Grain Yield

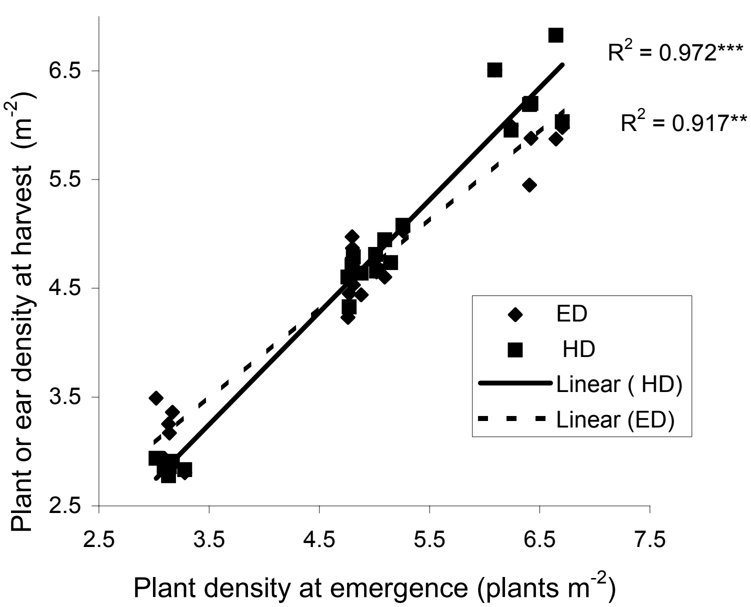


Figure 4.5 Relationship between Plant density at emergence and ear density at harvest

4.3 Relationship of Yield Components with Traits and Main Effects

Yield components may help to understand variation in GY of seed maize across environments. Yield components of the female of the three-way hybrid in relation to PD, ASI, EPP, KPE and TKW varied as a function of MPD and FPP. This section presents the relationship observed between the yield components that had a resultant effect on GY.

4.3.1 Relationship between Ear density and Grain Yield

The relationship between ED and GY is represented in Fig 4.6. A positive correlation (R^2 = 0.97), was established which showed that an increase in ED resulted in a corresponding increase in GY. Maximum GY (5.3 t ha-1) was obtained at ED of 4.71 ears m^{-2}. Further increase in ED from 4.71 ears m^{-2} resulted in a decline in GY.

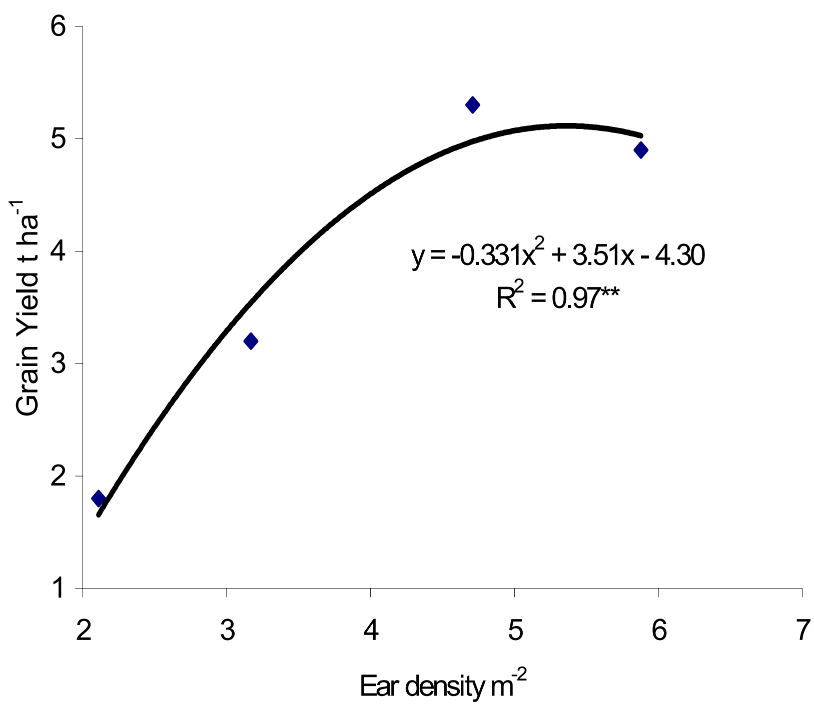


Figure 4.6 Relationship between Grain yield and Ear density

4.3.2 Relationship between Ears Per Plant And Plant Density At Emergence

The relationship between EPP and PD at emergence and EPP is represented (Fig 4.7). A negative correlation (R^2 =0.53), was established which showed that an increase in PD at emergence resulted in a corresponding decline in EPP. An increase in PD at emergence from 3.1 plants m^{-2} to 5.0 plants m^{-2} resulted in a decline in EPP from 1.11

to 0.98 ears m^{-2}. Further increase in PD at emergence to 6.20 ears m^{-2} resulted in a continuous decline of EPP to 0.96 ears m^{-2}.

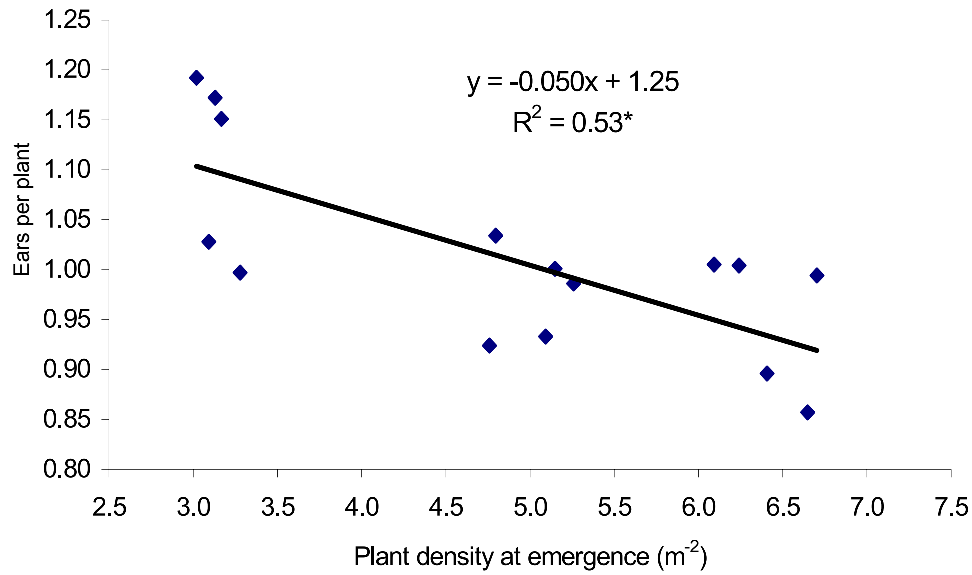


Figure 4.7 Relationship between ears per plant and plant density at emergence

4.3.3 Relationship between Kernels Per Ear and Plant density at harvest

The relationship between kernels per ear and plant density at harvest is presented in (Fig 4.7) to which a linear equation was fitted to the data. The linear equation was not significantly correlated (R^2= 0.01).

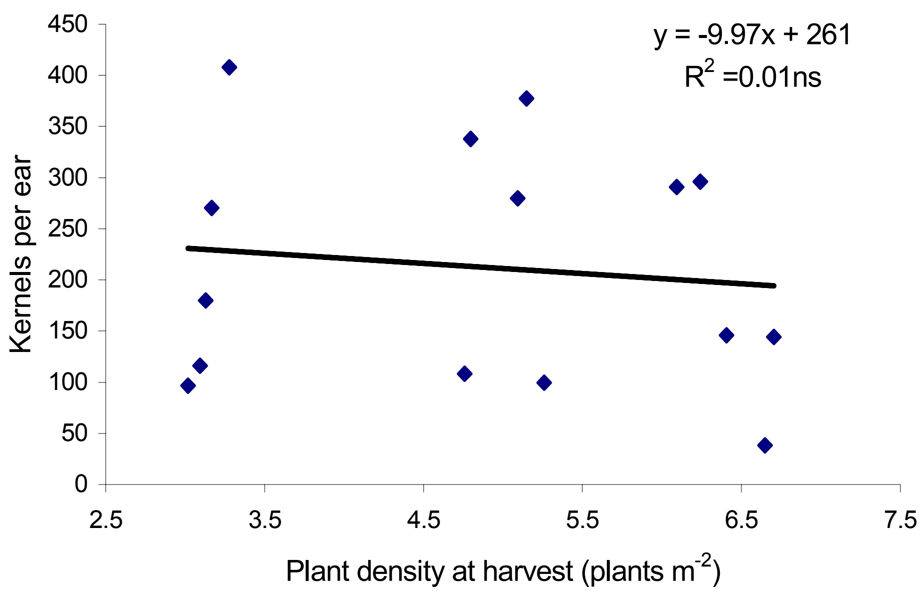


Figure 4.7 Relationship between kernels per ear and plant density at harvest

4.3.3 Relationship between Kernels Per Ear and Anthesis-Silking Interval

The relationship between Kernels Per Ear and Anthesis-Silking Interval is presented (Fig 4.9). A quadratic equation was fitted to the data. A high significant positive correlation (R^2 =0.92) was noted. Low KPE was obtained when ASI was less than three, where silking occurred earlier than the male lines. The greatest KPE (343) was noted when there was close synchrony between pollen shed and silking of female (ASI = 3days). Low KPE were also obtained when ASI was greater than three days, anthesis occurred earlier than silking

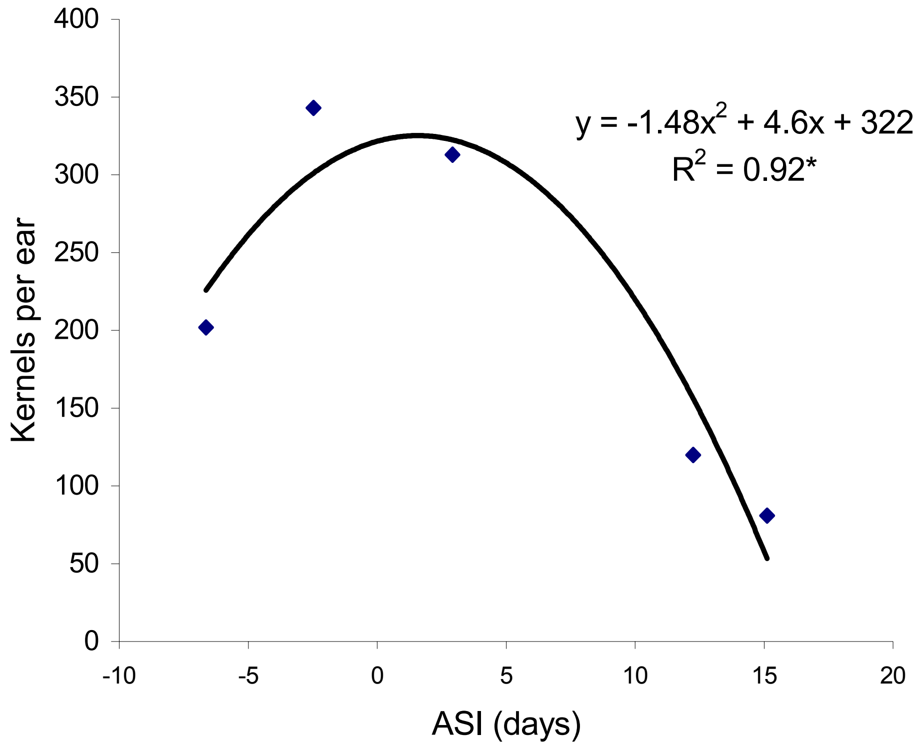


Figure 4.8 Relationship between Kernels per ear and Anthesis-Silking Interval

4.3.4 Relationship between Thousand Kernel Weight and ASI

The relationship between Thousand Kernel Weight and ASI is presented in (Fig 4.10). Low ASI (ASI= -7 days) had the greatest TKW (507 g). As ASI moved towards close synchrony between pollen shed of male inbred line and silking of female single cross there was a decline in TKW. An almost constant TKW (451 g) was obtained for the ASI range +3 days to +12 days. A further increase in the ASI (ASI>12) resulted in the lowest TKW (442 g) being obtained.

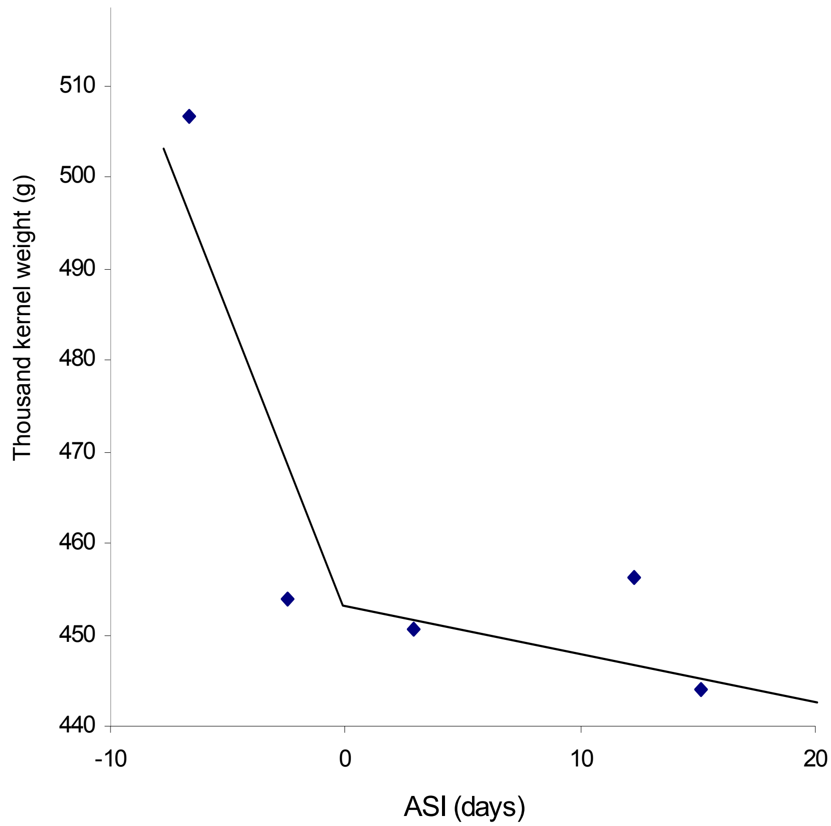


Figure 4.9 Relationship between Thousand Kernel Weight and ASI

4.3.5 Relationship between Thousand Kernel Weight and Kernels Per Ear

The relationship between Thousand Kernel Weight (TKW) and Kernels Per Ear (KPE) is presented (Fig 4.11). A quadratic equation was fitted to the data in which significant correlation (R^2 =0.77) was obtained. Greatest TKW (498 g) was noted for 218 KPE. Decline in TKW was witnessed with KPE ≈ 218. The lowest TKW (444 g) was observed when KPE was 81.

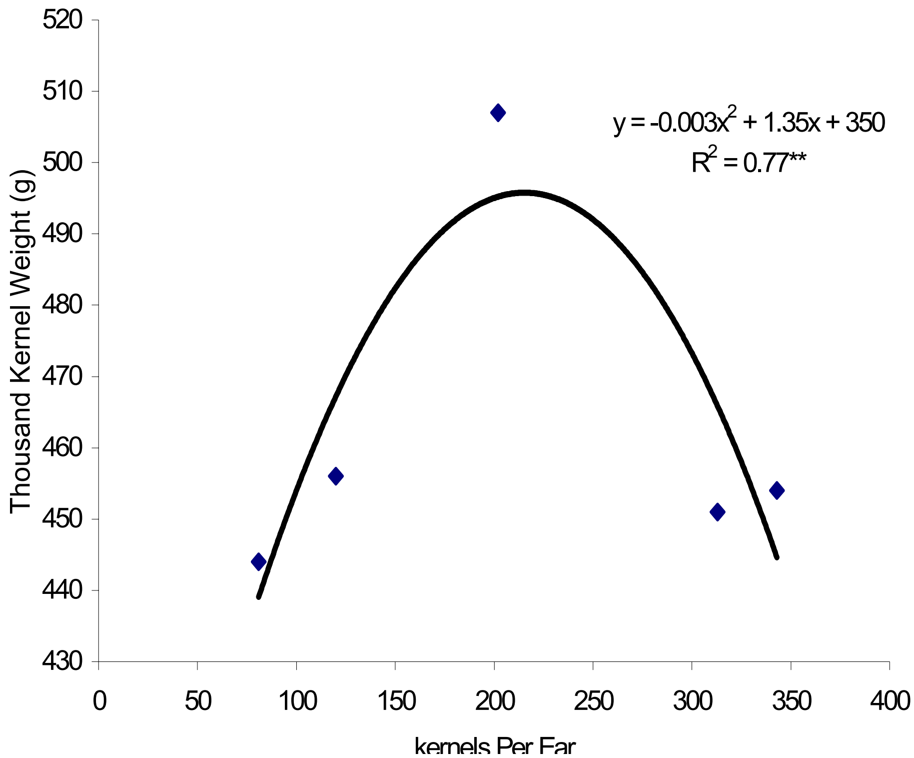


Figure 4.10 Relationship between Thousand Kernel Weight and kernels Per Ear

4.4 Simulation Output for Hybrid-Maize Simulation Model

Hybrid-Maize Simulation Model simulates the growth and yield of maize so as to enable the evaluation of grain yield using different combinations of planting date and plant density. The simulation output for Hybrid-Maize simulation model is presented (Table 4.3). The greatest yield was noted for high FPP (8.0 plants m^{-2}) and MPD –5 days of 12.04 plants m^{-2}. The data showed that the general trend was that the greatest yield was obtained for high FPP for the entire female planting dates Fig 4.12. The model could not deal with low FPP (2.7 plants m^{-2}) resulting in missing output that was noted for the simulation model output.

The model cannot cope with a hybrid seed field situation of male and female planting dates, which are different. As a result FPD used in this trial were assumed to be MPD. Hence the use of FPD in the model to estimate GY.

Table 4.3 Grain yield output for the simulation model

Female Plant Population (Plants ha^{-1})	Female Planting Date	Simulated Yield (t/ha) Grain Yield (t ha^{-1})	Rank
80 000	13/10/06	11.96	2
53 333		10.94	5
26 666		*	.
80 000	18/10/06	12.04	1
53 333		11.03	4
26 666		*	.
80 000	23/10/06	11.31	3
53 333		10.40	7
26 666		*	.
80 000	28/10/06	10.82	6
53 333		9.97	9
26 666		*	.
80 000	2/11/06	10.16	8
53 333		9.41	10
26 666		*	.

* Missing data from output.

4.4.1 The relationship Between Grain Yield and Female Planting Date

The relationship between GY and female planting date (FPD) for the two FPP (high and medium) is presented in Fig 4.11 and a quadratic equation was fitted to the data for each FPP. The equations showed that there was a significant correlation (R^2 = 0.97 and 0.97) between grain yield and female planting date for high (8.0 plants m^{-2}) and medium (5.3 plants m^{-2}) FPP, respectively. Grain yield was greatest for high FPP as compared to medium FPP. Quadratic equation for low FPP is missing as the simulation model cannot deal with low population density (2.7 plants m^{-2}).

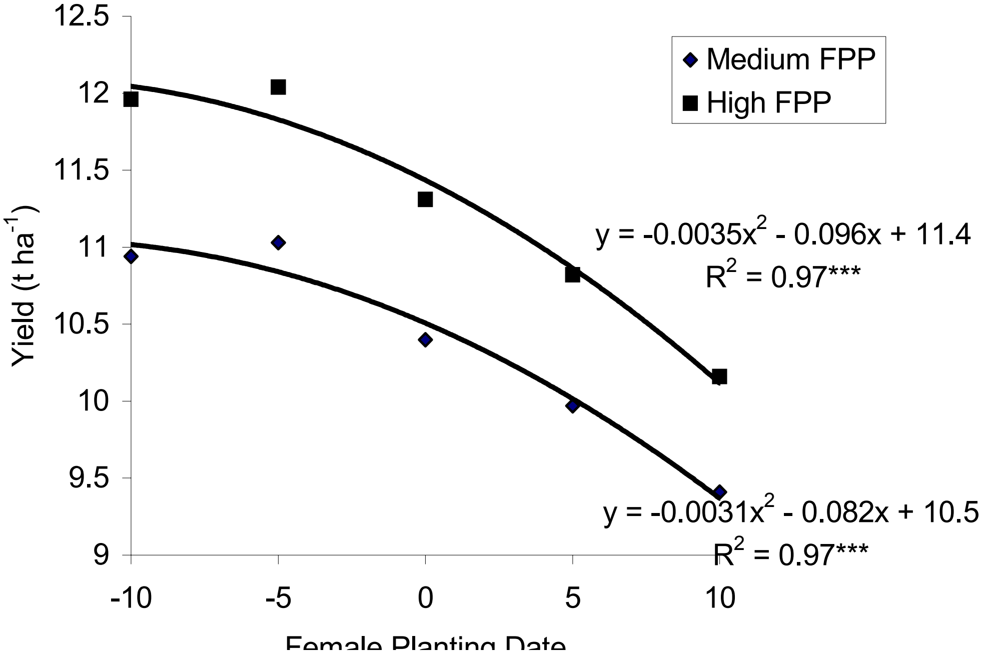


Figure 4.11 Relationship between grain yield and female planting date

4.4.2 Comparison of Predict yield and Observed yield

Comparison of model predicted yield and observed yield (Fig 4.13) showed that there was an over estimation of predicted yield as compared to the observed yield. At low observed yield there was a high-predicted yield.

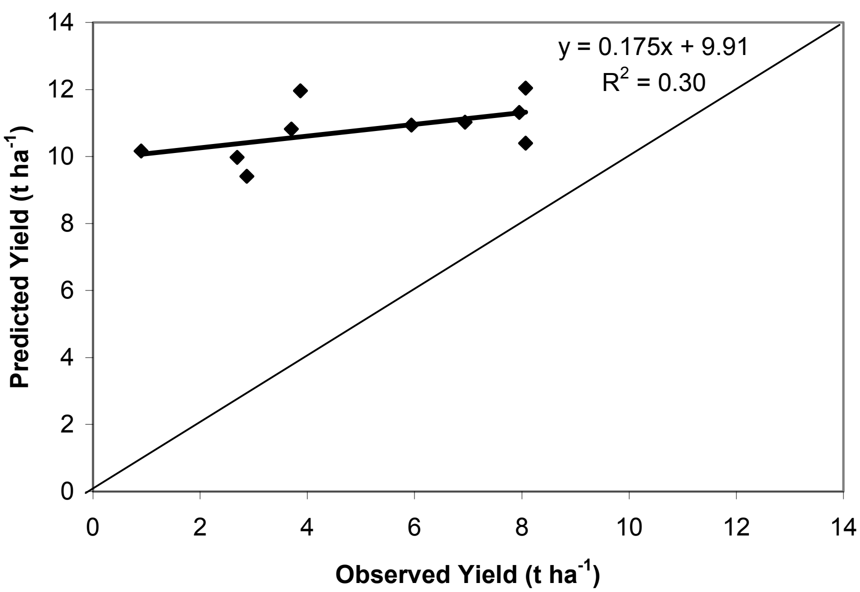


Figure 4.12 Comparison of Predicted yield and observed yield

4.5 Seed size grading

Summary of the percent width grades of the three-way hybrid seed for the FPP main effect is shown in Fig 4.13. Medium and High FPP had the smallest percent of extra small kernels as compared to low FPP. Small kernels had a higher percent for low FPP. Highest percent of Medium kernels was obtained for medium FPP. For the large kernels, there was no percent width kernel difference.

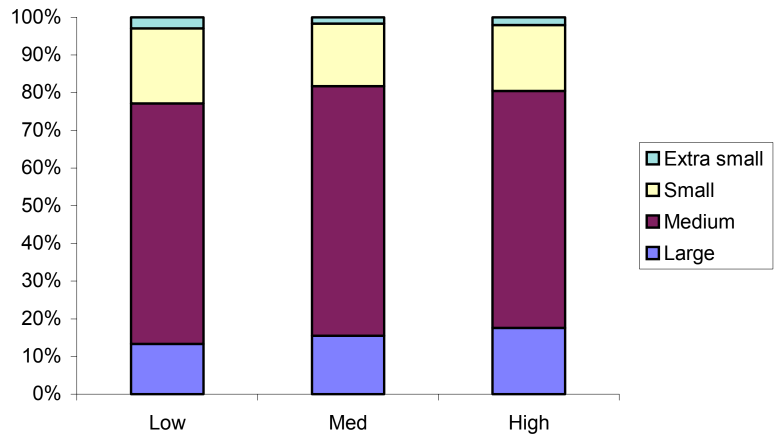


Figure 4.13 Percent Width of Seed for Female Plant Population Main Effect

Summary of the percent width grades of the three-way hybrid seed for the MPD main effect is shown in Fig 4.15. All the MPD had almost equal percent kernel grades except for MPD (0 days) where there were a higher proportion of small kernels and a corresponding low percent width of large kernels.

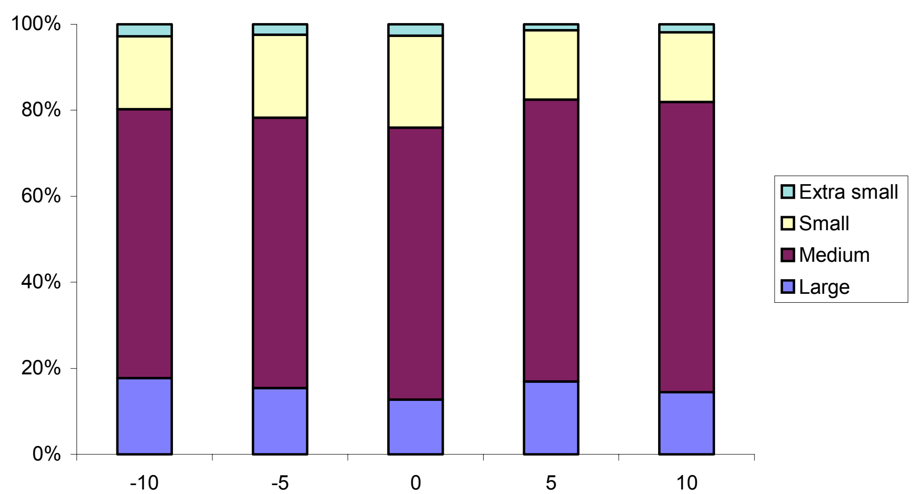


Figure 4.14 Percent Width of Seed For Male Planting Date

Summary of the percent thickness of the three-way hybrid seed for the FPP main effect is shown in Fig 4.15. Low and Medium FPP showed no difference in percent thickness for the three grades. High FPP had a higher percent of Round seed and a corresponding low percent of thick and flat seed for FPP main effect.

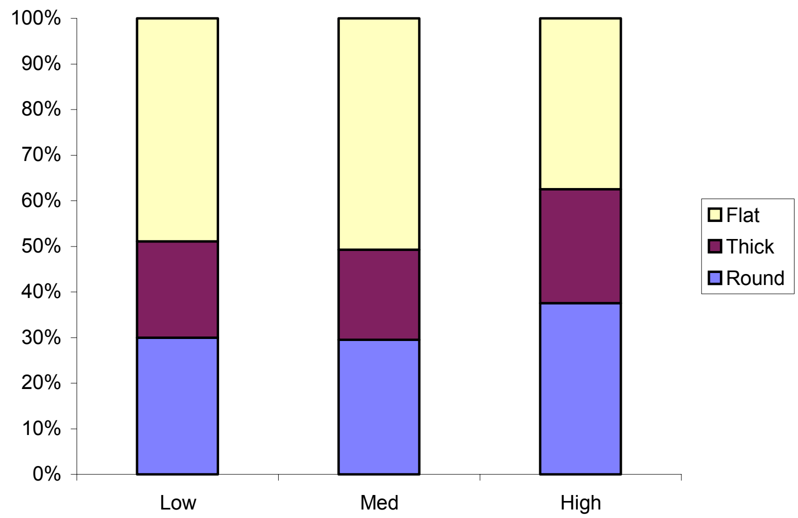


Figure 4.15 Percent Thickness of Seed for Female Plant Population

Summary of the percent thickness of the three-way hybrid seed for the MPD main effect is shown in Fig 4.16. MPD (5 days) had the highest percent of flat seeds. MPD (10 days) had the highest percent of thick seed. The lowest percent of round seeds was obtained on MPD (-5 days).

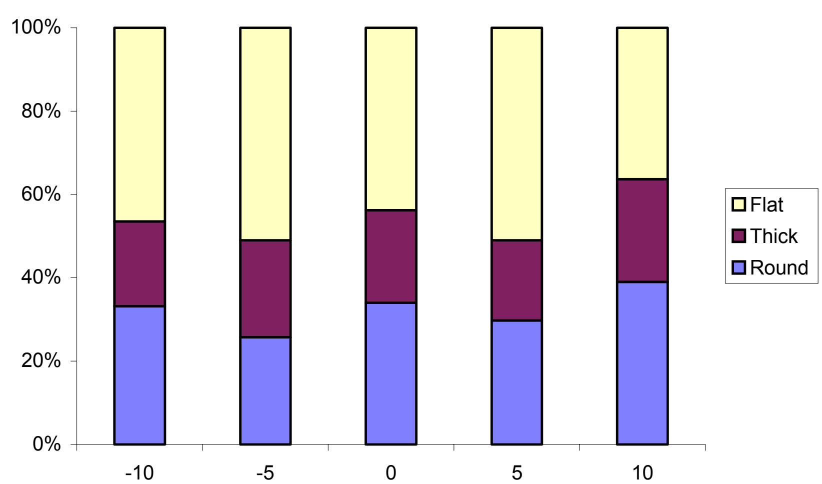


Figure 4.16 Percent Thickness of Seed for Male Planting Date

Chapter 5

DISCUSSION

5.1 Relationship between Days to Anthesis and Days to Silking

Ideally in a hybrid seed maize field, male plants should begin shedding pollen when the first female silks begin appearing (MacRobert, 2006). However, male and female plants might not always take the same time to reach the flowering stage. In this experiment, differences were observed in the time taken to reach flowering of the male and female plants. The time to fifty percent pollen shedding ranged from sixty-seven days for MPD (-10 days) to the maximum of ninety days after MPD (10 days) (Fig 4.1). The ideal flowering only occurred for MPD (0 days) when the male plants began to shed pollen almost the same time when the female silks began to appear. The time to fifty percent silking of the female occurred seventy-five days after planting. Hence, the resultant mis timing of male and female flowering due to variation in MPD, reduced yields and exposed the female seed parent to contamination from foreign pollen. Pollen shedding and silk emergence may take place over 10 to 14 days and may not coincide even if the male and female parents are planted on the same day (MacRobert, 2006). Contrary to this literature, pollen shedding and silk emergence took place over 13 to 19 days, but in agreement, for all the MPD except MPD (0 days), there was no coincidence for the male and female parents flowering.

5.2.1 Anthesis Silking-Interval

A short Anthesis Silking-Interval (ASI) is a key trait for obtaining high grain yield in maize seed production (Bolanos and Edmeades, 1993). This is equally the case in hybrid production where female plants are totally dependant on male plants for supply of pollen. In this experiment, a shift in the interval from close synchrony (+/-3 days) was associated with a decline in GY for the female of the three-way hybrid, in agreement with most reports from the literature (Bolanos and Edmeades, 1993; Duvick, 1997 and Edemeades *et al*., 2000). Hunter *et al*. (1981 and 1982) suggested that an increased ASI reduced kernel number because of lack of pollen for late-appearing silks while early appearing silks may have reduced receptivity to the pollen. Thus, in this work a shift in the ASI from close synchrony gave further evidence of the negative effects on reduction in grain yield. Close synchrony between pollen shed of male and silking of female (ASI= +/- 3days) had the greatest yield (Fig 4.1). There are two possible reasons for such a significant enhancement in grain yield. First and foremost, a much larger fraction of late-emerging silks are pollinated when pollen shed is delayed relative to silking, there is prolongation of the effective flowering period. Second, all the early emerging silks are pollinated as well because they remain receptive to pollen for several days after they appear (Bassetti and Westgate, 1993a, 1993b).

This clearly demonstrated why timing of silking by the female population in relation to pollen shed of male population is such an important management variable in hybrid seed production that should also be focused on as it has an impact on potential grain yield as evidence by the highly significant difference (P< 0.001) for grain yield for the ASI in Table 4.1 in agreement with reports form literature (Edemeades *et. al.,* 2000: Bolanos and Edmeades, 1993). This seems particularly clear for hybrid seed production since pollination could be less than desired for several reasons. First, pollen density is much less than in commercial maize field since inbreds typically produce less than do their hybrid counter parts. Second, Fonseca, Westgate, Doyle (2003) further reported that only a fraction of the field population is permitted to shed pollen from the male inbred parent. Actually, the major goal in hybrid seed production is to reduce the area dedicated to male rows as much as possible without decreasing the number of kernels harvested per area. Third, the level of pollen viability could be less than required for optimum pollination of receptive silks (Schneider, 2003). Fourth, pollen shed and silk extension on spatially separated plants increase the probability that floral asynchrony can lead to poor kernel set.

Delaying pollen shed to maximize pollination by late planting of male line (MPD = +5 and +10 days) did not increase the grain yield but increased the potential risk of out crossing from foreign pollen sources of pollen contrary with literature. Fonseca *et al.* (2004) using simulated data reported that delaying of pollen source from the original 1.2 to 3 days indicated that nearly sixty-eight percent of the silks would be pollinated and potential kernel yield would increase by twenty-three percent. If the interval were increased to 5 days, potential kernel yield would be increased by about thirty-eight percent, clearly indicating the potential of increasing GY by late planting of male line. Hence, the best approach to managing floral synchrony will depend on the time from planting to pollen shed on silking of the respective parents.

5.2.2 Relationship Between Grain Yield and Female Plant Density

Maize is sensitive to intra-specific competition as evidenced by the highly significant effect ($P < 0.001$) of FPP on GY. Stand density affects plant architecture, alters growth and developmental patterns and influences carbohydrates production and partition. Increased FPP from low (3.1 plants m^{-2}) to medium (5.30 plants m^{-2}) density resulted in increased yield (Fig 4.3). A further increase in FPP from medium to high (6.4 plants m^{-2}) resulted in a decline in GY in agreement with reports from the literature (Edmeades and Daynard, 1979a;Tetiokago and Gardner, 1988; Echarte *et al*. 2000; Sangoi *et al.* 2002; Borras *et al*. 2003). For each production system there is a population that maximizes the utilization of available resources, allowing the expression of maximum attainable GY on the environment. In this experiment, optimum density was noted from the regression equation to be 5.4 plants m^{-2}. When the number of individual plants per unit area was increased beyond this optimum density, there was a series of consequences that were detrimental to ear ontogeny and resulted in barrenness hence the decline in GY (Sangoi, 2000).

Decline in GY when plant density increased beyond the optimum density is usually associated with a decline in the harvest index and increased stem lodging caused by increase in inter-plant competition for solar radiation, soil nutrients and soil water (Tollenaar *et al*., 2000). This result in limited supplies of photosynthetic photon flux density, carbon and soil nutrients and consequently increases barrenness and decreases in kernel number per plant, kernel size and kernel weight. In agreement, Edmeades *et al*. (2000) reported interplant and intraplant competition affecting ASI as the underlying cause of the significant reduction in GY (Table 4.1). Intraplant competition may exist between ear and stem or root growth resulting in significant decline in GY. Maize GY development is a sequential process in which the potential number of EPP is determined first, followed by grain number per inflorescence and finally by grain size. Therefore, sequential variations in the level of carbon and nitrogen induced by different planting densities, or any other factor, may strongly influence GY formation and its components (Jacobs and Pearson, 1991).

5.2.3 Relationship Between Grain Yield and Harvest density

Maize is sensitive to intra-specific competition (Edmeades and Daynard, 1979). When ear density is increased there is a corresponding increase in GY until the optimum ear density is reached. Beyond the optimum ear density, an increase in ear density is accompanied by a decline in both plant biomass and grain yield per unit land area. Decline in GY beyond the optimum density is attributed to resource availability (i.e. water, nutrients, and irradiance) and the tolerance of a hybrid to intra-specific competition (Tollenaar *et al.,* 1977; Echarte *et al.,* 2000). According to a report by Gardner and Gardner (1983), in agreement with this work, low dry matter partitioning to reproductive structures as ear density increases accounts for the decline in grain yield.

5.2.4 Relationship Between Grain Yield and Harvest density

Relationship between grain yields and harvest density showed that as harvest density increased there was an increase in grain yield. Data for the HD showed that it was highly significant ($P< 0.001$) with a range of 3.1 to 6.4 plants m^{-2} (Table 4.1). GY showed a response to HD that produced maximum value at the optimum (medium) HD (Fig 4.4). At low HD, grain yield was not compensated by increased KPE, TKW or EPP while substantial low EPP occurred above the optimum HD (Tetiokago and Gardener, 1988). However, exceptions were observed in this experiment contrary to other reports in literature. A continuous increase in grain yield as HD increased from medium to high for MPD (-5 and +5) was noted (Fig 4.4). This can be accounted for by the fact that increased HD was used as an efficient management tool for maximizing grain yield by increasing the capture of solar radiation within the canopy for the two MPD.

The linear relationship between the GY and HD was further explained by the linear relationship between plant density at emergence and plant or ear density at harvest. As plant density increased at emergence a corresponding increase in the number of plants or ears harvested at maturity was noted (Fig 4.5). This is contrary to reports from literature. According to a report by Sangoi *et al.* (2000) high rates of planting slow the rates of axillary buds more than they do the shoot apex. The existence of this time interval permits the establishment of differential rates of polar transport of growth-promoting substances and nutrients into the shoot. These growth-promoting substances and nutrients would regulate the rate and pattern of ear shoot development and the number of functional ear shoots per plant. Later-initiated ear shoots may have received smaller amounts of such substances, thereby having less chance to become functional and produce grains.

5.3 Interaction Of Yield Components

Grain yield and its components, EPP, KPE, and TKW showed a dependence on the ASI. According to a report by Edmeades *et al.* (2000) GY and its component, KPE, show a dependence on ASI of the general form GY= exp $^{(a + b * ASI)}$. In this experiment, for all measured yield components there was a general significant reduction in GY with increase in main effects of MPD and FPP and the interaction of MPD and FPP for the various yield components (Table 4.1).

5.3.1 Relationship Between Plant Density At Emergence And Ears Per Plant

The relationship between plant density at emergence and ears per plant is represented in Fig 4.7. An increase in PD at emergence resulted in a corresponding decline in EPP; the linear relationship (Fig 4.7) indicated negative correlation (R^2 =0.53), being noted in agreement with some reports in literature (Edmeades and Daynard, 1979). According Edmeades and Daynard (1979) as plant density is increased, the ratio of ear growth rate (i.e. rachis + developing grain) to total shoot growth declines drastically. This decline can be attributed largely to decline in radiation reaching the ear leaf at high densities relative to low and medium population densities. The ear leaf provides a large proportion of its assimilate to the ear.

An unfavourable environmental condition through intraplant competition reduces dry matter partitioning from the ear leaf to the ear resulting in cessation of ear development and ear abortion. This is clearly illustrated in this experiment by the reduction in EPP with increase in PD at emergence. High densities produce low Plant Growth Rate (PGR), whereas low densities induce high PGR. Since dry matter partitioning to reproductive structures (ear) and kernel set respond to the amount of resources available for each individual plant. Competition may also exist between ear and stem or root growth resulting in a decline in the number of EPP as noted in this study.

5.3.2 Relationship Between Kernels Per Ear And Anthesis-Silking Interval

This study showed that there was curvilinear correlation between ASI and KPE (R^2 = 0.92). A quadratic function fitted to this data indicated that a curvilinear relationship (Fig 4.9) exists, with the greatest KPE (343) noted where there was close synchrony between pollen shed and silking of female (ASI= +/-3 days). As expected KPE was low when ASI was either less than three or greater than three days, in support to several reports from literature (Hall *et al.,* 1981; Westgate and Boyer, 1996). Hall *et al*. (1981) suggests three possible reasons for the association between KPE and ASI: lack of pollen leads to a, reduction in the kernels on the ear and reduction in kernel set. Westgate and Boyer (1996) proposed that these causes could be grouped as: lack of pollen because of asynchrony, non-viability of pollen or because anthers do not produce pollen and a slow rate of spikelet growth resulting in a large ASI, silk senescence, and abortion following pollination.

Carvova *et al.* (2000) reported that close synchrony between pollen shed and silk emergence is required for high kernel set per ear in maize. Increase in ASI resulted in lack of pollen for late appearing silks on apical ears (Hall *et al*., 1982), reduced silk emergence from sub-apical ears (Hall *et al.,* 1980), failure in ovary fertilization, and ultimately reduced kernel set. In this study increase in ASI (Table 4.2) resulted in reduced KPE indicating poor kernel set due to lack of pollen (asynchrony), reduction in pollen viability and silk receptivity. Reports from literature (Hall *et al.,* 1981 and Carvova *et al.,* 2000) suggest that perfect synchrony (ASI= 0 silking and anthesis on the same day) correspond to the highest kernel set per ear. In this study this was contrary but in agreement with several reports from literature (Bolanos and Edmeades, 1993: Duvick, 1997; Edmeades *et al.,* 2000) where perfect synchrony did not correspond to highest KPE. Close synchrony (ASI= +/- 3 days) corresponded to the highest KPE (Table 4.2).

5.3.3 Relationship between Thousand Kernel Weight and Kernels Per Ear

The relationship between TKW and KPE is presented in Fig 4.11 and a quadratic equation was fitted to the data. The equation showed that there was correlation (R^2 =0.78) between TKW and KPE. According to a report by Augustin *et al.* (2004) maize yield is a function kernel number per plant (KNP) at harvest and Kernel Weight per plant (KWP). In this study TKW was noted as a function of grain yield in which low KPE (KPE $\approx$100) had the lowest TKW. Small kernels found at the tip of the ear that have reduced grain filling period can account this. As the number of KPE increased the greatest TKW was reached (350 g). This can be accounted for by well-filled kernels at the butt of the ear where pollination starts of from which were noted. Such kernels are usually bigger in size and well filled due to a longer grain filling period as compared to smaller kernels found at the tip of the ear which have a reduced grain filling period. Further increase in KPE was accompanied by a corresponding decline in TKW. This may be accounted for by the fact that there was complete kernel set from the butt to the tip of the ear and as a result there was competition for assimilates during the grain filling stage.

5.4 Simulation output for Hybrid-Maize simulation model

Contrary to several reports (Jones and Kiniry, 1986; Ritchie and Wei, 2000 and Yang, 2006) Hybrid-Maize simulation model had an overestimation of GY potential of the female of the three-way hybrid for High and Medium FPP (Table 4.3). Greatest GY was noted for high FPP (12.04 t ha^{-1}) when female planting date was 18/10/06 (Table 4.3). Delay in the female planting date resulted in a decline in yield for the two FPP. This can be accounted for by reduced growing season for the late planted female population and also reduced grain filling period. An over estimate of the actual yield was also noted from the simulation output which might be due to incorrect model parameters for the female single cross and also the model is designed for United States maize.

Hybrid-Maize simulation model did not take into account other limiting factors during the run of the season, which might have also reduced the potential yield. Its inability to separate male and female planting dates in seed production is another factor that might have contributed to an over estimate of the actual yield. The assumption from the model is that there is no limitation in pollen density and timing of the pollen, which is contrary to variation brought about by the MPD and use of a male inbred line. Second limitation of the simulation model is its inability to estimate yield for low FPP (2.7 plants m^{-2}) (Table 4.3).

5.4 Seed Size grading

For the FPP main effect, this study showed that medium and high FPP had the smallest percent (less than or equal to two percent), of extra small kernels. Small percent of extra small kernels may be accounted for by perfect synchrony hence enhanced grain filling period. Contrary, low FPP had a higher percent (four percent) of extra small kernels, which can be accounted for by poor grain filling due to asynchrony. Low FPP also had the highest percent of small kernels. Medium kernels were dominant for medium FPP that can be accounted for by reduced competition for assimilates resulting in uniform medium kernels being produced.

In this study, MPD main effect had only one exception, which was MPD (0 days). There was a higher proportion of small kernels and a corresponding low percent width of large kernels. This was in agreement with expectation, where perfect synchrony was expected on this MPD resulting in a full cob being produced which has a large proportion of medium size seed and a low proportion of large and small size seed grades.

Thickness for FPP main effect in this study showed that there was no difference in low and medium FPP for the three thickness grades. This may be accounted for by limited or negligible difference being brought about by the variation of the 2 FPP (2.7 to 5.7 plants m^{-2}). However, an increase in the FPP to high 8.0 plants m^{-2} resulted in a higher percent of round seed and a corresponding low percent of thick and flat seed. Asynchrony due to stress brought by population density resulted in upper tip of the ear having a higher kernel set which accounts for the high percent of round kernels.

For the MPD main effect for thickness of seed grades. MPD (5 days) had the highest percent (fifty percent) of flat seeds. This may be accounted for by the fact that MPD (5 days) in this study may have had a higher proportion of mid-season pollen being available for pollinating the ear. Lowest percent of round seeds obtained on MPD (-5 days) may be accounted for by early pollen availability with very limited late pollen being available for pollination.

Chapter 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusion

1. Female seed yield was affected by time of male pollen shed relative to female silking (ASI), with highest yields associated with close synchrony (ASI= +/-3 days.
2. The main effects MPD and FPP, with the exception of Medium size Kernel weight seed, did not affect all the Seed grades.
3. Female seed yield was greatest at medium FPP of 5.4 plants m^{-2}.
4. ASI had a significant effect on KPE, with the greatest KPE (318) associated with close synchrony (ASI= +/-3 days).
5. Hybrid-Maize simulation model has limited potential for simulating hybrid maize seed production, as it does not accommodate limitations that may occur during the growing season; difference in male and female planting dates and pollen density and dispersion.
6. Fixed Parameters for the Hybrid-Maize Simulation model can only be used in maize commercial production.

6.2 Recommendation

1. Specific optimum plant density and male planting dates in relation to the female for hybrids should be determined to attain maximum grain yield in maize seed production.

2. Simulation of maize grain yield in hybrid maize seed production can only be done if the model has the ability to:
   a. Deal separately with male and female planting dates.
   b. Determine pollen flow from male plants to female plants.
   c. Deal with variation of population ratio for both male and female line.

3. Hybrid-Maize Simulation model may be used by Seed producing companies to determine the yield potential of a three-way hybrid seed field taking other factors of production constant except for low female population density.

4. Seed grading has to be carried out in seed production to ensure division of good seeds into uniform grades of size and shapes to suit the farmer's needs.

Chapter 7

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Chapter 8

APPENDICES

Appendix 1 Combination of factors and the treatments

Rep	Block	Plot	Treatment	Thinning date	Thinning ratio
1	1	1	(-5days & density2)	15/11/2006	1:1:1:1
1	1	2	(+5days & density2)	26/11/2006	1:1:1:1
1	1	3	(+10days & density3)	30/11/2006	2:1:2:1
1	2	4	(+5days & density3)	26/11/2006	2:1:2:1
1	2	5	(+5days & density1)	26/11/2006	1:0:1:0
1	2	6	(+10days & density1)	30/11/2006	1:0:1:0
1	3	7	(0days & density2)	21/11/2006	1:1:1:1
1	3	8	(-10days & density1)	11/11/2006	1:0:1:0
1	3	9	(-10days & density2)	11/11/2006	1:1:1:1
1	4	10	(0days & density1)	21/11/2006	1:0:1:0
1	4	11	(-5days & density1)	15/11/2006	1:0:1:0
1	4	12	(0days & density3)	21/11/2006	2:1:2:1
1	5	13	(+10days & density2)	30/11/2006	1:1:1:1
1	5	14	(-10days & density3)	11/11/2006	2:1:2:1
1	5	15	(-5days & density3)	15/11/2006	1:0:1:0
2	6	16	(+10days & density1)	30/11/2006	1:0:1:0
2	6	17	(-10days & density3)	11/11/2006	2:1:2:1
2	6	18	(-10days & density1)	11/11/2006	1:0:1:0
2	7	19	(0days & density2)	21/11/2006	1:1:1:1
2	7	20	(+10days & density3)	30/11/2006	2:1:2:1
2	7	21	(0days & density1)	21/11/2006	1:0:1:0
2	8	22	(+5days & density1)	26/11/2006	1:0:1:0
2	8	23	(+10days & density2)	30/11/2006	1:1:1:1
2	8	24	(-5days & density1)	15/11/2006	1:0:1:0
2	9	25	(-5days & density3)	15/11/2006	2:1:2:1
2	9	26	(0days & density3)	21/11/2006	2:1:2:1
2	9	27	(+5days & density2)	26/11/2006	1:1:1:1
2	10	28	(+5days & density3)	26/11/2006	2:1:2:1
2	10	29	(-10days & density2)	11/11/2006	1:1:1:1
2	10	30	(-5days & density2)	15/11/2006	1:1:1:1
3	11	31	(+5days & density3)	26/11/2006	2:1:2:1
3	11	32	(-10days & density1)	11/11/2006	1:0:1:0
3	11	33	(0days & density3)	21/11/2006	2:1:2:1
3	12	34	(-5days & density3)	15/11/2006	2:1:2:1
3	12	35	(-10days & density2)	11/11/2006	1:1:1:1
3	12	36	(-5days & density1)	15/11/2006	1:0:1:0
3	13	37	(+5days & density1)	26/11/2006	1:0:1:0
3	13	38	(+10days & density3)	30/11/2006	2:1:2:1
3	13	39	(-10days & density3)	11/11/2006	1:0:1:0
3	14	40	(+10days & density2)	30/11/2006	1:1:1:1
3	14	41	(0days & density2)	21/11/2006	1:1:1:1
3	14	42	(-5days & density2)	15/11/2006	1:1:1:1
3	15	43	(+5days & density2)	26/11/2006	1:1:1:1
3	15	44	(0days & density1)	21/11/2006	1:0:1:0
3	15	45	(+10days & density1)	30/11/2006	1:0:1:0

Appendix 2: Summary of Means of Main Effects of Yield and Yield Components

		ASI	PD	HD	ED	EPP	KPE	TKW	GY	YIELD % Mean	Rank
MPD	FPP	days	m^{-2}	m^{-2}	m^{-2}			g	$t\ ha^{-1}$	$t\ ha^{-1}$	
-10	Low	-7	3.1	2.78	3.25	1.17	180	539	3.17	71	10
-10	Medium	-8	5.1	4.95	4.60	0.93	280	483	5.94	133	5
-10	High	-5	6.4	6.19	5.45	0.90	146	498	3.87	87	8
-5	Low	-2	3.3	2.83	2.80	1.00	408	464	5.28	118	6
-5	Med	-4	4.8	4.71	4.97	1.03	338	447	6.94	155	4
-5	High	-2	6.2	5.95	5.99	1.00	296	451	8.07	181	1
0	Low	3	3.2	2.91	3.36	1.15	271	496	4.41	99	7
0	Medium	2	5.1	4.74	4.74	1.00	377	433	8.07	181	2
0	High	3	6.1	6.51	6.51	1.01	291	423	7.95	178	3
5	Low	12	3.1	2.86	2.94	1.03	116	417	1.43	32	14
5	Medium	12	5.3	5.08	5.03	0.99	100	497	2.69	60	12
5	High	12	6.7	6.03	5.98	0.99	144	454	3.70	83	9
10	Low	10	3.0	2.94	3.49	1.19	97	495	1.71	38	13
10	Medium	17	4.8	4.60	4.23	0.92	108	432	2.87	64	11
10	High	19	6.6	6.83	5.87	0.86	38	405	0.90	20	15
	GRAND MEAN	4.2	4.86	4.654	4.604	1.010	211.8	462.20	4.466	100	
	$LSD_{(0.05)}$	4	0.6	0.53	0.82	0.14	81	48	1.70		
	CV	10.6	12.2	11.8	18.5	14.5	39.6	10.8	39.3		

MPD = Male Planting Date, FPP = Female Plant Population, ASI = Anthesis-Silking Interval (days), EPP = Ears Per Plant, PD = Plant density per square metre, HD = Harvest density per square metre, ED = Ear density per square metre, KPE = Kernel Per Ear, TKW = Thousand Kernel Weight, GY = Grain Yield (t/ha), %Mean yield = % of overall mean yield

Appendix 3 Raw data for the three-way hybrid

Rep	Block	Plot	MPD	FPP	PS	DA	DS	ASI	PH	EH	TR	SL	HP	NPHT	FWT	TNET	MOIST	GDWA	CDWT	LAIA	TKWA	GYT
1	1	1	-5	2	102	75	73	2.00	195.33	152.00	19.61	0.00	22.00	71.00	19.60	90.00	11.60	10.76	14.42	2.53	534.31	8.63
1	1	2	5	2	97	82	78	4.33	182.67	136.67	11.34	0.00	18.00	64.00	9.86	68.00	11.30	3.69	6.68	2.51	532.43	2.97
1	1	3	10	3	134	85	79	6.00	197.33	140.67	21.64	0.00	29.00	89.00	5.51	93.00	10.63	1.42	3.38	2.49	471.55	1.15
1	2	4	5	3	144	85	77	7.67	196.00	147.67	23.61	0.00	27.00	89.00	12.89	85.00	11.00	6.55	8.48	3.08	494.39	5.29
1	2	5	5	1	52	82	76	6.33	190.00	136.33	0.00	0.00	27.00	87.00	4.31	43.00	10.83	1.50	2.93	1.37	539.06	1.22
1	2	6	10	1	50	79	74	5.33	185.67	139.33	14.00	0.00	12.00	34.00	4.42	39.00	10.90	1.66	3.09	1.20	508.01	1.34
1	3	7	0	2	96	75	73	2.33	205.67	155.33	19.79	0.00	20.00	67.00	25.15	65.00	11.27	15.12	18.17	3.06	474.35	12.17
1	3	8	-10	1	56	78	75	3.00	192.33	144.67	25.00	0.00	11.00	37.00	8.98	41.00	10.93	5.21	7.35	1.60	541.86	4.21
1	3	9	-10	2	92	80	78	2.00	195.00	147.33	16.30	0.00	21.00	62.00	13.28	54.00	9.87	7.33	10.32	2.59	551.91	5.99
1	4	10	0	1	53	78	75	2.67	196.67	140.00	20.75	0.00	12.00	34.00	11.61	38.00	10.83	6.72	8.38	1.70	529.93	5.43
1	4	11	-5	1	52	75	75	-0.33	182.33	135.67	19.23	0.00	12.00	32.00	9.45	33.00	9.97	5.71	7.09	1.44	529.07	4.66
1	4	12	0	3	121	75	75	0.00	184.00	139.33	10.74	0.00	26.00	86.00	22.66	87.00	11.13	13.49	17.13	3.14	442.33	10.87
1	5	13	10	2	95	77	75	1.67	188.00	149.00	7.37	0.00	19.00	64.00	5.73	73.00	11.13	9.08	13.68	2.77	567.31	7.32
1	5	14	-10	3	121	92	79	13.33	186.33	138.67	9.09	0.00	31.00	86.00	19.73	66.00	11.13	2.45	3.51	3.66	511.39	1.97
1	5	15	-5	3	118	77	78	-1.00	188.00	147.33	44.07	0.00	21.00	71.00	22.38	67.00	11.10	11.70	15.69	2.31	505.10	9.43
2	6	16	10	1	58	*	*	*	186.00	139.33	17.24	0.00	16.00	42.00	7.11	48.00	10.70	3.06	4.36	*	519.41	2.48
2	6	17	-10	3	124	79	80	-0.67	186.67	145.00	5.65	4.84	32.00	84.00	11.75	72.00	10.97	3.24	8.97	3.32	505.94	2.61
2	6	18	-10	1	56	77	75	1.67	183.67	138.33	1.79	0.00	11.00	33.00	6.91	37.00	10.70	2.43	4.88	1.51	570.32	1.97
2	7	19	0	2	82	81	79	2.00	163.00	95.67	6.10	0.00	12.00	52.00	10.70	52.00	10.43	5.48	8.08	1.84	406.51	4.46
2	7	20	10	3	98	79	72	6.67	156.33	99.33	23.47	0.00	20.00	77.00	2.21	58.00	10.80	0.86	1.63	2.23	358.41	0.69
2	7	21	0	1	64	81	76	5.33	158.67	106.67	15.63	0.00	12.00	39.00	7.84	50.00	10.77	3.13	5.75	1.79	435.36	2.53
2	8	22	5	1	58	89	76	13.00	153.67	102.00	1.72	0.00	10.00	36.00	2.15	29.00	9.83	0.60	1.56	1.26	327.79	0.49
2	8	23	10	2	89	82	71	10.67	222.00	98.00	12.36	0.00	18.00	61.00	2.46	36.00	9.73	0.58	1.83	2.42	369.72	0.47
2	8	24	-5	1	55	75	70	4.67	157.67	94.67	10.91	0.00	11.00	32.00	8.48	33.00	10.87	5.70	7.09	1.40	427.05	4.61
2	9	25	-5	3	97	79	70	9.33	164.33	97.67	9.28	0.00	16.00	56.00	13.18	60.00	10.40	8.83	11.06	1.78	374.36	7.18
2	9	26	0	3	98	79	72	7.33	162.00	112.33	10.20	0.00	25.00	73.00	13.16	79.00	11.00	8.56	10.81	2.22	349.68	6.91
2	9	27	5	2	86	85	72	12.67	157.67	103.67	15.12	0.00	18.00	60.00	3.34	51.00	10.80	1.17	2.35	2.23	442.91	0.94

2	10	28	5	3	112	84	74	10.00	155.33	103.33	6.25	0.00	28.00	70.00	4.85	81.00	11.17	1.88	3.51	2.51	464.96	1.52
2	10	29	-10	2	87	76	71	4.67	159.00	97.00	6.90	0.00	23.00	66.00	11.54	59.00	11.37	7.89	9.58	2.18	360.50	6.34
2	10	30	-5	2	82	75	70	4.67	152.33	90.33	15.85	0.00	18.00	53.00	11.53	53.00	10.73	8.10	9.71	1.93	356.29	6.55
3	11	31	5	3	106	76	72	3.67	145.67	100.33	14.15	0.00	24.00	69.00	9.34	60.00	11.27	5.32	7.10	2.56	402.31	4.28
3	11	32	-10	1	57	76	73	3.00	135.67	93.33	5.26	0.00	12.00	35.00	7.42	45.00	10.60	4.09	5.71	1.32	504.96	3.31
3	11	33	0	3	55	80	78	2.00	162.67	116.67	5.45	0.00	13.00	36.00	13.06	40.00	11.27	7.56	9.64	1.68	476.19	6.08
3	12	34	-5	3	122	81	79	2.00	177.67	134.00	6.56	0.00	26.00	79.00	16.73	84.00	9.83	9.28	12.16	3.27	473.23	7.59
3	12	35	-10	2	96	77	77	0.33	252.67	120.67	12.50	0.00	20.00	59.00	12.72	61.00	10.30	6.74	9.54	2.15	537.30	5.48
3	12	36	-5	1	70	81	76	4.67	161.33	121.33	11.43	0.00	18.00	43.00	12.61	40.00	10.97	8.14	10.21	1.73	436.39	6.57
3	13	37	5	1	57	76	74	2.33	172.67	121.33	14.04	0.00	8.00	36.00	6.54	39.00	10.67	3.20	4.84	1.72	384.97	2.59
3	13	38	10	3	127	88	75	13.00	167.33	123.00	8.66	0.00	31.00	92.00	4.69	71.00	10.60	1.07	2.82	2.89	384.98	0.87
3	13	39	-10	3	101	81	78	3.00	162.67	120.67	7.92	0.00	24.00	64.00	15.77	68.00	10.90	8.70	11.42	2.57	475.44	7.03
3	14	40	10	2	73	84	76	8.33	143.33	99.00	2.74	0.00	18.00	49.00	3.13	51.00	11.10	1.03	2.15	2.80	358.69	0.83
3	14	41	0	2	100	78	75	3.00	160.67	111.67	7.00	0.00	21.00	60.00	15.50	62.00	11.93	9.48	12.06	2.77	417.13	7.57
3	14	42	-5	2	75	74	77	-3.33	160.67	110.00	12.00	0.00	18.00	54.00	11.02	45.00	10.57	6.93	8.71	2.58	449.11	5.62
3	15	43	5	2	101	84	79	5.33	168.33	125.67	4.95	0.00	23.00	68.00	10.95	71.00	10.43	5.11	7.66	2.83	516.22	4.15
3	15	44	0	1	54	77	75	1.67	173.00	120.33	0.00	0.00	13.00	37.00	11.20	39.00	9.77	6.43	8.50	1.44	523.15	5.26
3	15	45	10	1	55	83	79	4.33	156.00	113.67	1.82	0.00	13.00	35.00	4.87	45.00	10.33	1.59	5.09	1.20	457.76	1.29

Appendix 4: Mean square values of main effects of percent seed number of seed grain of a three-way hybrid

Source of variation	Df	Mean Squares																
		L	LR	LT	LF	M	MR	MT	MF	S	SR	ST	SF	XS	XSR	XST	XSF	XXS
Block	2	314.309**	59.619ns	5.519ns	185.10**	802.087***	122.953ns	56.577*	205.625ns	1201.246***	35.176**	100.630***	350.807***	34.756***	0.002ns	3.790*	15.398***	0.552*
MPD	4	34.679ns	22.484ns	5.381ns	19.814ns	42.517ns	141.168ns	19.232ns	170.090ns	45.661ns	2.967ns	12.370ns	12.859ns	3.124ns	0.007ns	0.292ns	3.131ns	0.159ns
FPP	2	67.662ns	24.706ns	5.908ns	10.130ns	45.569ns	109.239ns	36.411ns	456.221ns	39.731ns	6.221ns	22.831ns	62.842ns	6.754ns	0.019ns	1.289ns	2.558ns	0.294ns
MPD * FPP	8	74.477ns	19.971ns	11.851ns	182.647ns	81.979ns	242.047ns	15.392ns	272.928ns	118.838ns	8.809ns	20.301ns	46.327ns	9.192ns	0.013ns	0.508ns	7.284ns	0.154ns
										65.343ns								
Error	28	55.039	19.496	7.716	747.598	38.038	145.273	16.753	190.866		5.677	9.527	30.792ns	3.34	0.015	0.724	2.299	0.13

*, **, *** = Mean square values significant at 0.05, 0.01 and 0.001

L= Large, R= Round, T= Thick, F= Flat, M= Medium, S= Small, X= Extra

Appendix 5: Mean square values of main effects of seed kernel weight of seed grain of a three-way hybrid

Source of variation	Df	Mean Squares																
		L	LR	LT	LF	M	MR	MT	MF	S	SR	ST	SF	XS	XSR	XST	XSF	XXS
Block	2	0.042ns	0.1358*	0.197ns	0.003ns	0.010*	0.012ns	0.009*	0.010ns	0.010**	0.010ns	0.006ns	0.007ns	0.126ns	0.089ns	0.008ns	0.072ns	0.038ns
MPD	4	0.028ns	0.035ns	0.110ns	0.028ns	0.001ns	0.002ns	0.002ns	0.012ns	0.000ns	0.004ns	0.001ns	0.002ns	0.075ns	0.015ns	0.059ns	0.082ns	0.033ns
FPP	2	0.000ns	0.033ns	0.086ns	0.021ns	0.009*	0.007ns	0.004ns	0.019ns	0.002ns	0.003ns	0.005ns	0.007ns	0.055ns	0.035ns	0.069ns	0.069ns	0.103ns
MPD * FPP	8	0.012ns	0.033ns	0.081ns	0.025ns	0.001ns	0.004ns	0.002ns	0.003ns	0.001ns	0.006ns	0.002ns	0.008ns	0.083ns	0.029ns	0.047ns	0.089ns	0.077ns
Error	28	0.017	0.026	0.082	0.029	0.002	0.004ns	0.002	0.008	0.002	0.005	0.002	0.01	0.064	0.028	0.036	0.064	0.067

*, **, *** = Mean square values significant at 0.05, 0.01 and 0.001

L= Large, R= Round, T= Thick, F= Flat, M= Medium, S= Small, X= Extra