Development of a decision support system to determine the best maize (*Zea mays*. L) hybrid - planting date option under typical New Zealand management systems

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ABSTRACT

A study was conducted with the aim of developing a decision support tool in the form of a crop simulation model, to help New Zealand (NZ) farmers make informed hybrid-specific decisions to optimise maize (*Zea mays* L.) yields through selection of the best hybrid for a given planting date (PD) and location. Field experiments were established (2006-2007) in four environments (ENVs) to generate data to modify and evaluate the CERES-Maize model. Planting between 20 September and 13 October (Waikato) or 6 November (Manawatu) maximised grain yields while the respective PDs for achieving highest silage yields were 9-15 October or 23 October. Optimum PDs varied seasonally. For instance, a 1^0C mean temperature (spring) decrease advanced optimum PD by 1-2 wk. A base temperature of 8^0C (T_b8) led to adequate estimates of thermal durations for the pre-flowering phase while T_b0 was more satisfactory during grain filling.

After minor model modifications using Waikato and Manawatu field data, CERES-Maize was successfully adapted for NZ conditions. Maize yields were simulated across eight contrasting ENVs using 31 yr weather data (1978-2009). High irradiance and moderate temperatures during grain filling resulted in the highest yields. This coincided with 1-18 October PDs. Temperatures $<18^0$C and $>25^0$C and irradiance <17 MJ m^{-2} d^{-1} during grain filling significantly reduced yields. Low spring temperatures also reduced leaf expansion, minimising source capacity. Planting date windows to achieve ≥95% of yield maxima ranged from 1-7 wk. Silage crops, warmer ENVs or early hybrids had wider planting windows and less crop failure risk when planted late. With early or late planting, yield reductions were greater in higher latitude ENVs where spring and autumn temperatures and radiation were much lower. Due to higher assimilate demand, late hybrids were generally more stress prone, whereas early hybrids were sink limited.

A multiple-linear regression equation based on temperature and relative humidity was established to estimate field grain drydown. Another relationship based on the Gompertz model was also developed to estimate silage maturity using thermal time. These functions were used to enhance CERES-Maize's ability to predict harvest maturity. To simplify data collection for the model, linear and non-linear models for relationships between tassel initiation and leaf number; total plant leaf area and area of the largest leaf; and leaf tip number and fully expanded leaves were also established.

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house chores during this period, in addition to helping with data collection and manuscript editing.

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LIST OF ABBREVIATIONS

ADF	Acid detergent fibre
ANOVA	Analysis of variance
ASI	Anthesis-silking interval
BOP	Bay of Plenty
CEC	Cation exchange capacity
CGR	Crop growth rate
CGR_{ES}	CGR for the emergence-silking interval
CGR_{SS}	CGR for the silking to silage harvest interval
CP	Crude protein
CRM	Comparative relative maturity
CV	Coefficient of variation
DM	Dry matter
dNDF	Digestible neutral detergent fibre
EL	Ear leaf
ENV	Environment
G2	Potential kernel number per plant
G3	Potential kernel growth rate under optimum conditions (mg d^{-1})
GY	Grain yield
HI	Harvest index
IPAR	Intercepted photosynthetically active radiation
k	Light extinction coefficient
KGR	Kernel growth rate
KN	Kernel number
KW	Kernel weight
LA	Leaf area
LAI	Leaf area index
LN	Leaf number
N	Nitrogen
NDF	Neutral detergent fibre
NIRS	Near-infrared spectroscopy
NIWA	National Institute of Water and Atmospheric Research
NZ	New Zealand

P1	Thermal time from emergence to end of juvenile phase
P2	Photoperiod sensitivity coefficient
P5	Thermal time from silking to physiological maturity
P_c	Critical value of daylength
PAR	Photosynthetically active radiation
PD	Planting date
PHINT	Phyllochron interval
PM	Physiological maturity
PRFT	Photosynthetic reduction factor
PTQ	Photothermal quotient
r	Correlation coefficient
R	Reproductive stage
r^2	Coefficient of determination
R^2	Coefficient of multiple determination
RGFIL	Grain growth rate
RMSE	Root mean square error
RUE	Radiation use efficiency
SE	Standard error
SLPF	Soil fertility factor
SY	Silage yield
T_b	Base temperature
TI	Tassel initiation
T_{max}	Daily maximum temperature
T_{min}	Daily minimum temperature
T_{ml}	Maximum lethal temperature
T_{opt}	Optimum temperature
TT	Thermal time
V	Vegetative stage
VE	Seedling emergence stage
Yc	% Yield change from maximum

CHAPTER 1: GENERAL INTRODUCTION, OBJECTIVES AND THESIS FORMAT

1.1 GENERAL INTRODUCTION

1.1.1 Climate

Maize (*Zea mays*, L.) is one of the most important arable crops in New Zealand (NZ) where about 50000 ha was planted in 2007 (Statistics New Zealand, 2008) over a wide range of environments (ENVs) ranging from Kaitaia in the north, to South Canterbury in the south (i.e., 35-44^0 S latitude). The NZ climate varies from warm subtropical to cool temperate at the extreme ends of the northern and southern regions. The climate is influenced by orography, with the long chain of mountains that extends the entire length of the country producing sharp west to east rainfall gradients, particularly in the South Island, and to a smaller extent, temperature variation. Most of the country receives between 600 and 1600 mm of annual rainfall which is spread fairly evenly throughout the year.

While westerly flow and seasonal patterns of eastward moving high and low pressure systems are the predominant atmospheric features of the climate, the oceanic locale, responsible for moist airstreams passing over the country, leads to moderate temperatures in most areas (Kenny et al., 1995). High temperature extremes, common in the US central Corn Belt, which can negatively affect crop performance, are therefore rare (see Table 1.1). The resultant stable and relatively cool, high radiation ENV is thus capable of producing higher average yields compared to other parts of the globe (Densley et al., 2006).

In the last 30 years, while there has been a trend towards higher minimum temperatures, there have also been fewer days with maximum temperatures >25^{0}C in some parts of NZ (e.g., central North Island) (Salinger and Griffiths, 2001). This has inadvertently resulted in the proliferation of maize production in areas that would have previously been considered marginal. Traditionally, the length of the maize growing season in most regions, such as Waikato or Manawatu, has been restricted to between October and April, after which probability of a killing frost exceeds 10% (NIWA, 2000).

Table 1.1 Comparison of average monthly minimum (Min), maximum (Max), mean temperatures and accumulated thermal time (TT) using base 8^{0}C for Iowa City (41.63^{0} N; 91.55^{0} W) (USA), Hamilton (37.87^{0} S; 175.34^{0} E) and Palmerston North (40.38^{0} S; 175.58^{0} E) (New Zealand) during a typical maize growing season.

	USA*				**New Zealand****					
	Iowa City				Hamilton			Palmerston North		
	Max	Min	Mean		Max	Min	Mean	Max	Min	Mean
Month		^{0}C		**Month**			^{0}C			
^April	17.4	4.9	11.1	^September	16.2	6.7	11.5	14.9	7.2	11.1
May	23.7	11.2	17.4	October	17.9	8.3	13.1	16.7	8.7	12.7
June	28.8	16.6	22.7	November	20	10	15.0	18.5	10.2	14.4
July	30.8	19.1	24.9	December	22	11.6	16.8	20.7	12	16.4
August	29.5	17.8	23.7	January	23.8	12.8	18.3	22.4	13.4	17.9
September	25.4	13.1	19.2	February	24.3	13	18.7	22.9	13.5	18.2
^^October	18.8	6.6	12.7	March	22.7	11.6	17.2	21.1	12.1	16.6
November	9.1	-0.4	4.3	^^April	19.9	9.2	14.6	18.4	9.8	14.1
December	1.3	-7.2	-2.9	May	16.6	6.6	11.6	15.3	7.4	11.4
January	-1.1	-10.3	-5.7	June	14.1	4.7	9.4	13.1	5.4	9.3
February	2.5	-7.1	-2.3	July	13.6	3.9	8.8	12.5	4.7	8.6
March	9.6	-1.2	4.2	August	14.6	5.1	9.9	13.3	5.4	9.4
ANNUAL	16.3	5.3	10.8	ANNUAL	18.8	8.6	13.7	17.5	9.1	13.3
Seasonal accumulated TT ^{0}Cd (T_b8)		**2320.1**		**Seasonal accumulated TT ^{0}Cd (T_b8)**		**1842.05**			**1728.7**	

*http://hurricane.ncdc.noaa.gov/cgi-bin/climatenormals/climatenormals.pl - 26 August 2008
**www.niwa.co.nz-26August 2008
^, ^^ - Start and end of maize growing season, respectively

1.1.2 Hybrid x environment interactions

In NZ, maize is of strategic importance to the dairy, pig and poultry industries, yet it occupies <10% of the total cropped area (Statistics New Zealand, 2008). Competition from other crops and livestock farming precludes any possibility of significant expansion of the maize cropping area. There is therefore a greater need to increase current yields on the existing cropped hectares. In order to maximise grain and silage yields, the best possible combination of hybrid and the growing ENV is critical.

Due to variations in climate and season length, optimum maize planting dates (PDs) differ across regions, and seasonally within regions. Optimum PD is considered here as that date where yield and/or profit are maximised, reducing production risks to minimal while at the same time, allowing the crop to fit within the overall farming system. In

NZ, maize is usually planted from early or mid-September to mid-November, with earlier PDs more common in the warmer parts of the north eastern North Island. Later plantings occur in the cooler regions and grain crops are generally planted earlier than silage crops.

Even though the NZ ENV has a potential to produce yields of ≥ 32 t ha^{-1} (silage) and ≥ 17 t ha^{-1} (grain) (Densley et al., 2006), many growers still fail to achieve the optimum hybrid x ENV combination required to maximise and stabilise their production, leading to national average silage and grain yields of around 20 and 11 t ha^{-1} (MAF, 2008). Failure to achieve correct timing for planting is one of the main contributors to low yields (Johnson and Mulvaney, 1980). Planting delays are usually due to excessive rain, unusually cold or wet soil conditions, late harvest of winter forage crops, contractor non-availability, occasional need for replanting because of poor stands, and in some cases, poor planning.

Previously, maize was usually grown on fertile soils and in areas where conditions were conducive for high yields. Introduction of short season varieties and marginal increases in minimum temperatures over the years have meant that maize is now being grown in cooler short season areas that were previously regarded as unsuitable for maize production. There is thus a need to provide growers with more informed and accurate recommendations on the best combination of hybrid, PD and other management factors.

Growers need to understand the implications of selecting one hybrid over others in terms of yield, adaptability, profitability and risks based on their conditions. The usual general recommendation is to grow a hybrid that can effectively utilise all available resources for the given conditions (i.e., the longest maturity for the ENV within the bounds of acceptable levels of risk). To do this requires knowledge of hybrid maturity and consideration of factors specific to that location and season (e.g., solar radiation, photoperiod, soils, water and temperature) so that their interaction with different stages of crop development can be determined.

Where planting has been delayed or where new areas are being sown, knowledge of the basic physiological processes as influenced by environmental fluctuations is critical for the development of mitigating strategies required to maximise and stabilise yields. In some instances, growers may need to switch from a full-season hybrid to an earlier one if planting is delayed. Before switching, an analysis to determine whether the decision maximises production goals should be conducted.

In NZ, like other parts of the world (e.g., USA), maize hybrids are classified into different maturities using the comparative relative maturity (CRM) system. The CRM system takes into account the grain moisture content of a hybrid at harvest relative to the moisture content of previously ranked hybrids (Bob Nielsen, pers. comm., 2011) but is seed company specific, making it difficult to directly compare hybrid maturities across seed sources. Considering the wide range of maize hybrids available on the NZ market and the difficulty in interpreting CRM ratings, a simpler method linked to rate and stage of development that can accurately predict all important crop development stages would be useful to farmers and extension agents.

1.1.3 Simulation modelling

Most maize planting recommendations are based on a specific set of agronomic field experiments that are rarely repeatable over time and space because of environmental or seasonal variation. Formulating a hybrid recommendation can therefore be daunting due to the complex nature of the interaction between the growing ENV and the hybrid's physiological response. It is thus useful that a reliable decision support system based on a crop simulation model be developed. A simulation model predicts crop development and yield, using real-time environmental conditions, or a set of long term historical weather data under a range of management options. Unlike methods that rely on thermal time (TT) alone when predicting crop maturity, simulation models also take photoperiod sensitivity and leaf number into account in order to adequately mimic genotype x ENV interactions. Crop models can thus afford growers the possibility of selecting the best possible combination of hybrid x management x soil x weather conditions required to maximise yields and profits, while at the same time minimising potential risks for their own situations.

Use of crop models could reduce potential risks associated with uncertainties of planting any given maize hybrid under variable conditions of weather, soil or management factors. Since all models are designed to fulfil specific functions, an appropriate model should be identified first. For example, AmaizeN, the most widely used maize model in NZ, was designed for the management of nitrogen (N), and in particular, to monitor leaching and the need to apply N (Li et al., 2009a,b). The identified model is then adapted for local conditions through calibration using data from the most representative and precise field experiments available. Calibration may involve adjustment of some parameters in order to get a better fit from model predictions. The final step involves verification of the calibrated model using a different data set to the one used for calibration. If predictions mimic real field situations the model can then be extended to growers as a suitable decision support tool.

A properly evaluated model would enable growers to synchronise critical crop growth stages with optimum environmental conditions. Due to the importance of accurately predicting phenology, which is mainly a function of temperature, solar radiation, genotype and photoperiod, a phenology-driven process maize model such as CERES-Maize (Jones and Kiniry, 1986) is necessary to generate reliable predictions. CERES-Maize is a predictive deterministic model capable of simulating daily phenological development and growth in response to environmental factors, and ultimately, yield. The model can be used to predict growth, development and maize yields for different hybrid genetics under variable weather, management and soil conditions, something that would take years of field experimentation to accomplish.

Despite the importance of ENV x hybrid maturity interactions on grain and silage yields, very little documented information exists in NZ. There is also no known tool available in NZ to help farmers make informed hybrid-specific decisions as they seek to optimise production and profitability through selection of the best hybrid choice for a given PD.

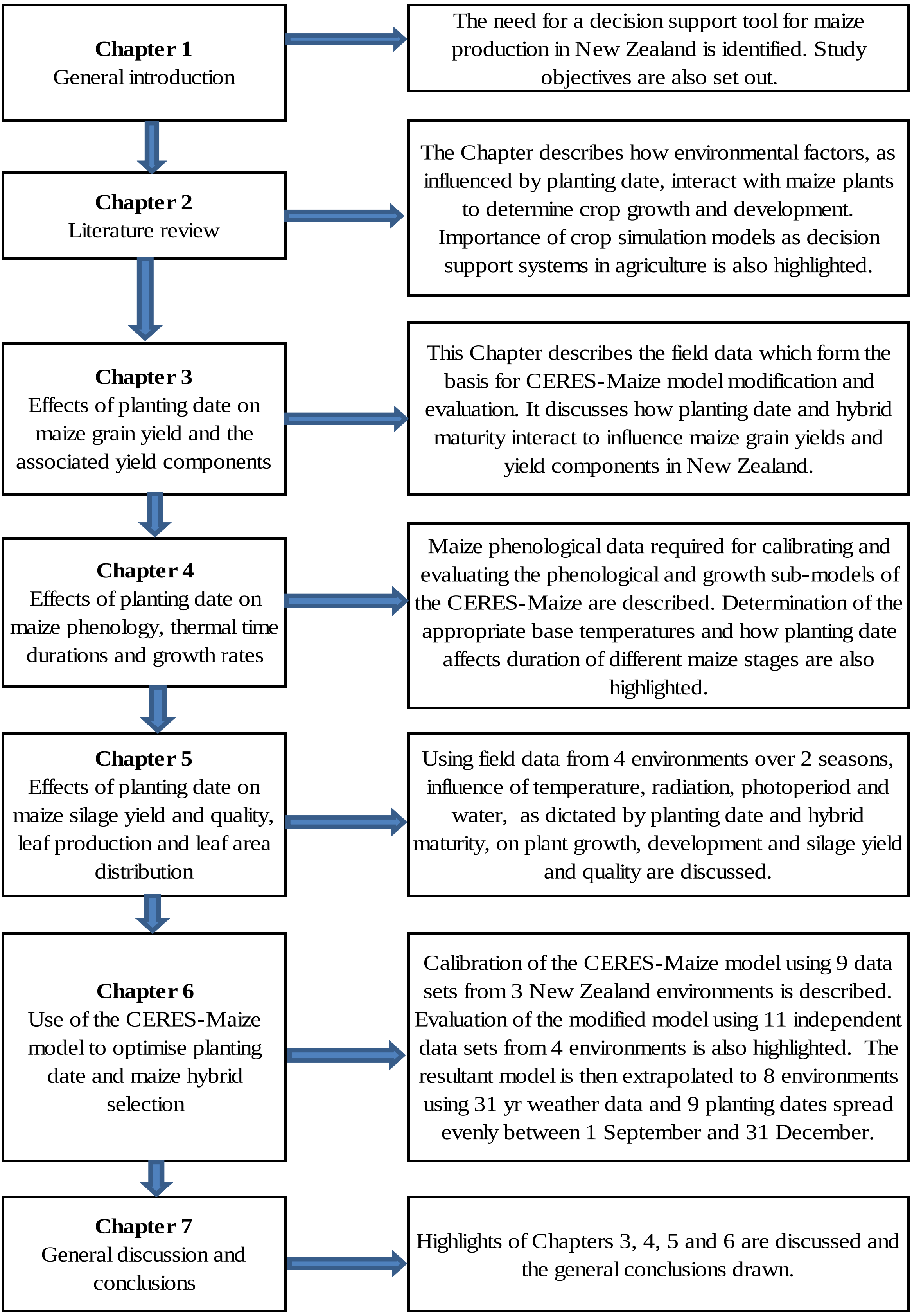
This study therefore aims to collect critical field data that will allow the modification and evaluation of the CERES-Maize model to predict how maize hybrids of varying maturities interact with PD and the ENV to determine the magnitude and stability of grain and silage yields over time. This includes generating and documenting field data on how the maize hybrids respond to environmental conditions as dictated by different PDs and locations.

1.2 OBJECTIVES OF RESEARCH

1.2.1 Specific objectives

i. Determine the effect of planting date on calender and thermal time on development, plant height, grain drydown, kernel size, grain and silage yield and quality in contrasting locations across NZ for a range of hybrids.
ii. Collect weather, phenological, agronomic and soil physical and chemical data required to calibrate and evaluate the CERES-Maize model.
iii. Use CERES-Maize as a decision tool to select the best hybrid or maturity (yield and profit) for planting and replanting situations under different planting date regimes.
iv. Using long term weather data, adapt the CERES-Maize model as a management tool to develop probability tables of yield losses by location, planting date and maturity for maize hybrids grown at their optimum plant density.
v. Repeat (iv) for some of the main maize growing areas of New Zealand and also test the model as a predictive tool in areas where maize is not currently grown.

1.3 THESIS FORMAT



Chapter 1
General introduction

The need for a decision support tool for maize production in New Zealand is identified. Study objectives are also set out.

Chapter 2
Literature review

The Chapter describes how environmental factors, as influenced by planting date, interact with maize plants to determine crop growth and development. Importance of crop simulation models as decision support systems in agriculture is also highlighted.

Chapter 3
Effects of planting date on maize grain yield and the associated yield components

This Chapter describes the field data which form the basis for CERES-Maize model modification and evaluation. It discusses how planting date and hybrid maturity interact to influence maize grain yields and yield components in New Zealand.

Chapter 4
Effects of planting date on maize phenology, thermal time durations and growth rates

Maize phenological data required for calibrating and evaluating the phenological and growth sub-models of the CERES-Maize are described. Determination of the appropriate base temperatures and how planting date affects duration of different maize stages are also highlighted.

Chapter 5
Effects of planting date on maize silage yield and quality, leaf production and leaf area distribution

Using field data from 4 environments over 2 seasons, influence of temperature, radiation, photoperiod and water, as dictated by planting date and hybrid maturity, on plant growth, development and silage yield and quality are discussed.

Chapter 6
Use of the CERES-Maize model to optimise planting date and maize hybrid selection

Calibration of the CERES-Maize model using 9 data sets from 3 New Zealand environments is described. Evaluation of the modified model using 11 independent data sets from 4 environments is also highlighted. The resultant model is then extrapolated to 8 environments using 31 yr weather data and 9 planting dates spread evenly between 1 September and 31 December.

Chapter 7
General discussion and conclusions

Highlights of Chapters 3, 4, 5 and 6 are discussed and the general conclusions drawn.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

Maize (*Zea mays* L.) is thought to have originated in Mexico (Benson and Pearce, 1987) and is now widely grown the world over under diverse climatic and management conditions. This chapter reviews research on how the maize crop responds to environmental fluctuations as dictated by different PD regimes. It is anticipated that by understanding the crop-environmental interactions, crop growth, development and projected potential yields can be predicted for, among other things, areas where maize has not been previously grown, or where new maize hybrids are being introduced.

Between planting and harvesting, the maize plant proceeds through a series of events that result in change to size (growth) and progress towards maturity (development) of the crop and its components (Ritchie et al., 1986b; Ritchie and NeSmith, 1991). Development is considered here as the attainment of a specific stage during the crop's life cycle whereas growth is the gain in biomass, leaf area (LA) or plant height. These events are affected by several environmental factors that include temperature, water, nutrient availability, carbon dioxide concentration, photoperiod and the flux of solar radiation. The review focuses on how major factors that vary with PD, in particular, temperature, radiation, photoperiod and water, interact with crop growth and development to determine crop production.

A significant amount of research on crop-ENV interactions has been conducted in a wide range of ENVs, and is synthesized here. In the review, "early" and "late" plantings are considered as extreme PDs. The last section of the review focuses on how crop simulation models can be used as decision support systems to simplify the process of interpreting crop-ENV interactions. The strength of crop models in simplifying the quantitative crop response to varying environmental and hybrid choices is highlighted. Examples of what crop models, particularly CERES-Maize model, have been used for are given. Briefly described below is a set of terms used to describe events involved as the crop transforms from seed to maturity.

2.1.1 Phenological development

The term phenology is used here to describe the sequence of events during the maize development process from planting to harvest maturity.

Key developmental stages described are:

a. *Emergence* - Appearance of coleoptile above ground (see Plate 2.1).

b. *Tassel initiation (TI)* - Occurs when leaf initiation is completed. The apical meristem elongates and marks the commencement of reproductive growth.

c. *Phyllochron* - Thermal time taken between the appearances of successive leaf tips, often calculated as the inverse of rate of leaf tip emergence above the whorl.

d. *Anthesis* - Appearance of extruded anthers on tassels of 50% of all plants.

e. *Silking* - Appearance of silks at ear tips on 50% of all plants.

f. *Physiological maturity* (PM) **-** Marks cessation of dry matter (DM) accumulation and is generally assumed to coincide with black layer formation (Daynard and Duncan, 1969). For purposes of this thesis, PM is therefore considered as the stage when kernel black layer has been formed.

g. *Grain filling* - Period between pollination and PM which is divided into three stages as described by Bewley and Black (1985), namely:

i. *Lag phase* of 10-20 d during which the plant goes through active cell division and differentiation to determine kernel size with rapid increase in water content while kernel DM accumulates exponentially with time.

ii. *Linear grain filling* stage whereby kernel dry weight increases rapidly and linearly with time for 25-40 d. Water content also increases rapidly to reach maximum seed volume at the end of the lag phase, before being replaced by accumulating DM reserves (Borrás et al., 2009).

iii. *Maturation or drying phase* where kernel growth slows, and kernels continue to lose moisture until they reach maximum DM accumulation at PM.

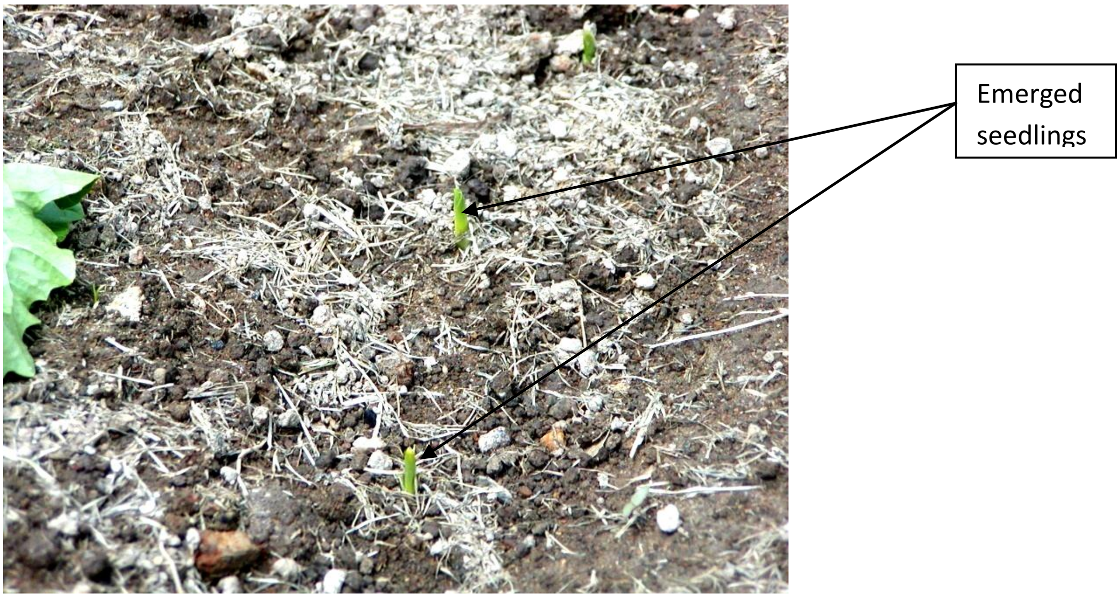


Plate 2.1 Illustration of maize seedlings at emergence (VE).

The crop development stages described above are classified according to the system proposed by Ritchie et al. (1986b), and are divided into vegetative (V) and reproductive (R) stages. The designation of the V-stage is based on the leaf stage, with each leaf stage defined according to the uppermost leaf whose collar is visible, indicating that it is fully expanded (Plate 2.2). The "V" subdivisions are designated as follows:

VE – Emergence (Plate 2.1)

V1 – When the lower-most leaf (with characteristic rounded tip) has a visible leaf collar

V(n) – When the nth leaf has a visible leaf collar

VT - When the lowest branch of the tassel is visible and silks have not emerged.

Leaf tip appearance (number of leaf tips that have emerged from the whorl; Plate 2.2) is also used to describe the leaf stages (Kumudini and Tollenaar, 1998). Whereas the full leaf collar is the main measure of developmental stage in literature, phyllochron, defined above, is based on the appearance interval of leaf tips rather than leaf collars since leaf tip appearance rate is generally linear across the whole duration of leaf emergence (Hesketh and Warrington, 1989). However, provided the number of leaf collars is known, leaf tip number can be estimated (see section 5.4.12, Chapter 5).

Plate 2.2 A maize seedling illustrating leaf tip and fully expanded or visible leaf collar.

Even though the maize reproductive (R) stage begins at TI, R-staging commences at silking, continues through grain filling and ends when the kernels reach PM. Some of the main subdivisions are defined below:

R1 - when silk is visible outside the husk and marks the beginning of kernel development.

R3 - kernels have reached linear grain filling stage.

R6 - a black or brown pseudo-abscission layer has formed in the placental-chalazal region where the kernel attaches to the cob, indicating cessation of kernel growth and attainment of PM.

2.2 EFFECTS OF ENVIRONMENTAL FACTORS ON CROP GROWTH AND DEVELOPMENT

2.2.1 Temperature

Even though photoperiod, water, solar radiation and fertility play a significant part in crop growth and development, temperature is considered to be the primary factor driving development rate (Baron et al., 1975; Hodges, 1991; Bollero et al., 1996; Stewart et al., 1998b), particularly in temperate germplasm where maize genotypes are relatively photoperiod insensitive (Bonhomme et al., 1991; Ellis et al., 1992a; Bonhomme et al., 1994; Birch et al., 1998c).

Growth and development occur between two cardinal temperatures, a base temperature (T_b) and a maximum lethal temperature (T_{ml}). At T_b, development is assumed to be zero and reach a maximum at an optimum temperature (T_{opt}), before falling again to zero at T_{ml}. Temperatures of the vast majority of field ENVs fall between T_b and T_{opt}, where there is a linear relationship between temperature and rate of development. This has allowed the advent of the "thermal time" concept, also known as "heat units", to describe and predict crop development. Thermal time can thus be defined as a measure of development rate which is independent of the temperature regime in which the crop is grown, and can be used to predict crop development more reliably than calendar days (Dwyer and Stewart, 1986; Wilson and Salinger, 1994; Kenny et al., 1995; Shaykewich, 1995; Stewart et al., 1998a; Dwyer et al., 1999a). Provided photosensitivity among hybrids is constant or absent, or where other factors are not affecting development rate, the right choice of hybrid to fit within a known season length can thus be accurately determined using temperature alone. Calculation of TT involves subtracting T_b from the mean daily temperature, and is fully illustrated in section 3.3.3, Chapter 3.

Base and optimum temperatures of 10 (T_b10) and 30^{0}C (T_{opt}30) are widely used for maize in the US (Gilmore and Rogers, 1958; Cross and Zuber, 1972; Tollenaar et al., 1979), with 41^{0}C considered as T_{ml} (Ritchie and NeSmith, 1991). Under field conditions, T_b10 appears too high for maize (Derieux and Bonhomme, 1982; Warrington and Kanemasu, 1983a,c; Hesketh and Warrington, 1989; Muchow and Carberry, 1989; Ritchie and NeSmith, 1991; Bonhomme et al., 1994; Bollero et al., 1996; Vinocur and Ritchie, 2001), resulting in an underestimation of development rate at lower temperatures. In field situations, T_{opt}30, T_b6 (Bonhomme et al., 1994) and T_b8 (Major et al., 1983) have been observed in some European and Canadian maize germplasm.

Other research has also shown that maize may have variable T_b (Warrington and Kanemasu, 1983b) and T_{opt} for different stages of growth and development (Muchow, 1990; Ritchie and NeSmith, 1991; Fortin et al., 1994; Roth and Yocum, 1997). This partly explains different TT requirements documented in literature for the reproductive and vegetative phases (Major et al., 1983; Plett, 1992; Roth and Yocum, 1997; Edwards et al., 2005). Specifically, T_b0 has been reported as ideal for grain filling in a wide range of maize germplasm (Lenga and Keating, 1990; Muchow, 1990; Birch et al., 1998c). This finding also explains the inconsistent TT values observed for grain filling in some studies conducted at below normal temperatures (Ellis et al., 1992b; Dwyer et al., 1999a). Consequently, this raises a question on the adequacy of the widely accepted use of a single T_b value for all phases of the crop cycle.

Even though maximum rates of maize development are assumed to occur at 30 or 34^{0}C (Cross and Zuber, 1972; Jones et al., 1986), Ellis et al. (1992b) observed that for some cool-adapted highland tropical germplasm, T_{opt} for the emergence-TI duration was lower than for the TI-flowering interval. The authors noticed that increasing temperature from 24-28^{0}C had no influence on the rate of development between emergence and TI. Coligado and Brown (1975) observed similar results between 25 and 30^{0}C in Corn Belt germplasm, suggesting that T_{opt} between emergence and TI lies between 24 and 30^{0}C.

A degree of failure of the TT system to accurately predict phenological development, particularly under cool temperature conditions, has thus been reported (Bollero et al., 1996; Roth and Yocum, 1997; Stewart et al., 1998a). These failures could be due to several factors, for example, inconsistent or incorrect measurement of temperature at the site; too low or too high T_b; T_b variation by development stage or genotype (Warrington and Kanemasu, 1983b; Ellis et al., 1992b); interactions among environmental factors other than temperature (Tollenaar et al., 1979; Plett, 1992; Birch et al., 1998c) or use of air rather than soil temperature for the period when the meristem was below the soil surface. Between planting and emergence of the apical meristem above the soil surface, soil temperature is appropriate for estimating TT (Swan et al., 1987; Vinocur and Ritchie, 2001; Padilla and Otegui, 2005).

Other environmental conditions can also alter TT duration of some developmental stages. For example, silking can be delayed by water stress (Hall et al., 1981; Herrero and Johnson, 1981; Grant et al., 1989) or long photoperiods (Edmeades et al., 2000). While temperature plays a dominant role during vegetative growth, grain filling also depends on other factors (Stewart et al., 1998a,b). Limited assimilate availability or reduced capacity for continued metabolism due to kernel moisture decrease can hasten the end of grain filling (Wardlaw, 1972; Tollenaar and Daynard, 1978b; Afuakwa et al., 1984; Sala et al., 2007a). This shortened grain filling can lead to a complete cessation of kernel growth through formation of a black abscission layer. Daynard (1972) also found that black layer formation could occur earlier if cool weather or frost ensued during the week prior to PM. This artificial shortening of the grain filling duration also results in reduced kernel size (sink) and, ultimately, yield.

The inconsistency in TT observations has thus led some researchers to conclude that maize hybrids have the capacity to adjust the thermal requirement for phenological development if planted late (Sutton and Stucker, 1974; Nielsen et al., 2002). For example, Nielsen et al. (2002) reported a quadratic relationship between grain filling thermal duration and PD as well as a hybrid x PD interaction for both silking and PM thermal requirements.

Temperature affects crop growth and development in different ways. While developmental response to temperature is a much steeper curve with a well defined optimum (T_{opt}30), growth follows the response of photosynthesis to temperature, which is a relatively flat curve, with a much lower T_{opt} (Figure 2.1). This difference explains why the best yields occur at temperatures well below T_{opt} for development. Muchow et al. (1990) recorded higher grain yields (GYs) at cooler temperatures (20 vs. 35^0C), though Wilson et al. (1995) found that mean temperatures below 18^0C decreased yields. Lower yields under suboptimal temperatures are more likely due to reduced grain growth rate and low radiation use efficiency (RUE) during grain filling. Photoinhibition (van Hasselt and van Berlo, 1980) and reduction in photosynthetic activity (Duncan and Hesketh, 1968; Long et al., 1983; Nie et al., 1992) have also been reported under cool conditions. Effects of high temperatures are also discussed in section 2.2.5.

Because the rate of biomass accumulation in maize is largely influenced by the amount of intercepted photosynthetically active radiation (IPAR), leaf area index (LAI; area of leaf per unit area of ground) plays a major role in determining GY (Muchow et al., 1990). Increased LAI enhances IPAR, which explains the exponential response of canopy photosynthetic rate to LAI (Stewart et al., 2003). Research has shown that maximum LAI occurs between 18 and 25^0C (Daynard, 1971; Wilson et al., 1973; Hunter et al., 1977). Hunter et al. (1977) also observed lower LA per plant at 30 vs. 20^0C.

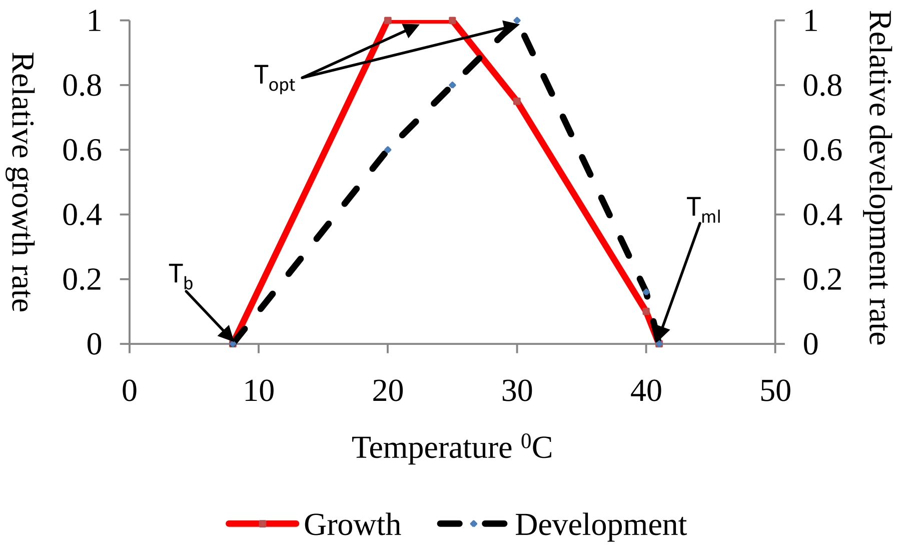


Figure 2.1 Comparison of maize crop growth and development rate responses to temperature.

Bollero et al. (1996) showed that lower early season soil temperatures (15^{0}C) increased LA of the lower crop canopy whereas at 25^{0}C, the upper canopy was larger. Larger upper canopies tend to encourage higher GYs since top leaves intercept most of the radiation and translocate more photosynthate to the ear during grain filling (Simmons and Jones, 1985). Even though most leaves are initiated when the apical meristem is below ground level, LA is affected by ambient temperatures during leaf expansion. As the meristem emerges above the surface, leaves expand in acropetal succession and are therefore exposed to differing temperatures during the temperature-sensitive stage of leaf expansion. Leaf expansion is also sensitive to water stress.

Between 15 and 25^{0}C, leaf number shows a curvilinear response to temperature encountered just prior to TI, with more leaves formed at higher and lower temperatures, and fewest at 18^{0}C, though it is probable that these relationships vary with the adaptation of the germplasm (Warrington and Kanemasu, 1983c). A similar response in Corn Belt hybrids has also been reported by Coligado and Brown (1975) under temperatures of up to 30^{0}C. However, a glasshouse study conducted by Duncan and Hesketh (1968) showed that between 15 and 36^{0}C, there was a linear increase in leaf number with temperature. Since phyllochron generally increases under high temperature conditions (Birch et al., 1998e; Padilla and Otegui, 2005), at elevated temperatures, increased leaf numbers and phyllochron could therefore increase TT to flowering and consequently, PM, another reason for variable TT requirements for development. However, at higher temperatures, decrease in LA usually outweighs any increase in leaf number, resulting in reduced LAI (Lindquist et al., 2005).

Jones et al. (1984) observed that temperature extremes (≤15 or ≥35^{0}C) during grain filling reduced kernel weight (KW), with the lag phase being the most sensitive. Stressful conditions during the lag phase reportedly decreased GY even if conditions improved during linear grain filling. This is not surprising because the number of endosperm cells, thought to influence kernel sink potential, is determined during the lag phase (Reddy and Daynard, 1983; Jones et al., 1985). Kernel number (KN) per plant, which is positively correlated to GY (Otegui et al., 1995a; Andrade et al., 1999; Rajcan and Tollenaar, 1999), is also mainly determined during the lag phase (Tollenaar et al., 1992). Kernel weight, a more stable trait than KN (Borrás et al., 2009), is determined at later stages of grain filling and is dependent on assimilate supply, irrespective of endosperm cell number (e.g., Hanft et al., 1986). Similar results have also been reported under field conditions for maize (Cirilo and Andrade, 1996) and sorghum (*Sorghum bicolor* L.) (Kiniry and Musser, 1988).

2.2.2 Solar radiation

Provided all factors are non-limiting, cumulative IPAR is strongly related to total biomass accumulation (Monteith, 1977; Kiniry et al., 1989; Muchow et al., 1990; Andrade et al., 1992; Otegui et al., 1995b; Edwards et al., 2005) and GY (Tollenaar and Bruulsema, 1988; Muchow, 1990; Cirilo and Andrade, 1994a; Wilson et al., 1995). Both IPAR and RUE determine assimilate production rate, which is critical for growth, kernel set and grain filling (Muchow, 1988; Muchow and Carberry, 1989; Bonhomme, 2000).

Even though radiation cannot be manipulated under field conditions, some plant attributes or variables can influence IPAR. For example, early maturity hybrids, due to their shorter stature and lower total LA, generally accumulate less IPAR per plant. Maximum IPAR per unit area can therefore be achieved by increasing planting density. However, IPAR per plant also falls in the process, as reported by Andrade et al. (1993b) who observed reduced IPAR per plant at high plant densities.

Very high plant densities or unfavourable environmental conditions during silking can promote ear abortion (Edmeades and Daynard, 1979a; Jacobs and Pearson, 1991; Otegui and Melón, 1997). Nonetheless, Tollenaar et al. (1992) found that newer maize hybrids with improved stress tolerance produced more kernels per plant and per unit area under stressful conditions (e.g., high population densities) than their older counterparts. This was attributed to high crop growth rates (CGR) during silking, improved partitioning of assimilate to the developing ear, and a greater tendency to prolificacy. Newer hybrids also have improved leaf staygreen characteristics which increase cumulative IPAR during grain filling (Duvick, 1992; Tollenaar and Aguilera, 1992; Rajcan and Tollenaar, 1999).

In NZ, modern maize hybrids are planted at relatively high densities of ≥100000 plants ha^{-1} without any obvious barrenness or lodging. These high rates are sustainable largely due to the cool (Table 1.1, Chapter 1) sunny conditions that generate less LA per plant, prolong plant staygreen, extend crop duration and thus, reduce the degree of remobilisation from the stem. The cool temperatures slow development rate, consequently increasing photothermal quotient (PTQ; Nix, 1976), which is the ratio of cumulative IPAR to cumulative TT. Higher PTQs are therefore associated with greater yields. Plants are also shorter in cool conditions, thus reducing lodging susceptibility.

Even though CGR is directly proportional to IPAR, grain filling rate is not greatly affected by day-to-day variation in photosynthesis (Cirilo and Andrade, 1996). Periodic variation in assimilate supply can be cushioned through remobilisation of soluble carbohydrates from stalks (Daynard et al., 1969). Remobilisation should, however, be considered a short term supplier of photosynthate since the majority of assimilates during grain filling come from current photosynthesis (Westgate, 1997; Bänziger et al., 2000). Prolonged remobilisation may exhaust stem reserves, shortening grain filling and inducing lodging (Cirilo and Andrade, 1996).

Between 13 and 25^{0}C, Birch et al. (1998e) and Padilla and Otegui (2005) noted that while phyllochron increased concomitantly with temperature, at high radiation levels (often associated with high temperatures), phyllochron declined. Birch et al. (1998e) showed that a 50% radiation reduction in-field resulted in phyllochron increasing from 37 to 50^{0}Cd. High planting densities, especially in conditions of decreasing radiation levels could therefore increase phyllochron and consequently delay silking (Iremiren and Milbourn, 1980; Borrás et al., 2007). Reducing planting density in situations of low photosynthetically active radiation (PAR) levels will be effective in increasing IPAR per plant and the flux of assimilates per plant for kernel setting and grain filling.

2.2.3 Water

In most farming regions around the world, drought accounts for a significant amount of crop yield losses (Bruce at al., 2002), estimated at 15 and 17% of average annual yields in temperate and tropical climates, respectively (Edmeades et al., 2002). Much higher drought-induced yield losses (depending on severity and timing) in both temperate and tropical ENVs have also been documented (Rosen and Scott, 1992; Campos et al., 2004). Where irrigation is unavailable, planting time is critical since the incidence, timing and intensity of drought can have a profound effect on yields.

Global climate change is expected to increase temperature, evapotranspiration rates and drought occurrences, and alter rainfall patterns. Despite being a C_4 plant, known to use water more efficiently than C_3 plants (Reddy et al., 2004), maize is one of the most sensitive crops to water stress, especially during flowering when grain is being set (Pandey et al., 2000; Çakir, 2004; Welcker et al., 2007).

Even though drought is not a major constraint to maize production in most parts of NZ (Harman, 1999), some crops invariably experience moisture stress at some stage during the season. Its severity depends on soil type, weather patterns and flowering time and thus, Jamieson et al. (1995) reported that drought was one of the main causes of GY variation over seasons in NZ.

To maximise yields, maize requires 500-800 mm of water per season, depending on crop duration and evaporative conditions (Brouwer and Heibloem, 1986). Even though this requirement is largely met in most NZ areas, even distribution, necessary to match plant requirements throughout the growing season, is the key. In situations where moisture deficit is likely, growth duration of a hybrid must be matched with the available water supply such that stress susceptible stages are synchronised with periods of the least probability of water stress (Edmeades et al., 1999). This can be achieved by adjusting PD and/or hybrid maturity. Synchronisation of development and rainfall patterns is, however, only possible when there is a high degree of predictability about the timing of stress, which is rarely practical under field conditions due to the random timing and intensity of drought. Since susceptibility to water stress is hybrid dependent, selection of a more tolerant hybrid could also reduce the impact of drought.

Drought effects on maize include, but are not limited to, stomatal closure, reduced photosynthesis and assimilate production, decreased cell and organ expansion, increased anthesis-silking interval (ASI), accelerated leaf senescence, and assimilate remobilisation from stalks which may promote lodging (Bänziger et al., 2000). When drought is severe, a decline in biochemical capacity for carbon assimilation and utilisation is observed (Reddy et al., 2004). Drought also affects nutrient mobility in the soil, thereby reducing N availability and uptake, causing some degree of N deficiency that may play a role in accelerating leaf senescence and reducing photosynthetic rates (Bänziger et al., 2000). Wolfe et al. (1988b) found that delayed leaf senescence resulted in N remaining in leaves for longer, a prerequisite for maintenance of high rates of photosynthesis. Betrán et al. (2003) consequently showed that under drought conditions, delayed senescence and GY were positively correlated. Sensitivity of crops to drought is dependent on stage of development (Doorenbos and Kassam, 1979) and is highest during and just after flowering (Grant et al., 1989; Bänziger et al., 2000).

2.2.3.1 Drought effects during vegetative growth

Pre-anthesis stress reduces leaf and stem elongation through reduced cell expansion and extension (Hsiao, 1973; Westgate and Boyer, 1985; NeSmith and Ritchie, 1992; Kiziloglu et al., 2009), decreasing plant height (Acevedo et al., 1979; Gavloski et al., 1992; Traore et al., 2000) and LA (Çakir, 2004). Other reports have attributed total DM reductions of up to 30% to a decline in stem elongation, leaf size and increased phyllochron caused by water stress during the pre-flowering period (Çakir, 2004). Short internodes and reduced LA limit assimilate storage for grain filling, causing decreased KW (Moser et al., 2006). Severe water stress can also delay TI (Abrecht and Carberry, 1993) and consequently, silking and maturity (Farré and Faci, 2006; Payero et al., 2006). Reduced leaf numbers have also been observed under severe drought occurring prior to TI (Jordan, 1983; NeSmith and Ritchie, 1992; Abrecht and Carberry, 1993; Kiziloglu et al., 2009).

While the main effects of water stress on yield are through decreased photosynthesis and KN due to ear and kernel abortion (Bänziger et al., 2000; Earl and Davis, 2003), pre-anthesis drought affects KN and KW through canopy size reduction (Claassen and Shaw, 1970; Pandey et al., 2000). There is a modest capacity for maize plants to respond to fewer kernels per plant by increasing KW, when growing conditions return to optimum during grain filling. Such a response was reported by Kiniry et al. (1990) who noted that after artificially reducing KN, KW was somewhat flexible, increasing by 0-25%, depending on genotype. Though small, contributions due to increased KW gain may compensate for the negative effects of pre-anthesis drought on KN, as observed by Eck (1986). In some situations, harvest index (HI) can increase with pre-anthesis stress (Lorens et al., 1987; Moser et al., 2006). Most of this could be due to reduced vegetative growth and shorter plants, followed by relatively normal ear growth.

2.2.3.2 Drought effects during flowering

Severe stress during flowering results in kernel abortion and significant reduction in kernel set, causing yield losses of 50-100% (Grant et al., 1989; Bolaños and Edmeades, 1993a; Pandey et al., 2000). This supports findings by Doorenbos and Kassam (1979) who reported that maize was about 3-4 times more prone to drought if water stress occurred during anthesis rather than during vegetative growth or grain filling, with much less yield loss encountered if stress occurred during the ripening stages. The most drought susceptible period is considered to be approximately 2 wk either side of anthesis (Shaw, 1974; Schussler and Westgate, 1995; Boomsma and Vyn, 2008). Kernel number determination occurs during this period (Jamieson et al., 1995). Çakir (2004) observed a 20% reduction in KN when water stress occurred at tasselling, vs. 32-35% if stress coincided with the tasselling to ear formation stage. Since maize GY is highly correlated with KN under drought stress (r=0.9; Bolaños and Edmeades, 1996), yield depression under severe stress at flowering, as observed by several researchers (e.g., Poneleit and Egli, 1979; Otegui et al., 1995a; Andrade et al., 1999; Rajcan and Tollenaar, 1999; Capristo et al., 2007) is not surprising.

Water stress immediately prior to silking usually slows ear growth more rapidly than tassel growth, thereby increasing ASI (Bänziger et al., 2000; Campos et al., 2004; Farré and Faci, 2006). Delays in silk emergence of up to 8 d under drought conditions have thus been documented (Hall et al., 1981; Herrero and Johnson, 1981; Grant et al., 1989). This significantly reduces chances of successful pollinations since pollen grains only have a limited lifespan (Bassetti and Westgate, 1994). Longer ASI is negatively correlated with GY (Bolaños and Edmeades, 1993b, 1996) because of a reduction in KN caused by loss of silk receptivity, decline in fertilisation and an increase in embryo abortion (Westgate, 1997; Bänziger et al., 2000; Bruce et al., 2002).

In NZ, most crops flower between mid January and early February. Coincidentally, these are the hottest (see Table 1.1, Chapter 1) and driest months and could increase pollination failure or kernel abortion in dry years. Therefore, where water stress risk is high (e.g., sandy soils), only drought tolerant hybrids should be planted.

2.2.3.3 Drought effects during grain filling

Leaf growth, final size and orientation, and growing kernels are the main determinants of source and sink strengths through their respective relations with light interception and yield (Welcker et al., 2007). Under typical drought situations, the primary limitation to maize photosynthesis is reduced leaf internal CO_2 concentration which is caused by stomatal closure as leaves attempt to minimise water loss through evapotranspiration (Saccardy et al., 1996). Temporary wilting or leaf rolling also occurs under water stress conditions (Jones et al., 1986; Wolfe et al., 1988a; Xianshi et al., 1998; Bruce et al., 2002), reducing photosynthesis due to lower interception and conversion of PAR into biomass (Otegui et al., 1995b; Moser et al., 2006; Welcker et al., 2007). Reduced photosynthetic rate during grain filling decreases source flux, thus minimising assimilate flux to the developing ear.

During grain filling, water stress influences KW differently, depending on growth stage (Bajwa et al., 1987; Roy and Tripathi, 1987). Stress within the first 3-4 wk of grain filling leads to kernel abortion while stress in last 3-4 wk leads to shrivelled grain and accelerated leaf senescence (Edmeades et al., 2000).

2.2.4 Photoperiod

Maize is a short-day plant that responds to long days by initiating more leaves and delaying TI, triggering a corresponding delay in flowering. Photoperiod sensitivity is considered to occur 4-8 d prior to TI if daylength exceeds the critical value (P_c) of 12-13 h (Kiniry et al., 1983b; Bonhomme et al., 1991; Birch et al., 1998b). In extremely sensitive tropical germplasm, long days can promote an increase in ASI, massive vegetative growth and almost no GY (Edmeades et al., 2000). While photoperiod sensitivity can occur at TI or a few days thereafter (Struik, 1982), the effects are much smaller than the response in the week prior to TI (Kiniry et al., 1983b; Ellis et al., 1992a).

Photosensitivity tends to decline with adaptation to increasing latitude and longer days. Temperate hybrids are usually less sensitive to photoperiod than tropical hybrids (Bonhomme et al., 1991; Bonhomme et al., 1994). For instance, Ellis et al. (1992a) found that photoperiod sensitivity was almost zero in hybrids adapted to shorter season temperate areas. In a growth chamber study of a US Corn belt hybrid conducted under high light intensity (typical of real field conditions), response to photoperiod was reported to be 0.71 leaves h^{-1} for daylengths $>P_c$ (Warrington and Kanemasu, 1983c). Values of up to 2.55 leaves h^{-1} have been reported in tropical highly photoperiod sensitive hybrids (Bonhomme et al., 1991; Birch et al., 1998b). Other researchers working with hybrids adapted to higher latitudes have observed leaf number increases of between 0.21 (Coligado and Brown, 1975) and 0.38 (Hesketh et al., 1969) h^{-1} above a 12.5 h threshold.

Delayed TI will normally also delay PM, causing grain drydown issues, particularly for late maturing hybrids. Such a problem is less of a concern for silage since the crops are usually harvested at 35% whole plant DM, and the reduced HI caused by increased vegetative biomass growth may not necessarily alter silage nutritive value to a large extent (Dhillon et al., 1990). Despite the aforementioned, higher GYs have been observed in early germplasm under long photoperiod conditions (Hunter et al., 1977) and this could be attributed to increased LA (Hesketh et al., 1969) which enhances IPAR and DM production.

2.2.5 Interaction between temperature and solar radiation

Even though environmental factors affect crops independently, most of the responses are largely due to their interactions. Temperature and solar radiation are considered to have a direct interactive effect on crop production (Muchow et al., 1990) for the greater part of the crop cycle duration. For example, between emergence and silking, effects of low IPAR levels can be exacerbated by low temperatures that reduce RUE (Cirilo and Andrade, 1994a). Concomitantly, Muchow et al. (1990) noted that GY losses due to high temperatures (28^0C) were minimised if grain fill coincided with high solar radiation. To maximise yields, a combination of moderate temperatures and high IPAR conditions is required as it results in greater PTQ (see section 2.2.2). This agrees with Otegui et al. (1995b) who noted that at high temperatures, even if IPAR was maximised, the low PTQ values reduced GYs. In a simulation study, Muchow et al. (1990) reported that under high solar radiation levels and mean temperatures of around 19^0C, which promote increased crop duration and maximal leaf area, maize yields were maximised.

2.2.6 Interaction between temperature and photoperiod

Temperature and photoperiod impact TI and flowering through their direct effects on leaf number. Tollenaar and Hunter (1983) observed that other than their individual influences on leaf number, their effects on TT to flowering were additive rather than interactive. Long photoperiods and low temperatures can independently increase leaf number (Breuer et al., 1976; Warrington and Kanemasu, 1983c; Ellis et al., 1992a,b). While both factors influence leaf number between the juvenile (period following seedling emergence but prior to TI) and TI stages, the period immediately after the juvenile stage is photoperiod and temperature sensitive, whereas the brief phase just prior to TI is only photoperiod sensitive (Tollenaar and Hunter, 1983).

Other peripheral findings on this subject include temperature x photoperiod interactions on KN (Hunter et al., 1977). Struik et al. (1986) attributed these findings to carryover effects of poor synchronisation between pollen shed and silk emergence. This concurs with Bonhomme et al. (1994) and Edmeades et al. (2000) who noted a positive correlation between photosensitivity and ASI. Therefore, for photosensitive hybrids, stress conditions that delay silking, such as drought, could be more detrimental under long daylengths.

2.2.7 Interactions between water and other environmental factors

Water is considered a solvent for all crop processes. Prevailing environmental conditions determine yield response to water stress, leading to seasonal and spatial variation in drought intensity (Norwood, 2000; Moser et al., 2006; Payero et al., 2006; Kiziloglu et al., 2009). For instance, despite evapotranspiration being positively linearly related to silage yield (SY) (Çakir, 2004; Kiziloglu et al., 2009), transpiration efficiency, defined as net photosynthetic carbon fixation per unit of water transpired, generally decreases under hot dry conditions as relative humidity falls **(**Jamieson et al., 1995). Extremely high temperatures (>34^{0}C) which often coincide with drought may also suppress photosynthetic rates (Earl and Davis, 2003). In situations of high drought potential, PD should be such that flowering (most sensitive development stage) does not coincide with periods of high temperatures and high evaporative demand.

Unfavourable temperature and water conditions significantly influence the light extinction coefficient (k). The extinction coefficient determines how canopy structure and orientation influence the efficiency with which a given leaf intercepts radiation, and ranges between 0.4 and 0.66 for a fully developed maize crop under temperate conditions (Jones and Kiniry, 1986; Birch et al., 2003; Lizaso et al., 2003). Farré et al. (2000) observed k values of 0.5 and 0.2-0.3 for irrigated and water stressed maize crops, respectively. The reduction in k under drought situations is caused by leaf rolling which reduces the radiation interception of each unit of LAI.

Under non-limiting water conditions, higher radiation levels would increase photosynthetic rates, resulting in higher biomass production and, consequently, yield. Conversely, under moisture stress situations, higher solar radiation could reduce yields by increasing evapotranspiration and temperature. Bert et al. (2007) therefore noted that correlation between maize yield response and solar radiation was dependent on soil water availability. Similarly, even though light saturation is not common in maize, under drought conditions, an imbalance caused by excess radiation supply in relation to metabolic demand can cause permanent photo-oxidative damage to leaf tissues (Foyer and Noctor, 2000). In their work, Earl and Davis (2003) showed that of the three main mechanisms that contributed to GY loss under drought situations (RUE, IPAR, HI), reduced RUE was the most important. Loss attributable to IPAR was the least, only showing significant effects under severe water stress. Decrease in RUE reduces DM accumulation per unit PAR absorbed over time (Stone et al., 2001) or whole canopy net CO_2 exchange rate per unit absorbed PAR (Jones et al., 1986).

Complexity of crop response to the interactive effects of environmental factors under field conditions usually make predictions of developmental durations difficult. While TT to silking duration is generally constant in the absence of photosensitivity, Roth and Yocum (1997) found that under water stress, delayed planting increased TT to silking. The anomaly could be attributed to silking delay due to drought or phyllochron variations, and is another example of how environmental factors interact to influence crop development in a relatively complex manner.

2.3 HYBRID SELECTION TO MAXIMISE YIELD

For maximum yields to be achieved in a particular ENV and conditions, an appropriately adapted hybrid with the highest yield potential must be planted at its optimum planting density for grain or silage production. High yields are due to the increased availability of assimilate supply (source) for grain filling as well as the capacity of the reproductive sink component (kernels) to accommodate the available assimilates. Kernel sink capacity can be defined as the intrinsic ability of the endosperm to attract and accumulate assimilates (Jones et al., 1996). Source refers to ability of the plant to produce assimilates, which is initially driven by photosynthesis and subsequently by a capacity to remobilise previously fixed reserves. To ensure high yields, there is therefore need for the greatest assimilate flux to the ear at flowering, and this will generally be around the longest day (22 December), though in NZ it generally will not alter much 2-3 wk either side of it. Highest yields were reported as occurring when flowering coincided with maximum radiation levels in NZ (Sorensen et al., 2000). Modern hybrids however have a finely tuned source-sink balance and a significantly increased tolerance of stresses at flowering, compared with older hybrids (Campos et al., 2004).

Ideally, silking should coincide with periods of adequate moisture, moderate temperatures and high IPAR levels to maximise PTQ and consequently, sink size. While the hybrid genetic make-up and maturity have a considerable influence on source and sink capacities, sink size is partly determined by growth conditions during the lag phase (Reddy and Daynard, 1983; Jones et al., 1985, 1996). Otegui and Bonhomme (1998) defined the critical phase determining sink size to encompass a period of 227^{0}Cd before and 100^{0}Cd after silking. Tollenaar et al. (1992) described this period as 1 wk pre-silking to 3 wk post-silking. Andrade et al. (1993a; 2000) considered it to occur over 30 d, centred on silking, while Kiniry and Knievel (1995) identified it as 7-10 d after silking. Elsewhere, Lafitte and Edmeades (1995) noted the lag phase duration lasted for 15-20 d. Despite small differences in defining the window, these findings agree that environmental conditions around silking are critical for sink size determination. Therefore, when choosing hybrids for planting, the risk of silking occurring under suboptimal conditions must be minimised. Hybrids known to be susceptible to drought at flowering must be avoided if probability of the occurrence of mid-season drought is high.

To maximise yields, a good match between hybrid and environmental conditions is also required. The right maize hybrid is usually one that can realise the full yield potential of the growing season and the inputs provided by the grower with an acceptable risk level of yield reduction (Lauer, 1998). Bruns and Abbas (2006) observed that long duration hybrids generally yielded more than early maturing hybrids under non-limiting season lengths and also when both were planted early (Staggenborg et al., 1999; Sorensen et al., 2000; Capristo et al., 2007). When planted early, short duration hybrids fail to fully utilise available solar radiation and other resources at the end of the season (Figure 2.2). When planted late, short season hybrids usually yield similarly to, or greater than full season hybrids (Staggenborg et al., 1999). Early maturing hybrids planted at the right density may therefore be more profitable, especially if later hybrids require artificial drying for safe storage, and if an early and unexpected cessation to the season from drought or frost restricts grain filling in the full season hybrid. Early hybrids are consequently more suitable for cooler areas, late planting situations or where early harvest is required, whereas late hybrids are more suitable for warmer regions where it is highly probable that the full growing season will be available. Profitability and risk must be considered when selecting maize hybrids for different management and environmental conditions.

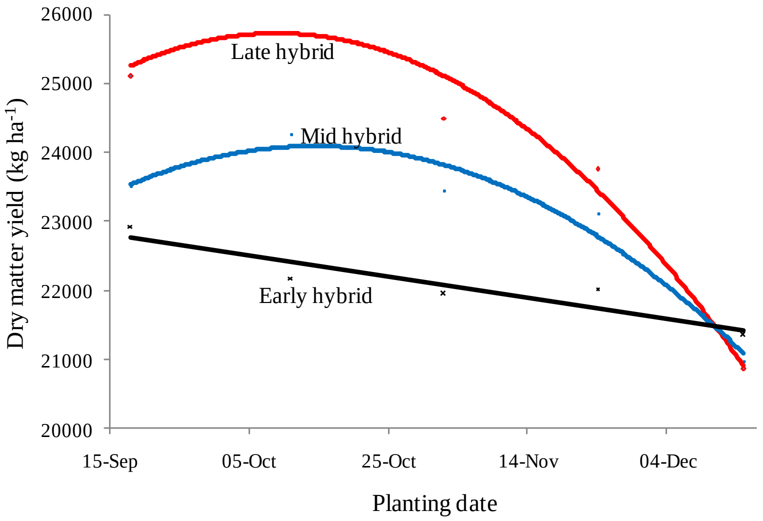


Figure 2.2 Effect of planting time on silage yields of maize hybrids differing in maturity in a Waikato environment (Source: Tsimba et al., 2008, unpublished data).

Suitability of a hybrid to grow within a region or specific timeframe can be accurately estimated if its maturity and the inter-annual variations in weather are known. For most growers, availability of several maize hybrids on the market complicates selection of the best hybrid that can mature within a given timeframe while at the same time maximising yield and profitability. Genetic Technologies Limited (representing Pioneer® Hi-Bred International Inc. in NZ) for example, has 29 commercial hybrids of varying maturity on the market (Genetic Technologies, 2008). This number, in addition to those from other seed companies only add to confusion among NZ maize growers.

While TT requirement is critical in determining hybrid fit within an ENV, in the commercial sector, hybrids are usually rated for relative maturity by their CRM. As already described in section 1.1.2, the CRM rating is a relative value based on an arbitrary definition rather than absolute days or TT. The CRM system therefore cannot adequately provide information required to determine maturity fit within an ENV. Even though relative rankings for maturity based on CRM have general utility, the units are relatively meaningless outside of the US Corn Belt. Unlike some US states where cross checks among seed companies exist (e.g., Minnesota CRM system), in NZ, the system is company specific, meaning that comparing ratings across companies is not simple. Some seed companies such as Pioneer® Hi-Bred International Inc. also quote, where necessary, TT requirement to reach specific developmental stages. While this is a significant development, T_b10 is usually used, making predictions of developmental stages less reliable in cooler regions such as NZ where errors in the assumed T_b rapidly accumulate (NeSmith and Ritchie, 1991).

2.4 IMPACT OF EARLY PLANTING ON MAIZE GROWTH AND DEVELOPMENT

Planting is usually conducted when soils are warm or dry enough to be worked without compromising structure and when potential for plants to coincide with a spring or autumn killing frost is minimal. While early planting is generally thought to promote higher yields, the benefits are usually overstated. Yield reductions due to early planting are widely cited in literature (e.g., Kaspar et al., 1987; Swan et al., 1987; Kaspar et al., 1990). Johnson and Mulvaney (1980) found that yield loss due to planting 2 wk before or after the optimum date was around 5%, with greater losses reported if planting was conducted outside this range even if other conditions were non-limiting. The convex relationship between PD and yield, particularly for long duration hybrids which are adapted to the NZ growing ENV, is also illustrated in Figure 2.2.

Advantages due to early planting are negated by, among other factors, effects of colder soils on maize growth and development. Typically, early planting is associated with low soil temperatures, uneven and slowed emergence, reduced LA, plant growth and development (Al-Darby and Lowery, 1987; Swanson and Wilhelm, 1996), reduced stands, depressed seedling vigour and delayed maturity (Burrows and Larson, 1962; Griffith et al., 1973; Mock and Erbach, 1977; Imholte and Carter, 1987). Temperatures during early development stages determine rate of canopy development and leaf expansion, influencing IPAR (Muchow and Carberry, 1989). While accumulated radiation received during the crop cycle is usually highest with early planting, the delayed canopy development decreases yields through reduced IPAR and RUE (Muchow and Carberry, 1989; Otegui et al., 1995b). The slower emergence and growth rates may also expose plants to soil borne pests and diseases for longer durations. Other variables affected by low soil temperatures include reduction in plant height (Al-Darby and Lowery, 1987) due to reductions in internode elongation and leaf numbers (see sections 5.4.7 - 5.4.8, Chapter 5). Plant height alone is generally not thought to affect GY.

Effects of lower soil temperatures can be mitigated by delaying planting until soil temperature is >10^0C (Miedema, 1982; Shaw, 1988). Norwood (2001) also observed that crops planted when maximum soil temperatures were ≤16^0C resulted in significantly depressed yields even if optimum temperature conditions ensued during pollination and grain filling. Similarly, Bollero et al. (1996) found that soil temperatures at planting were linearly related to GY. Elsewhere, Walker (1969) noticed a 20% increase in seedling dry weight for every 1^0C increase in soil temperature between 12 and 26^0C. Such a response may however not occur in material that are adapted to cooler conditions as shown by Hardacre and Eagles (1989) who found that when grown in a $16/6^0$C temperature regime, seedling dry weights of tropical highland germplasm were 2-4 times greater than some lowland tropical germplasm and some Corn Belt Dent hybrids.

Hybrids or germplasm that can tolerate early stress or are adapted to cool conditions may have some comparative advantage in early season plantings. Hence, Eagles and Hardacre (1979) noted genetic variation for early growth at mean soil temperatures of 12.5^0C. Lower temperatures were also found to influence emergence, shoot weight and leaf number differentially among genotypes. Similarly, Ellis et al. (1992b) found that material adapted to tropical highland ENVs had lower T_{opt} for the emergence-TI development stage compared to tropical lowland genotypes. Richner et al. (1996) also showed that soil temperature reductions of $2\text{-}3^0$C below 15^0C could reduce root development in maize seedlings sensitive to low temperatures. This can reduce water and nutrient uptake, leading to increased vulnerability and yield losses under sub-optimal conditions. Due to improved cold tolerance in the spring, new maize hybrids adapted to the Corn Belt and to NZ are better able to tolerate low temperatures during establishment compared to older ones.

The effects of low soil temperatures in delaying crop development early in the season can extend beyond meristem exposure to cool temperature as observed by Bollero et al. (1996) who noted that cool soil temperatures (15 vs. 20^0C or 20 vs. 25^0C) between emergence and the V5 stage reduced TT to tasselling. There is a possibility that use of T_b10 may also have underestimated development at lower temperatures.

2.5 IMPACT OF LATE PLANTING ON MAIZE GROWTH AND DEVELOPMENT

Late planting affects maize yields through reduction in PTQ, a major determinant for biomass per unit crop development. This is largely because the high soil and air temperatures experienced with late planting shorten the calendar time required for vegetative growth, reducing the opportunity for the crop to capture radiation (Allison and Daynard, 1979; Cirilo and Andrade, 1994a; Wilson et al., 1995; Yang et al., 2004). With late planting, yields are therefore limited primarily by assimilate source, unlike early planting which is affected more by sink capacity. Significant maize yield losses with late planting are widely reported in local and overseas literature (Johnson and Mulvaney, 1980; Wilson et al., 1994; Swanson and Wilhelm, 1996; Lauer et al., 1999; Sorensen et al., 2000; Wiatrak et al., 2004). These findings as well as those reported under early planting corroborate a convex upward quadratic grain yield response to PD, usually with a weak maximum (Johnson, 1978; Nafziger, 1994; Swanson and Wilhelm, 1996; Norwood, 2001).

Late planting may also expose photosensitive germplasm to longer photoperiods in the period prior to TI, increasing leaf numbers and consequently delaying flowering (Chase and Nanda, 1967; Allen et al., 1973; Aitken, 1980; Kiniry et al., 1983b; Warrington and Kanemasu, 1983a; Ellis et al., 1992a,b; Birch et al., 1998b). Maturation is also delayed, increasing risk to frost damage and high artificial grain drying costs.

Grain filling for late planted crops usually coincides with declining temperatures and IPAR. Temperatures $\leq 17^0$C slow effective grain filling rate (Cirilo and Andrade, 1996), resulting in reduced KW and decreased GYs (Cirilo and Andrade, 1994a,b). Lower temperatures during grain filling also reduce photosynthetic rates (see section 2.2.1). Decreasing radiation levels as days shorten in the autumn further exacerbate the reduction in IPAR accumulation during later stages of grain filling, reducing yields. Cirilo and Andrade (1996) observed that at higher plant densities, lower temperature and radiation levels can significantly reduce CGRs. To reduce the potential for barrenness under late planting conditions (low radiation), planting densities should therefore be lowered to increase IPAR per plant. Low temperatures and high relative humidity after PM also slow grain drydown, increasing the probability of field losses due to the prolonged time the crop is in the paddock, which consequently increases the need for artificially drying grain.

A build up in disease and leaf feeding insects during the season could also affect late planted crops more than early planted crops. For example, in the Waikato, late planted crops are usually quite prone to common rust, which is caused by the fungus *Puccinia sorghi*. This is consistent with Wiatrak et al. (2004) who reported that foliar diseases had a more significant effect on late planted maize crops. This would put extra pressure on maize grown in disease prone areas and in particular, where the hybrids are susceptible to disease. Plants affected by foliar diseases will have accelerated senescence, reducing photosynthetic capacity through decreased IPAR and RUE (Otegui et al., 1995b), and reduced LA duration will negatively impact yield (Wilhelm et al., 1987) through a reduction in amount of fixed carbon (Norman and Arkebauer, 1991).

Unfavourable conditions during grain fill usually reduce HI. Even though relative yield loss caused by delayed planting is less for maize silage than grain (Wiatrak et al., 2004), reduced silage quality due to poor grain fill has been reported (Wilson et al., 1994). Wilson et al. (1995) observed a linear decrease in HI when temperatures were $<19^0$C during grain fill. Similar results have been reported by Daynard (1971) who observed higher LAI and lower GYs with delayed planting. In NZ, low grain-dense silage may occur with late planted crops, especially if grain fill occurs around April when temperature and IPAR levels start decreasing (see Table 3.1 and Table 3.2, Chapter 3). The low grain content consequently decreases silage digestibility (Wiatrak et al., 2004). Similarly, Cox et al. (1994) reported high negative correlations between HI with Acid detergent fibre (ADF) ($r=-0.79$) and neutral detergent fibre (NDF) ($r\leq-0.82$).

2.6 CROP SIMULATION MODELS

Because of increasing pressure on land, water, resources and profitability, there has been a greater need for more informed agricultural decision making in recent years (Potgieter et al., 2003). There are not many documented studies in NZ on how maize hybrids of varying maturities respond to different conditions as dictated by different PDs. Conducting sufficient PD field studies is time consuming and costly, often resulting in findings that are not necessarily repeatable over time and space. Due to the complicated nature of the interaction between environmental factors and crop growth and development, traditional agronomic methods are therefore not the most efficient and effective way of generating or providing reliable information on hybrid-ENV interactions because of their limited capacity to sample target ENVs. For example, optimum PD for maize depends largely on location, hybrid (Swanson and Wilhelm, 1996) and season (Johnson and Mulvaney, 1980). Because of seasonal, climatic or soil variations, PD results based on field experimentation within a specific season often cannot be extrapolated to other seasons or regions (Saseendran et al., 2005). To overcome the complexity, a decision support system which allows farmers to choose the best option for their production system is thus necessary. A sound and feasible approach involves use of a crop simulation model linked to many years of historical weather data. In NZ, because of the widespread use of computers, models are likely to be easily adopted at the farm level, potentially enhancing and simplifying decision making by growers.

A crop simulation model can be defined as "a dynamic representation of crop processes in a systems context, which seeks to replicate and explain how environmental and management conditions or genetic variation influence crop growth, development, yield and quality" (Sinclair and Seligman, 2000). They are therefore a simplified representation of the real system in the form of equations (France and Thornley, 1984; Hanks and Ritchie, 1991).

Crop simulation models using long term or real time weather data are now widely used for decision making at the field, regional or global level to predict yield (Liu, et al., 1989; Stewart and Dwyer, 1990; Raddatz et al., 1994; Bouman, 1995; Thornton et al., 1997; Yun, 2003; Soler et al., 2007; Binder et al., 2008; Braga et al., 2008) or for farm management and policy decision making (Verhagen et al., 1995; Boote et al., 1996; Izauralde et al., 1996; Hoogenboom, 2000; Xie et al., 2001; Gungula et al., 2003). Models are also used to synthesize experimental data in a quantitative conceptual framework and to identify knowledge gaps that need further research (Stewart et al., 1998b; Boote et al., 2001; Lizaso et al., 2005; López-Cedrón et al., 2005). Models therefore help improve scientific understanding of crop behaviour under field conditions (Sinclair and Seligman, 2000).

The main advantage of models is their ability to utilise a large sample of individual annual weather data over 20-100 yr rather than long-term average weather data, and thus mimic inter-annual variation. One of the limitations of models is their inability to forecast the effects of conditions that the crop will experience in the current season. This could reduce their usefulness if the season deviates from normal. While simulation models help in simplifying complex interactions in cropping systems, they are not a replacement of agronomy experimentation and expert knowledge. They are simply another tool to aid in systems analysis and decision making.

For a model to accurately predict crop performance, it should precisely simulate the effects of soil x crop x climate interactions on phenological processes. In modern temperate hybrids, these processes are primarily dependent on soil depth and texture, radiation and temperature, and to a much smaller extent, photoperiod. Failure to adequately predict phenological stages would compromise timing of management operations and yield estimations. Since models generally use constant values that are fixed for particular ENVs (Birch et al., 1998d), they must be adequately tested for local conditions before release for widespread use. To assess prediction power or ability to accurately simulate crop phenological development in an array of ENVs and cropping conditions, the model must be calibrated and validated or verified over a range of ENVs (Piper et al., 1998).

Model calibration involves adjusting parameter values to minimise the difference between field observed and model estimated values (Klepper and Rouse, 1991). Validation or verification on the other hand involves comparing model outputs against an independent data set (Schlesinger et al., 1979; Rykiel, 1996) without altering any parameter values. A properly calibrated and validated crop simulation model, combined with long-term weather data, can be utilised to develop probability tables of yield response from hybrids of a given maturity and genotype sown on a specific date or condition (Mathews et al., 2002). Risks associated with each option or combination can also be estimated.

Many crop process models exist and each of them is usually specific in purpose (Jagtap and Jones, 2002) and nature. In NZ, the AmaizeN model has been developed to help farmers in scheduling N fertiliser management for maize crops through maximising return from fertiliser inputs as well as meeting NZ regulatory requirements on nitrate leaching. It includes estimates of grain and silage yields, and can be adapted to use actual weather data from any location. AmaizeN however lacks the capacity to simulate the individual hybrid differences in genetic x ENV responses. A detailed description of the model has been documented by Li et al. (2009a,b).

CERES-Maize is one of the most widely used maize crop models (Jones and Kiniry, 1986) and this could be due to several factors; age, reliability, simplicity and adaptability (López-Cedrón et al., 2008). The model is part of the DSSAT cropping system models and helps decision makers reduce time and human resource requirements for analysing complex decisions (Tsuji et al., 1998). It is a deterministic model designed to simulate maize growth, development and yield using a daily time-step. The model utilises hybrid specific inputs (genetic coefficients) to distinguish between different hybrid responses to the ENV (Hoogenboom et al., 2003) and has consequently been used as part of a decision support system for making hybrid choices (e.g., Jones et al., 2003). It has also been successfully utilised to quantify production potential of maize outside its normal growing season (Soler et al., 2005; Binder et al., 2008). Ability to achieve the latter will help in the determination of crop performance in areas where maize has not been grown before, such as the cooler parts of NZ where season length is limiting.

The detailed phenology and yield component information generated by CERES-Maize allows the user to evaluate hybrid characteristics in different ENVs under variable conditions (Xie et al., 2001), provided the hybrid characteristics have been accurately determined beforehand. Model output helps formulate informed decisions when trying to understand comparative hybrid performance for a particular location over years. A full description of CERES-Maize model is documented elsewhere (Jones and Kiniry, 1986; Ritchie et al., 1998; Hoogenboom et al., 2003; Jones et al., 2003).

Crop models are often used to simulate GY under optimum N and water situations (Roman-Paoli, 2000; Binder et al., 2008; Braga et al., 2008). Even though CERES-Maize has been extensively tested under different soil and climatic conditions (Hodges et al., 1987; Carberry et al., 1989; Jagtap et al., 1993; Ben Nouna et al., 2000; López-Cedrón et al., 2005; Soler et al., 2007; Yang et al., 2009), unsatisfactory predictions have been reported in ENVs with variable moisture regimes (Carberry et al., 1989; Wu et al., 1989; Ben Nouna et al., 2000; Lopez-Cedron et al., 2008). If CERES-Maize is to be used in rainfed regions, the model must therefore be modified and evaluated where necessary, to improve predictions under such conditions. Ability to accurately predict crop performance under extreme conditions is an important requirement if model use is to be extended to production situations that are resource limited. Saseendran et al. (2005) have calibrated the CERES-Maize model and used it to estimate the probability of achieving an economic break-even for GY under irrigated conditions in the US. Since almost all maize crops in NZ, particularly the North Island, are rainfed, there is a need to expand this study for both grain and silage yield under typical NZ conditions.

CERES-Maize (v4.0) has been evaluated and found to more closely predict biomass and GY under cool temperate ENVs than its predecessors (López-Cedrón et al., 2005). López-Cedrón and co-workers found that the model's predictions improved further when they inserted temperature functions for cooler climates, as proposed by Wilson et al. (1995).

In NZ, where many hybrids are available, making decisions on when and what to plant can be a daunting task for growers. Development of a decision support tool that relates hybrid response to PD for both maize silage and grain is thus necessary. This study therefore aims to fill that gap through use of a calibrated and verified crop simulation model.

2.7 SUMMARY OF LITERATURE REVIEW

Crop growth and development are greatly influenced by temperature, radiation, water availability, and to a lesser extent, photoperiod. These all vary in time and space. To understand how PD affects crop performance, predicting how these factors interact to influence maize hybrids at various growth stages is important.

Provided water is not limiting, temperature and solar radiation have a direct and most significant effect on crop production. Moderate temperatures (20-25^{0}C) and high solar radiation levels promote maximum growth and yields, though crop development rate is maximised around 30^{0}C. Low yields at high temperatures are usually due to reduction in crop cycle duration, which lowers the PTQ. Low temperatures (<19^{0}C) inhibit plant growth and development, and reduce LAI. Delayed canopy development reduces IPAR, which determines total biomass accumulation and maize yields. Low radiation levels during grain fill slow grain growth and reduce HI, resulting in decreased digestibility of maize silage. Low radiation and temperature during grain filling also reduce photosynthetic rates, RUE and slow effective grain filling rate, further reducing KW and KN.

Photoperiods >12.5 h and temperatures >18^{0}C around TI may increase leaf number, delaying flowering and PM in sensitive hybrids. This may cause grain to drydown more slowly at lower temperatures, increasing field losses due to the prolonged crop exposure in the field and increasing costs of artificial grain drying.

High yields are due to an increased flux of assimilates for vegetative growth and grain filling but must be accompanied by a sink capacity that can accommodate those assimilates. The literature describes a quadratic yield response to PD with a weakly defined optimum. With late planting, yields are limited by assimilate source whereas with early planting yields are constrained more by sink capacity. Full season hybrids generally outyield early hybrids when planted early and vice versa for late PDs. Establishing the optimum PD for an ENV and its tradeoffs with yield as it is altered remains an important research and farm management goal, one which this thesis is attempting to address. Repeatable prediction of specific hybrid phenology remains an essential task if PDs are to be optimised.

To maximise yields, critical development stages (e.g., flowering) must be matched with the most favourable environmental conditions. Successful prediction of the timing of developmental stages, or the identification of limiting factors to crop production would help develop intervention strategies to mitigate yield limiting conditions. Synchronising phenology with optimum conditions is however only possible if crop development can be predicted with certainty. Deviations from the expected TT durations observed in some studies can be attributed mostly to use of wrong T_b values or interactions between environmental factors that have not been accounted for.

Due to the linear relationship between temperature and development, suitability of a hybrid to grow within a region or specified time can be accurately estimated using TT. Since maize hybrid maturities in the seed industry are mostly based on the CRM rating system, it is almost impossible to accurately predict development or the effects of abiotic factors on yield. Optimum PD is dependent on seasonal variations of weather and the recommended regional optimum PDs in literature can be misleading since the weather in the year the research was conducted may significantly differ from other years. To overcome shortcomings of field-based recommendations on hybrid choices for different PD situations, adequately evaluated crop models are an attractive option.

To estimate crop processes, simulation models combine all major factors involved in crop growth and development. A model capable of predicting how hybrids respond to different abiotic conditions would simplify or clarify maize planting decisions. A high degree of predictive power is required before adopting a model. A deterministic model, CERES-Maize, has been widely used to simulate maize growth, development and yield for purposes such as formulating decisions on comparative hybrid performance for a particular ENV, using genetic coefficients to distinguish among hybrid responses. Other uses include quantifying maize production potential in new areas.

The reviewed literature revealed a gap on how maize hybrids of varying maturities respond to different conditions as dictated by different PDs, and showed the need for development of a decision tool that relates maize hybrid maturity and genotype to PD for NZ conditions. Due to the complicated nature of interaction effects among environmental factors on maize growth and development, simulation models are considered the best option to accurately predict crop performance.

CHAPTER 3: THE EFFECT OF PLANTING DATE ON MAIZE GRAIN YIELDS AND YIELD COMPONENTS.

3.1 ABSTRACT

Four experiments were established in Waikato and Manawatu (2006 and 2007) to determine how planting date (PD) influenced maize (*Zea mays* L.) grain yield (GY) and yield components. Five or six hybrids of three maturity classes (early, mid and late) were sown on four or five PDs between 18 September and 15 December (Waikato) or 16 October - 10 December (Manawatu). Each experiment was designed as a randomised complete block with a split-plot treatment arrangement replicated three times.

Maximum GY was obtained with 18 September - 13 October (Waikato) or 6 November plantings (Manawatu). Late hybrids outyielded earlier hybrids when planted early. Because of a balanced source-sink ratio, early hybrids yielded consistently across all PDs, matching or outyielding late hybrids when planted late. Despite this, early hybrids failed to take advantage of the optimum conditions due to early PDs. Lower spring temperatures and consequently, smaller canopy sizes in Manawatu depressed early planting yields. Relative to 6 November, 10 December PD reduced GY by 16% (early hybrids) or >30% (mid and late hybrids). The larger yield reductions in Manawatu were due to lower minimum temperatures (11 vs. 13^0C) and average radiation (11 vs. 20 MJ m^{-2} d^{-1}) during grain filling. In Waikato, PD effects were less marked due to warmer spring mean temperatures and a slower decline in autumn temperatures and radiation.

Grain yield was highly correlated with kernel number (KN) (r=0.9***) and weight (KW) (r=0.76***). Lowest KN and GY were obtained under late plantings, low rainfall (<20 mm) and/or radiation (<18 MJ m^{-2} d^{-1}) around flowering, or when mean temperatures $\leq 15^0$C or irradiance <11 MJ m^{-2} d^{-1} occurred during grain filling. Kernel weight and KN responses to late planting or water stress were more apparent in late than early hybrids. Kernel weight was more stable than KN under late planting or water stress conditions. Water stress affected late PDs more than early PDs. Total biomass, harvest index and test weight decreased with delayed planting. For instance, test weight declined by 0.1 kg $hl^{-1}d^{-1}$, to fall below the minimum industry threshold (67 kg hl^{-1}) if planted after 24 November across all environments.

3.2 INTRODUCTION

Due to differences in hybrid maturity and length of growing seasons across NZ, the ideal PDs for maize vary among regions and from year-to-year within regions. It is critical that the right maize hybrid be selected for planting. Late hybrids may fail to mature before the first killing frost occurs. Similarly, early hybrids usually fail to fully utilise available solar radiation for the period when temperatures are suitable for growth and therefore, will not realise the full yield potential of the growing season and the inputs provided by the grower (Lauer, 1998). It is therefore critical to identify the window where yields and profitability can be optimised with different hybrid maturities and genotypes under different management and environmental conditions.

High GYs are due to increased availability of assimilate supply (source) for grain filling and the capacity of the reproductive sink component (kernels) to accommodate the assimilates. Research conducted in NZ showed a yield penalty from planting early hybrids if season length was sufficient for later maturing hybrids (Sorensen et al., 2000). Likewise, when planted late, yields of early hybrids could equal, or outperform full season hybrids (Staggenborg et al., 1999). Moreover, early hybrids may also be more profitable where later hybrids require additional artificial drying for safe storage.

Source-sink balance alters when crops are planted either early or late. Kernel number, which defines sink size, is positively correlated with CGR around flowering (Edmeades and Daynard, 1979b; Tollenaar et al., 1992) and GY (Otegui et al., 1995a; Bolaños and Edmeades, 1996). Since sink size determination occurs around silking (Tollenaar et al., 1992; Andrade et al., 1993a; Kiniry and Knievel, 1995), conditions during flowering have a large bearing on potential GY.

Yield reductions due to early or late planting are well documented in literature and are summarised in sections 2.4 and 2.5 (Chapter 2). In summary, while early planting reduces IPAR through delayed canopy development, high temperatures under late planting situations reduce calendar time for crop development, consequently decreasing yields (Fischer and Palmer, 1984; Wilhelm et al., 1987; Otegui et al., 1996). Cool nights during grain filling, common under late planting situations, reduce RUE (Jones et al., 1986), and this effect sometimes extends for several days (Stone et al., 2001).

In situations where mid-season drought is likely to occur, late planting may also expose crops to water deficits during flowering. This may delay silking, increasing the ASI and thus, reduction of sink size through ear abortion or poorly pollinated ears (Westgate and Boyer, 1986; Bolaños and Edmeades, 1996). Anthesis-silking interval defines the duration between anthesis and silking, and is a predictor of seed set in many maize hybrids when under stress at flowering (Edmeades et al., 2000). Drought effects can thus be minimised by adjusting planting time and hybrid maturity so that flowering occurs when drought risk is nominal.

Test weight or bulk density of the grain is the weight of a known volume of grain, usually expressed as kg hl^{-1}. Test weight is imprecise as it is affected by grain shape (Haardacre, pers. Comm.., 2011). It is however, a critical quality trait in some grain markets where it is used to determine grades and selling price (Nelson, 1980). It is also affected by environmental conditions (Lee et al., 2007) and these are largely influenced by PD. Higher test weights are associated with better filled kernels and a higher percentage of hard endosperm. Low test weight grain thus requires more volume to store or transport, and also tends to retain moisture in storage, increasing spoilage risk.

Knowledge of the basic phenological and physiological processes as influenced by variable environmental conditions is key to the development of mitigating strategies required to optimise and stabilise yields in cases where planting has been delayed, or where hybrids are being sown in new and untested areas. The present study therefore provides the experimental data underlying a decision support tool that will be used to make hybrid-specific recommendations based on variable PDs and weather conditions. The range of PDs and ENVs evaluated in this study were designed to create contrasting environmental conditions that represent a wide range of situations for maize growth and development in NZ. This, and two companion papers (Chapters 4 and 5), report experimental results relating to GY and associated yield components, TT durations, SY and maize phenological and growth processes. Data from these studies is used to calibrate and validate/evaluate a crop model-based decision tool (Chapter 6).

The objective of this Chapter was to determine how PD and ENV affect HI, sink size, grain test weight, barrenness, and grain and total biomass yields of maize hybrids differing in maturity.

3.3 MATERIALS AND METHODS

3.3.1 Site and planting details

Four replicated experiments were established over two growing seasons at three locations in the Waikato and Manawatu Regions of New Zealand. These were at Rukuhia Research Station (37.87^0 S, 175.34^0 E; 50 m above sea level) in 2006 (RUK07) and 2007 (RUK08), Ngaroto Research Station (37.97^0 S, 175.32^0 E; 84 m above sea level) in 2007 (NGA08) and Massey University Pasture and Crop Research Unit (No. 1 Dairy Farm) (40.38^0 S, 175.58^0 E; 18 m above sea level) in 2007 (MAS08). The latter was situated in the Manawatu Region on a Manawatu fine sandy loam (Dystric Fluventric Eutrochrept). Both Rukuhia and Ngaroto Research Stations are situated in the Waikato Region on a Horotiu sandy loam soil (Vitric Orthic Allophanic) and an Ohaupo silt loam (Typic Orthic Allophanic), respectively (Hewitt, 1998).

While the Manawatu site had a history of long term pasture, both Waikato ENVs had been in long term maize monoculture for up to 25 yr. History of the Waikato sites closely mirrors a typical monoculture farming system common in NZ for maize grain production, while the Manawatu site characterises silage production under a dairy farming system. The selected sites can also be considered to be a fair representation of soil and weather conditions for their respective regions. Rukuhia and Ngaroto respectively typify low and high potential yielding sites for their region. The Manawatu site was selected due to its contrasting climatic conditions and shorter season length compared to Waikato. The higher latitude of the Massey University site (40^0 S) compared to the Waikato sites (38^0 S), results in cooler mean spring temperatures and a more rapid decline in solar radiation and temperature during the autumn. The lower spring temperatures mean that planting in Manawatu is generally later than Waikato.

Data from the four experiments (i.e., years and locations) were treated as independent ENVs (Milliken and Johnson, 1994). Despite the Rukuhia experiment being repeated, the two seasons were quite different, with the first having typical rainfall and the second being extremely dry. The first season was therefore considered to represent a soil ENV with a relatively low yield potential under normal rainfall conditions, whereas RUK08 was characteristic of that same soil in a very dry season.

Prior to planting, soil tests were conducted on each ENV to determine the paddock nutrient level. Soil pH, Olsen P, cation exchange capacity (CEC), base saturation, sulphate-S, total C and N and organic matter in the upper 60 cm were determined in order to calculate fertiliser and lime requirements to ensure non-limiting nutrient supply (Blakemore et al., 1972; Edmeades et al., 1984). The RUK07 experiment received 92, 50 and 50 kg ha^{-1} of N, P and K, respectively, as base fertiliser in the form of Cropzeal (12:10:10) and urea (46-0-0) in early spring. Additionally, at planting, Nitrophoska (12-10-10) was applied as starter fertiliser at a rate of 48, 40 and 40 kg ha^{-1} of N, P and K. When six fully expanded leaves had emerged, 365 kg ha^{-1} urea was applied as a sidedressing. In total, 308 kg N, 90 kg P and 90 kg K ha^{-1} were applied to the crop. Both NGA08 and RUK08 received a total of 324 kg N, 81 kg P and 40 kg K ha^{-1}. Based on initial soil test results, MAS08 did not require base or starter fertiliser, but received a total of 220 kg N ha^{-1} as sidedress.

Soon after base fertiliser application in early spring, the trial area was disc ploughed to 25 cm to incorporate the fertiliser and surface trash. Immediately before planting, the seed bed was cultivated to remove weeds and to loosen the soil. The Waikato experiments were planted using a 2-row Wintersteiger® precision vacuum seeder while the MAS08 experiment was planted using a 2-row cone seeder and thinned to the desired final plant density.

Initial soil water contents and bulk density for each soil horizon within the profile for each PD treatment were measured gravimetrically at or prior to planting. The soil samples were obtained from three horizon layers (0-20 cm, 20-45 cm and >45 cm) using soil cores of 4.8 cm diameter by 5 cm height, taken from the midpoint of each horizon, while the deepest sample was collected from 55 cm depth. The samples were weighed immediately and oven dried to constant weight at 105^{0}C for 24 h.

Weeds were controlled by a combination of 3 l ha^{-1} Roustabout® (840 g a.i. l^{-1} acetochlor) and 3 l ha^{-1} atrazine (600 g a.i. l^{-1} atrazine) applied as a pre-emergent herbicide at planting. Additional weed control was obtained by applying 200 ml ha^{-1} Callisto® (480 g a.i. l^{-1} mesotrione) in combination with 1.5 l ha^{-1} Gesaprim® (500 g a.i. l^{-1} atrazine) as post emergence herbicides prior to canopy closure. Any problematic weeds were subsequently controlled by hand weeding.

Pests such as cutworm were controlled by spraying with Lorsban® 40EC (40 g a.i. l^{-1} chlorpyrifos) between the second (V2) and fourth (V4) leaf stages at a rate of 700 ml ha^{-1}. The treatments were also sprayed (complete leaf cover) with a combination of 500 ml ha^{-1} Opus® (125 g a.i. l^{-1} epoxiconazole SC) and 500 ml ha^{-1} Comet® (250 g a.i. l^{-1} pyraclostrobin EC) to prevent confounding effects of common rust. This was done at approximately V8 stage or earlier if rust infection occurred prior to the V8 stage.

3.3.2 Experimental design and treatments

Four and five PD treatments were established at MAS08 and the Waikato ENVs, respectively. Planting dates were widely spread to include very early, typical and very late PDs for each ENV, and were as follows:

RUK07 - 18 Sept., 11 Oct., 2 Nov., 24 Nov., and 15 Dec., 2006.
RUK08 - 20 Sep., 13 Oct., 1 Nov., 22 Nov., and 13 Dec., 2007.
NGA08 - 21 Sep., 11 Oct., 1 Nov., 22 Nov., and 13 Dec., 2007.
MAS08 - 16 Oct., 6 Nov., 23 Nov., and 10 Dec., 2007.

Hereafter, PD treatments will be referred to as PD1, PD2, PD3, PD4 and PD5, respectively. At MAS08, PD1 was considered missing in subsequent data analyses.

Six single cross hybrids representing three maturity groups; short season (38P05 and 38H20), mid season (36M28 and 36B08) and full season (34D71 and 34P88) were planted in Waikato ENVs. Hereafter, hybrid maturities will be referred to as early, mid and late, respectively. At MAS08, 36M28, 36B08 (late), 38H20, 38P05 (mid) and 39G12 (early) were planted. The later maturity hybrids sown in the Waikato were considered too late and not adapted to the Manawatu Region. An earlier hybrid, 39G12, sown in the Manawatu, was considered too early for the Waikato ENVs. These hybrids were selected from a pool of 29 Pioneer® hybrids that are commercially available in NZ, and were considered representative elite hybrids for their maturity classes.

In order to achieve a uniform plant population density, all plots were planted at 130000 plants ha^{-1} and thinned at the V4 leaf stage to achieve population densities of 110000 plants ha^{-1} for 39G12, 38H20 and 38P05 and 105000 plants ha^{-1} for the rest. These densities were based on agronomic planting density optima required to maximise both grain and silage under unstressed conditions (Genetic Technologies Ltd., 2004, unpublished data). Since grain and silage crops require different planting densities, the selected rates were a compromise between the optima for grain and silage production.

Each experiment was designed as a randomised complete block design with a split-plot treatment arrangement replicated three times. Planting dates were considered as the main plots and hybrids as sub-plots, each randomised within the next higher level. Planting dates were randomized within the field to avoid confounding PD effects with any trends in soil fertility or texture.

Plot sizes varied across ENVs as follows:
RUK07 - 6 rows x 9.5 m long x 0.76 m apart;
RUK08 - 6 rows x 14 m long x 0.76 m apart;
NGA08 - 4 rows x 14 m long x 0.76 m apart;
MAS08 - 6 rows x 10 m long x 0.70 m apart.

Apart from PD and hybrid treatments, all other management factors were held constant. To minimise impact of adjacent treatments, the two outside rows in each plot were considered as borders. Additionally, approximately 1 m at either end of the harvested or sampled plot area was also considered as border. Planting date treatments were separated by an additional four to six border rows on either side of each treatment.

3.3.3 Weather

Daily weather data were collected from planting through to harvesting. Rainfall, air temperature, solar radiation and wind speed were obtained from the nearest National Institute of Water and Atmospheric Research (NIWA) automated weather stations, ranging in distance from 400 m to 12 km from the plots. Temperatures at the level of the apical meristem were recorded for each PD treatment every hour using “WatchDog 100” (Spectrum Technologies®, Inc.) data loggers wrapped in plastic and inserted in the soil at approximately 5 cm depth between rows in the trial plot area. After TI, the loggers were unwrapped, raised 20-75 cm above the ground (depending on apical meristem height) and placed within a radiation shield to measure within-canopy temperature (Plate 3.1). Tassel initiation was taken as the appropriate stage to switch from soil to air temperature recording (Cooper and Law, 1978; Swan et al., 1987;

Wilson et al., 1995), since the growing point is considered to have moved from below to above the soil surface at this stage (Ritchie et al., 1986b). Soil temperature is thus expected to have less influence on development than air temperature after TI. The weather data set included hourly mean soil and canopy temperatures recorded in the plot, and minimum and maximum daily air temperatures, wind speed, solar radiation and rainfall recorded at the nearby weather station. Seven irrigations totalling 178 mm water were applied by overhead sprinklers at MAS08 to prevent the crop suffering from drought stress. Irrigation was not available at the Waikato ENVs.

Plate 3.1 Positioning of a "Watch Dog" temperature logger suspended above the ground but within the crop canopy and apical meristem level.

Temperature data were used to calculate TT as follows:

$\boldsymbol{TT}= \frac{\boldsymbol{Tmax+Tmin}}{\boldsymbol{2}} - \boldsymbol{T_b}$, where T_{max}, T_{min} and T_b are daily maximum, daily minimum and the base temperatures, respectively. If $T_{max} > 30^0$C, then $T_{max} = 30^0$C, and if $T_{min} < T_b$, then $T_{min} = T_b$ (Gilmore and Rogers, 1958). Where necessary, these adjustments were made prior to averaging T_{max} and T_{min}.

3.3.4 Grain yield and grain yield components

At RUK07, a bordered area of 7.6 m^2 (2.5 m x 0.76 m x 4 rows) was hand-harvested for GY at least 2 wk after PM. Harvested areas for the other ENVs were 9.8 m^2 (3.5 m x 0.7 m x 4 rows), 5.9 m^2 (3.9 m x 0.76 m x 2 rows) and 11.9 m^2 (3.9 m x 0.76 m x 4 rows) for MAS08, NGA08 and RUK08, respectively. Number of plants, ears, lodged and barren plants per plot were recorded before harvest on the area designated for harvest. For consistency, ears containing <10 kernels were considered barren (Tollenaar et al., 2004).

Harvested ears were shelled with a portable sheller, and tested for grain moisture and test weight using a GAC 2100 grain analysis meter (DICKEY-john®, Auburn, IL; Plate 3.2). Grain yield and test weight were adjusted to a 14% moisture content basis. Test weight was adjusted for moisture using the function established by Dorsey-Redding et al. (1990):
$TWT = TWT_i + 2.9189 + 0.3404 * (M-14\%)$, where TWT, TWT_i and M are adjusted test weight (kg hl^{-1}), harvest test weight (kg hl^{-1}) and harvest moisture (%), respectively.

Plate 3.2 Measuring grain moisture and test weight using a GAC 2100 meter.

Individual KW was estimated from a random subsample of 1000 kernels from each plot. Number of kernels m^{-2} was estimated as: $\frac{Total\ plot\ grain\ weight\ m^{-2}}{Mean\ plot\ KW}$. Average KN plant^{-1} was estimated as the ratio of KN m^{-2} and plants m^{-2}. Sink size was assumed to be equivalent to GY plant^{-1} (KN x KW (g)). To estimate HI, stover remaining after grain harvest was harvested by cutting the plants at ground level. The plants were immediately weighed to determine fresh weight and a known sub-sample dried to constant weight at 75^{0}C. Harvest index was estimated as the ratio of total grain weight (0% moisture) to total aboveground DM weight at harvest.

3.3.5 Data analysis

Analysis of variance (ANOVA) to determine effects of PD on hybrid performance and their interactions with hybrid maturity was conducted using the Mixed Procedure (Proc Mixed) in SAS (Littell et al., 2006). Hybrid within a maturity group was considered a random factor, while all other factors were treated as fixed effects. Where appropriate, estimate and contrast statements in SAS were used to estimate and compare the linear combination of PD and hybrid maturity main effects. Combined analyses across ENVs were conducted to establish the presence or absence of ENV x treatment interaction effects. All data analyses across ENVs resulted in significant ENV x maturity x PD, ENV x maturity or ENV x PD interactions, suggesting that planting or maturity effects were ENV dependent. Due to the significant lack of homogeneity of variance across the four ENVs, data from each ENV were eventually analysed separately (Gomez and Gomez, 1984). The General Linear Model Procedure of SAS (Proc GLM) was used to regress the measured traits on PD, while simple correlations (Proc CORR) were used to determine the nature of relationships among the measured traits. Where correlations among traits were similar across ENVs and/or hybrid maturities, data were aggregated across ENVs and maturity classes.

For data presentation, only results that were significantly different from each other or from zero at $P<0.05$ level are discussed. The following notation *, ** and *** is used to indicate significance at $P<0.05$, $0.001<P<0.01$, and $P<0.001$ respectively, while NS refers to $P\geq0.05$.

3.4 RESULTS

3.4.1 Weather data

Table 3.1 and Table 3.2 illustrate the average monthly weather data during the experiment period for the four ENVs (RUK07, RUK08, NGA08 and MAS08). Average T_{max} for September and October at MAS08 were at least 1-2^{0}C lower than the Waikato ENVs. Thereafter, maximum temperatures across the four ENVs were comparable, ranging from 18-27^{0}C. Average September T_{min} values were however higher at MAS08 (6.8^{0}C) compared to the three Waikato ENVs (≤6.2^{0}C). Long term weather data (Table 1.1, Chapter 1) showed that, on average, Manawatu generally experienced higher T_{min} values in October. MAS08 T_{max} values were also lower than the other three in May, consistent with the higher latitude and shorter season length. Despite the long term January Waikato average T_{max} values of 24^{0}C (NIWA, 2001), NGA08 and RUK08 experienced much higher temperatures in a dry hot summer of 2008 (27±0.4^{0}C). Thereafter, temperatures were about 1^{0}C higher than average, before reaching the long term average in April. The T_{max} values for MAS08 were 1-2^{0}C warmer than average between January and March while RUK07 temperatures were consistent with long term averages for the region, except for the abnormally low night temperatures in December that averaged 9^{0}C vs. the long term average of 12^{0}C (see Table 1.1, Chapter 1, for comparisons with long term weather data).

Table 3.1 Average monthly minimum (Min) and maximum (Max) temperature data for RUK07, MAS08, NGA08 and RUK08 during the experiment periods of 2006-07 and 2007-08.

	RUK07		MAS08		NGA08		RUK08	
Month	Max	Min	Max	Min	Max	Min	Max	Min
				^{0}C				
September	17.0	6.2	15.4	6.8	16.7	6.2	16.5	5.6
October	17.1	7.8	15.6	7.3	17.6	7.9	17.3	8.2
November	18.7	10.7	18.4	8.1	20.2	8.2	19.9	8.3
December	19.7	8.8	21.7	12.0	22.7	12.6	22.5	12.5
January	23.4	13.4	23.7	13.5	27.0	13.8	26.6	13.6
February	24.5	12.1	24.0	13.0	25.2	13.2	24.7	13.2
March	23.4	12.1	23.1	12.7	25.1	11.5	24.5	11.7
April	19.8	7.8	19.9	10.1	20.8	10.2	20.5	10.1
May	18.1	7.2	15.2	4.7	16.6	4.8	16.0	5.0
Average	20.2	9.6	19.7	9.8	21.3	9.8	20.9	9.8

Table 3.2 Mean monthly radiation and total rainfall data for MAS08, RUK07, RUK08 and NGA08 during the experiment periods of 2006-07 and 2007-08.

	Radiation				Rainfall			
Month	RUK07	MAS08	NGA08*	RUK08	RUK07	MAS08	NGA08	RUK08
	MJ m^{-2} d^{-1}				mm			
September	13.9	12.8	12.8	12.8	27.6	39.8	60.4	52.2
October	15.9	15.2	18.2	18.2	125.0	62.0	97.1	97.8
November	19.2	23.2	20.7	20.7	74.8	63.2	39.4	55.6
December	22.6	21.7	21.3	21.3	67.3	44.6	74.6	64.4
January	21.2	23.9	24.4	24.4	115.1	64.0	7.2	7.0
February	21.0	22.3	20.4	20.4	37.5	46.0	35.0	40.0
March	15.2	16.6	16.4	16.4	107.8	40.0	16.9	13.8
April	11.7	11.1	11.5	11.5	32.7	94.4	133.7	133.8
May	8.0	8.1	9.3	9.3	62.0	43.6	97.8	80.0
Total	4501.6	4713.2	4717.4	4717.4	649.8	497.6	562.1	544.6

* Data obtained from same source as RUK08

Rainfall was moderate at RUK07, while drought occurred at the other three ENVs. Unlike MAS08 where irrigation was applied, for RUK08, and to a lesser extent NGA08, water stress was severe during the late December to late March period. RUK07 was the only ENV to have experienced at least some precipitation every 2 wk during the growing season. Between 1 January and 31 March (critical flowering and grain setting period covering all PD treatments) the total amounts of precipitation were 260, 150, 59 and 61 mm for RUK07, MAS08, NGA08 and RUK08, respectively. Mean temperatures for the three "08" ENVs were between 1 and 2^0C higher than long term average during the critical growing period, thereby increasing evapotranspirative demand.

Solar radiation was greatest between early November and late February, with the highest readings recorded between 22 December and 5 January. RUK07 experienced the least average solar radiation during the critical grain filling period of January to March (19 MJ m^{-2} d^{-1}) compared to ≥20 MJ m^{-2} d^{-1} for the other ENVs. A significant reduction in solar radiation in April was evident under all ENVs, with values falling to about 50% of January levels.

3.4.2 Grain yield

Across the four ENVs, the highest GYs were observed at MAS08 and the least at RUK08 (Table 3.3). Both RUK07 and MAS08 showed significant maturity x PD interactions where late hybrids significantly outyielded early hybrids when planted early (Figure 3.1a,b).

Table 3.3 Grain yields at 14% moisture content (t ha^{-1}) for NGA08, RUK08, RUK07 and MAS08 over 4 or 5 planting dates (PDs); se is pooled standard error across PD treatments for all hybrids, and a and b are linear and quadratic regression estimates, expressed as t d^{-1} from PD1.

	NGA08	RUK08	RUK07			MAS08		
			Hybrid maturity					
PD	All	All	Early	Mid	Late	Early	Mid	Late
t ha^{-1}								
1	13.94	6.80	13.23	14.66	15.26	-	-	-
2	13.40	6.42	13.91	14.65	14.07	14.94	16.43	17.71
3	13.07	6.15	13.41	13.06	13.19	17.33	18.62	18.17
4	11.78	7.28	11.96	12.05	11.66	15.59	17.65	17.76
5	11.13	4.72	12.40	11.02	0.00	14.53	11.89	12.45
se	0.311	0.278	0.350	0.350	0.350	1.015	0.718	0.718
Significance								
PD	***	***	***			***		
Maturity	NS	NS	**			NS		
PD*Maturity	NS	NS	***			***		
Regression coefficients								
Linear	***	*	NS	***	**	NS	-	-
a	-0.035	-0.016	-	-0.045	-0.148	-	3.733	2.700
Quadratic	-	-	NS	-	-	NS	***	*
b	-	-	-	-	-	-	-0.006	-0.004
r^2	0.73	0.17	-	0.89	0.69	-	0.96	0.83

With late planting, earlier hybrids either significantly exceeded or matched later hybrids for GY. At RUK07 late hybrids resulted in a yield decline of 24% between PD1 and PD4 to a yield of 12 t ha^{-1} whereas for early hybrids the decline was only 10% to 12 t ha^{-1} for the same period. On the other hand, while yield reduction between PD4 and PD5 at MAS08 was only 7% for early hybrids, it was ≥30% for mid and late hybrids.

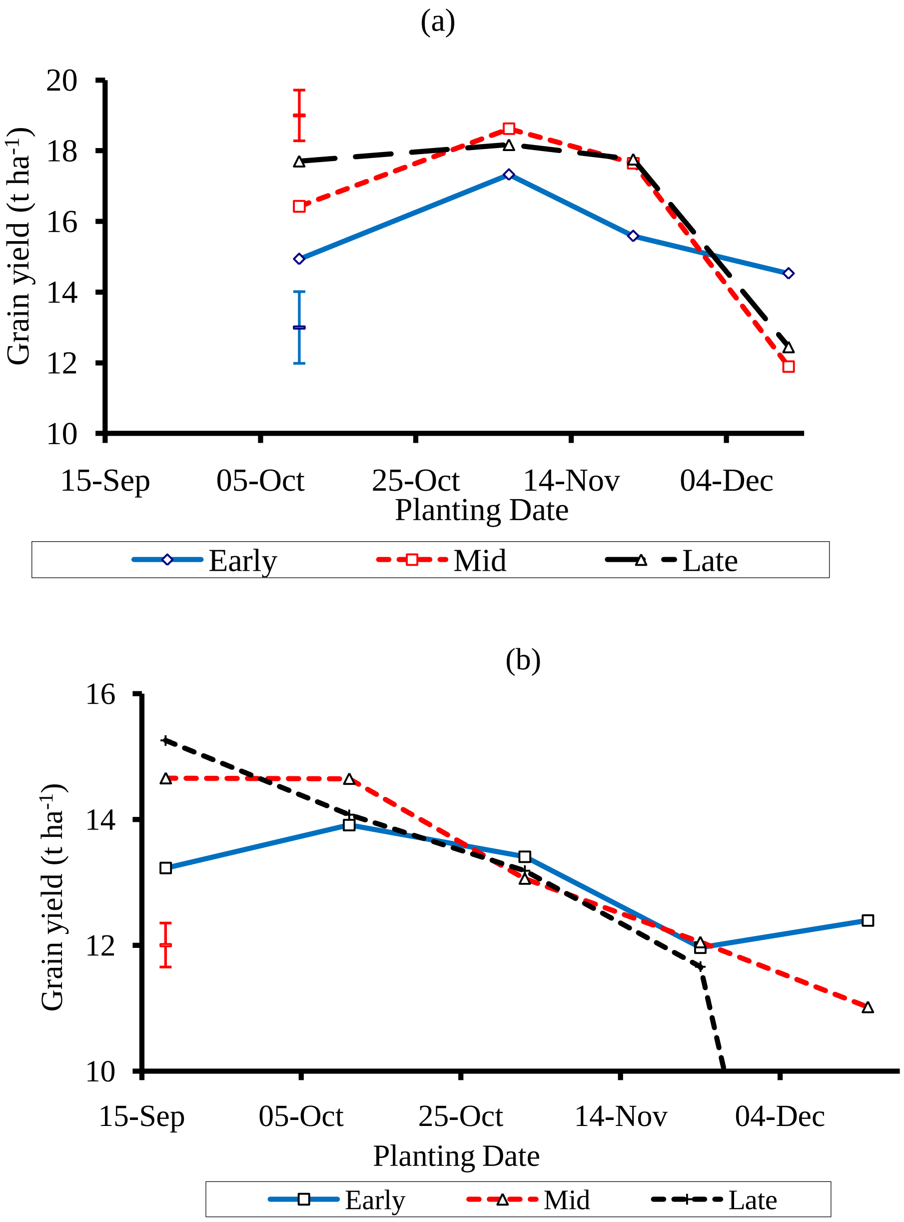


Figure 3.1 Grain yields at (a) MAS08 and (b) RUK07 across 4 and 5 planting dates (PDs), respectively. The vertical bars show standard errors (±se) over treatment means. The red bar in (a) is the pooled se across PDs for mid and late hybrids whereas the blue bar represents se for early hybrids.

At RUK07, mid and late maturity hybrid yields declined linearly at -45 and -150 kg ha^{-1} d^{-1} of planting delay. With PD5, frost damage occurred before late hybrids had matured. This was considered a crop failure, resulting in the resultant grain not harvested, and was awarded a zero GY. Regression analysis showed no significant trend with PD for the early group (Table 3.3; Figure 3.1b).

At MAS08, mid and late hybrids showed a significant quadratic yield response to PD and yields were maximised around PD3 (6 November) before declining (r^2=0.96***;

r^2=0.83*, respectively, Figure 3.1a). Similar to RUK07, early hybrids' GYs at MAS08 were reasonably stable across all PD treatments. Even though Figure 3.1a shows a trend towards a yield maximum with intermediate PDs, GY for all but PD3 were not significantly different. Yield response of early hybrids to PD was thus noticeably less than for later hybrids. However, when planting was conducted at the optimum time, early hybrids were outyielded by later hybrids.

At RUK08 and NGA08, the three maturity groups responded similarly to PD, where the highest yields of 13.9 t ha^{-1} were obtained under PD1 conditions at NGA08. A linear response to PD delay was observed at NGA08, resulting in 35 kg ha^{-1} d^{-1} yield loss across all hybrids (r^2=0.73***). Despite the very low summer rainfall (see Table 3.2), NGA08 was only moderately affected by moisture stress due to its superior soil physical characteristics relative to RUK08 (see Plate 3.3; also see Plate 3.4). This was also evidenced by the shallower depth of Rukuhia soils (45 cm) compared to those at Ngaroto (>1.5 m) which could hold approximately 119 mm of total available water in the top 1 m compared to 76 mm for RUK08 (Landcare Research, 2009). Maize roots at NGA08 are likely to have grown beyond the 1 m depth, potentially tapping into additional soil water reserves.

At RUK08 where moisture stress effects were larger, yields ranged from approximately 5 to 7 t ha^{-1}, with the highest yields achieved under PD1 and PD4. Despite the higher yields with PD4, a significant, but weak linear relationship constituting a yield loss of 16 kg ha^{-1} d^{-1} was observed across all hybrids (r^2=0.17*). At both RUK08 and NGA08 ENVs, effects of PD on yield were considered to have been confounded by water stress.

Across all ENVs, significant correlations were observed between GY and KN $plant^{-1}$ (r=0.90***), KW (r=0.76***), barrenness (r=-0.72***), ears $plant^{-1}$ (r=0.76***) and % green LA at maturity (r=0.59***; see section 4.4.12, Chapter 4 for details on this trait).

Plate 3.3 Comparison of RUK08 (top) vs. NGA08 (bottom) soils.

3.4.3 Biomass yield at grain harvest

Total biomass yields were highest at MAS08 and least at RUK08, thus resembling GY responses. The PD x maturity interactions were only significant at RUK07 and RUK08 (Table 3.4). At MAS08 there was a significant quadratic response of biomass yield to PD (r^2=0.54***), with maximum yields of 28 t ha^{-1} obtained at PD4. A significant linear response was observed at NGA08 where biomass yield changes of -70 kg ha^{-1} d^{-1} (r^2=0.68***) from the initial 24 t ha^{-1} were obtained with early planting.

Table 3.4 Biomass yields for NGA08, RUK08, RUK07 and MAS08 over 4 or 5 planting dates (PD); se is the pooled standard error across PD treatments for all hybrids; a and b are linear and quadratic regression estimates, expressed as t d^{-1} from PD1.

	NGA08	MAS08	RUK07			RUK08		
			Hybrid maturity					
PD	All	All	Early	Mid	Late	Early	Mid	Late
t ha^{-1}								
1	23.6	-	20.8	23.4	24.6	14.2	14.4	16.4
2	23.7	26.4	22.2	23.1	23.6	15.9	15.4	14.0
3	22.5	27.3	21.4	22.3	21.5	14.5	13.6	13.4
4	19.4	27.7	19.2	20.3	21.5	13.9	13.4	14.8
5	18.5	23.0	20.1	18.9	-	10.8	11.5	10.8
se	0.54	0.75	0.87	0.87	0.87	0.91	0.91	0.91
Significance								
PD	***	***		***			***	
Maturity	NS	NS		NS			NS	
PD*Maturity	NS	NS		***			***	
Regression coefficients								
Linear	***	**	NS	**	*	NS	**	**
a	-0.070	2.846	-	-0.053	-0.052	-	-0.037	-0.051
Quadratic	-	**	NS	-	-	NS	NS	-
b	-	-0.005	-	-	-	-	-	-
r^2	0.68	0.54	-	0.71	0.59	-	0.60	0.63

At RUK07 and RUK08, both mid and late hybrids displayed a linear response of total biomass to PD, whereas response of early hybrids was not significant. Mid and late hybrids recorded yield changes of about -50 kg ha^{-1} d^{-1} at RUK07. It should, however, be noted that for the latter class, the estimate considers only the first four PD treatments since PD5 was considered a missing value for biomass yield. Considering the significant decrease in yields between PD4 and PD5 for mid hybrids, it is highly likely that if the late group had been harvested, the rate of yield decrease would have been even greater. A higher rate of yield decline for late (-51 kg ha^{-1} d^{-1}) vs. mid hybrids (-37 kg ha^{-1} d^{-1}) was observed at RUK08 where yields averaged 14 t ha^{-1}. When compared to RUK07, drought appeared to have reduced total biomass yields for RUK08 by about 40% (Table 3.4).

3.4.4 Harvest Index

The highest values for HI were attained at MAS08 (0.53) and least at RUK08 (0.39). At RUK08 and NGA08, late hybrids had significantly lower HI values than earlier hybrids.

The respective values for early, mid and late hybrids were 0.41, 0.40 and 0.36 for RUK08 and 0.53, 0.51 and 0.49 for NGA08. However, at MAS08 where moisture conditions were optimum throughout the whole growing period, HI was similar across maturities. Other than RUK07, all ENVs showed no PD x maturity interaction for HI.

At MAS08, where HI averaged 0.53, 0.57, 0.53 and 0.48 for PD2 through to PD5, a highly significant quadratic relationship between PD and HI was observed (r^2=0.74***). Using regression analysis, 3 November was estimated as the PD that maximised HI for all hybrids in this ENV (Figure 3.2a).

At NGA08 and RUK08 a significant PD effect on HI existed, with respective values for PDs 1-5 being 0.51, 0.49, 0.50, 0.52 and 0.52 (NGA08) and 0.39, 0.37, 0.38, 0.45 and 0.37 (RUK08).

At RUK07 neither linear nor quadratic regressions described the relationships between HI and PD for all three maturities (Figure 3.2b). Harvest index for early, mid and late hybrids ranged from 0.53-0.55, 0.50-0.55 and 0.47-0.54, respectively.

Over the four ENVs, significant correlations were observed between HI and KN plant^{-1} (r=0.80***), KW (r=0.64***), barrenness (r=-0.78***), senescence at 50% grain fill (r=-0.77***) and senescence at PM (r=-0.69***) (see section 4.4.12, Chapter 4 for details on senescence).

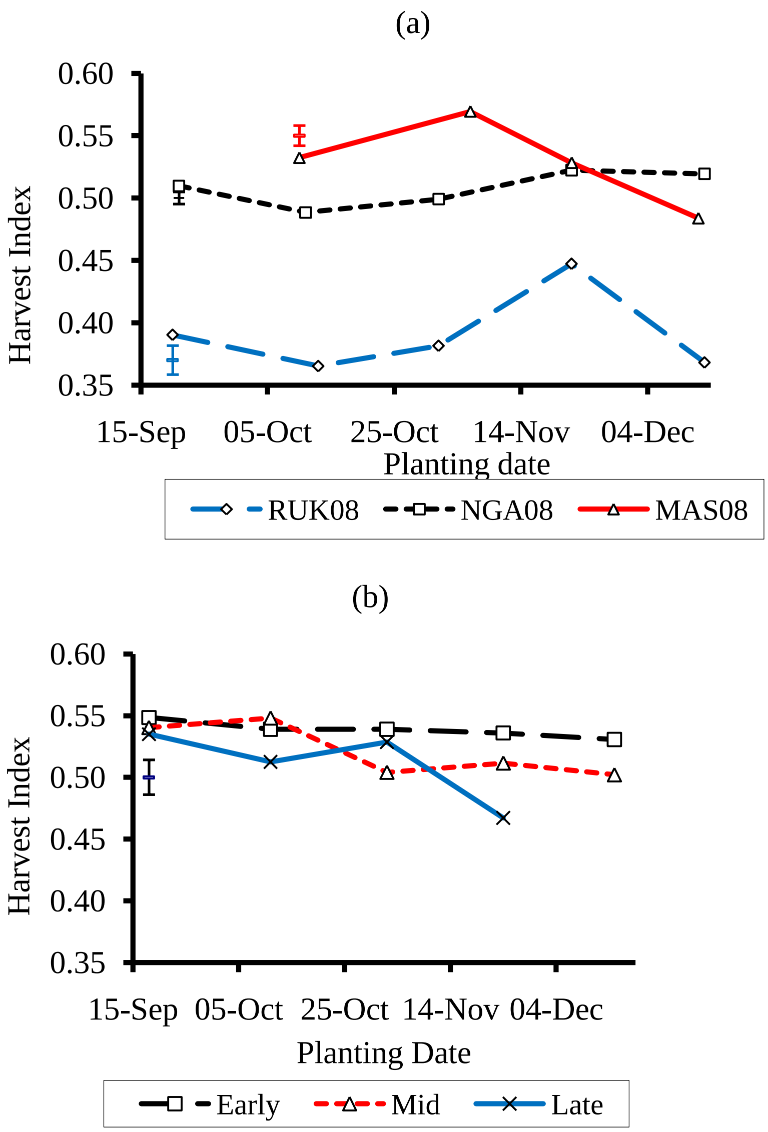


Figure 3.2 Harvest index for (a) RUK08, MAS08, NGA08 and (b) RUK07 across four or five planting dates. The vertical lines show standard errors (±se) across treatment means.

3.4.5 Kernel weight

The highest average KW values were observed at MAS08 (0.36 g) and lowest at RUK08 (0.16 g). Environmental differences in KW generally mimicked GY, consistent with the high correlation between GY and KW (r=0.76***). At MAS08 and RUK08, maturity x PD interactions were significant. While KW tended to decline with PD at MAS08, early hybrids were more stable across PDs. For instance, KW in early hybrids varied from 0.26-0.32 g vs. 0.24-0.36 g for late hybrids (Table 3.5). Consequently, a quadratic response of KW to PD was observed for mid (r^2=0.77*) and late hybrids

(r^2=0.82*) (Figure 3.3a). At RUK08, early hybrids, however, showed the largest weight variation of 0.16-0.25 g kernel^{-1} vs. mid hybrids which ranged between 0.20-0.25 g kernel^{-1}. Again, early hybrids showed no PD effect on KW, but there was a general decrease in KW with delays in planting for late (-0.8 mg kernel^{-1} d^{-1}; r^2=0.50*) and mid hybrids (-0.6 mg kernel^{-1} d^{-1}; r^2=0.45*; Figure 3.3b).

At RUK07 and NGA08, KW was also strongly influenced by PD similarly across hybrids, with the largest and least observed under early and late plantings, respectively. These ranged from 0.29-0.25 g kernel^{-1} (RUK07) or 0.28-0.23 g kernel^{-1} (NGA08). Linear regression adequately explained response to PD, resulting in an average KW decrease of 0.5 and 0.6 mg kernel^{-1} d^{-1}, for RUK07 and NGA08, respectively.

Table 3.5 Kernel weight for NGA08, RUK08, RUK07 and MAS08 across four or five planting dates (PDs); se is pooled standard error across PD treatments for all hybrids.

	NGA08	RUK08	RUK07	MAS08
PD		g		
1	0.28	0.23	0.29	-
2	0.28	0.23	0.28	0.34
3	0.27	0.23	0.27	0.33
4	0.26	0.23	0.25	0.31
5	0.23	0.17	-	0.24
se	0.009	0.006	0.019	0.015
Significance	***	***	***	***
Maturity				
Early	0.25	0.21	0.26	0.30
mid	0.29	0.23	0.29	0.29
Late	0.26	0.21	-	0.31
se	0.144	0.008	0.019	0.003
Significance	NS	NS	NS	NS
PD*Maturity				
Significance	NS	***	NS	***

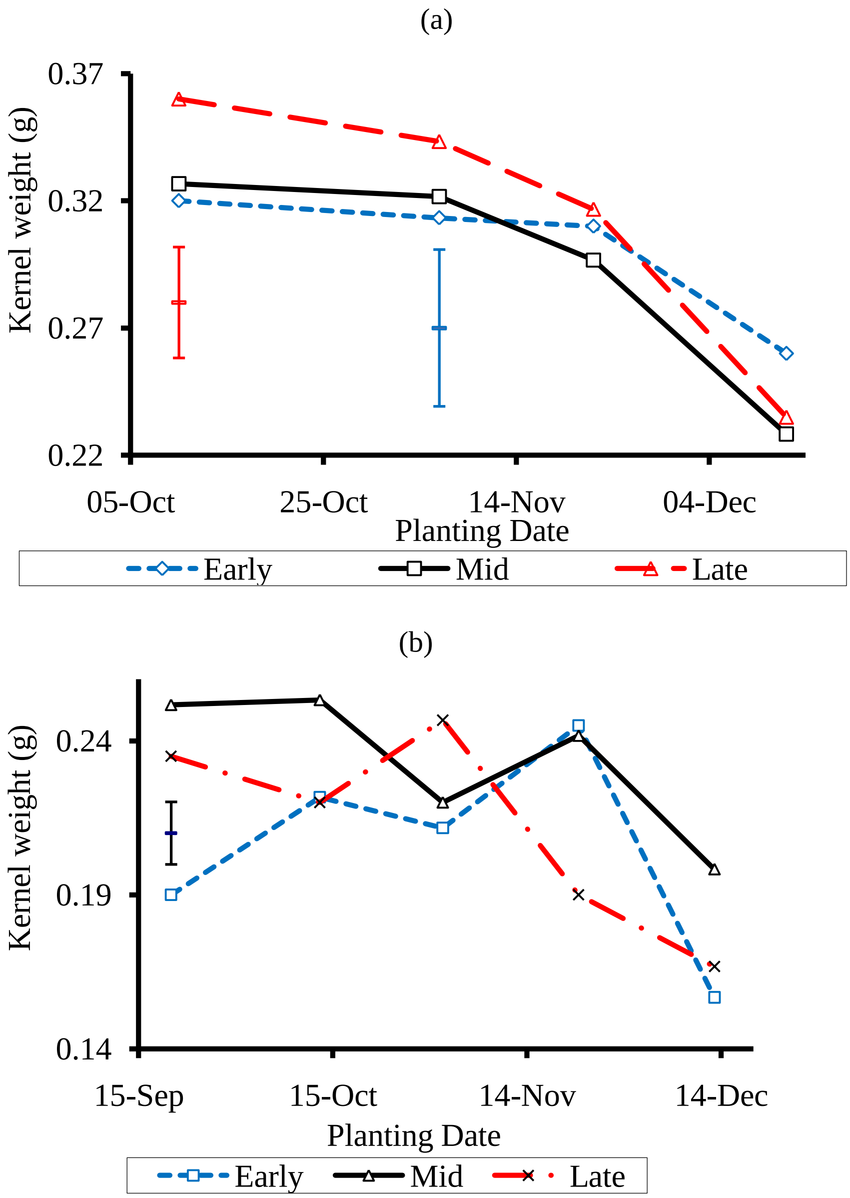


Figure 3.3 Kernel weight at (a) MAS08 and (b) RUK08 over 4 and 5 planting dates (PDs). The vertical bars show standard errors (±se) across treatment means. The blue bar in (a) is se across PDs for early hybrids whereas the red bar is the pooled se across PDs for mid and late hybrids.

3.4.6 Ears per plant and barrenness

Ratios of ear to plant number of >1 indicate prolificacy while values <1 imply barrenness. Across PDs, the average number of ears plant^{-1} were 1.06 (MAS08), 0.98 (NGA08), 0.97 (RUK07) and 0.90 (RUK08). The observed data indicated some prolificacy at MAS08 and an average of 10% barrenness at RUK08. The effect of PD on barrenness at MAS08, NGA08 and RUK07 was independent of hybrid maturity.

The range of barren plants between PDs was 0-3, 1-3 and 2-6% for the three ENVs. The highest proportion of barren plants at RUK07 (6%) was observed under the PD1 treatment. This was unexpected and was likely due to an interaction between chemicals applied for common rust control and environmental factors. The other four PD treatments at RUK07 resulted in <3% barrenness.

RUK08 experienced significantly more barrenness than the other three ENVs. Overall, PD2, 3 and 5 had higher barrenness levels than PD1 and 4, reflecting the timing of rainfall events. A significant maturity x PD interaction was observed, with late hybrids experiencing barrenness more under stressful conditions (e.g., PD2 and PD5). The proportion of barren plants from PD1 through to PD5 for the three maturities was: 4, 9, 10, 7 and 9% (early); 3, 12, 17, 6, 11% (mid); and 6, 19, 9, 6 and 20% (late). While late hybrids experienced the highest levels of barrenness under PD2 and PD5, the mid class was worst affected at PD3 and this could be attributed to timing of silking relative to rainfall events. Early maturities however had a similar level of barrenness across PDs. Only late hybrids showed a relationship between barrenness and GY (r=-0.82**).

3.4.7 Kernel number per ear

Kernel number per ear reflected plant sink size in single eared hybrids. The highest average KN ear^{-1} (402) was recorded at MAS08, vs. 392 observed at NGA08 and RUK07, and 259 at RUK08. The KN ear^{-1} ranking over ENVs was consistent with the high correlation between KN ear^{-1} and GY (r=0.84***). RUK07 and RUK08 showed significant maturity x PD interactions for KN ear^{-1}. Despite the significant PD effects at MAS08 (**) and NGA08 (***), there was no consistent pattern to the decrease in KN ear^{-1}. The average KN ear^{-1} for the first to last PD were 410, 398, 414 and 388 for MAS08 and 427, 394, 377, 380 and 383 for NGA08.

Similarly, at RUK08 there was no consistent pattern of variation with PD for all hybrids. Kernel number ear^{-1} varied from a high of 300 (PD1) to 256 (PD4) in early hybrids. For late hybrids, KN ear^{-1} was also highest at PD1 (300) and lowest under PD3 (203). More stable values of 226 to 254 were observed with mid hybrids.

At RUK07 while KN ear^{-1} for early hybrids ranged from 372 to 413, there was no clear trend with PD. However, for mid and late maturity hybrids where KN ear^{-1} varied from 349 to 390 and 389 to 488, significant linear decreases of 0.5 and 1.5 kernels ear^{-1} d^{-1} were recorded for mid and late hybrids, respectively.

3.4.8 Kernel number per plant

At MAS08 the average KN plant^{-1} was 426 while NGA08, RUK07 and RUK08 averaged 385, 381 and 234 kernels, respectively. Individual ENV analysis revealed significant PD x maturity interactions at RUK07 and RUK08. At MAS08, KN decreased linearly from a maximum of 447 to 377 at a rate of 1.2 kernels plant^{-1} d^{-1} (r^2=0.34**). Though significant, at the moderately drought stressed NGA08 ENV, the relationship between KN plant^{-1} and PD was not consistent, varying from 419, 388, 369, 370 and 382 for PDs 1 to 5, respectively.

At RUK07, linear reductions of 0.5 (r^2=0.50*) and 1.1 kernels plant^{-1} d^{-1} (r^2=0.75**) were evident for mid and late hybrids, unlike early hybrids which were more stable. The highest values were 452 and 382 kernels plant^{-1} for late and mid classes.

At RUK08, the highest KN plant^{-1} was obtained with either PD1 or PD4 for mid and late hybrids. There was a significant variation in KN plant^{-1} between PDs for late vs. early and mid hybrids. Kernel number plant^{-1} for PD1 to PD5 averaged, respectively, 287, 253, 260, 237 and 248 (early); 245, 211, 200, 237 and 201 (mid); 276, 193, 185, 290 and 182 (late).

3.4.9 Grain yield per plant

Plant sink size, or GY plant^{-1} was expressed as the product of dry KW (g) and KN plant^{-1}, and was significantly higher at NGA08 (101 g) and RUK07 (104 g) than RUK08 (50 g). At 130 g plant^{-1}, MAS08 had the highest average sink size. At MAS08 and NGA08, sink size plant^{-1} significantly decreased with PD as follows: 150, 144, 134 and 90 g (MAS08); 115, 108, 101, 95, 87 g (NGA08). The average sink size for early, mid and late hybrids were 124, 131 and 134 g (MAS08); 99, 101 and 103 g (NGA08); 100, 109 and 108 g (RUK07); 52, 51 and 47 g (RUK08).

At RUK07 and RUK08, a significant PD x maturity interaction for GY plant^{-1} existed. While mid and late hybrids at RUK07 followed the same trend as MAS08 and NGA08, ranging from about 120 to 90 g plant^{-1}, early hybrids showed a quadratic response in the order, 103, 107, 102, 88 and 92 g plant^{-1} for PD1 to PD5. At RUK07, there were no significant differences in sink size between mid and late hybrids across the five PD treatments. Early hybrids had significantly lower sink sizes under the first two PDs, after which, no differences existed among the three maturities. At the drought stressed RUK08 ENV, GY plant^{-1} of early hybrids showed marginal response to PD between PD1 and PD4, only varying between 54 and 58 g. Sink size under PD5 was significantly lower at 39 g. Mid and late hybrids' GY plant^{-1} response to water stress was greater, averaging 61, 54, 44, 57 and 40 g (mid); 65, 43, 45, 55 and 30 g (late), for PD1 to PD5.

3.4.10 Kernel number m^{-2}

Average KN m^{-2} was highest at MAS08 (4567) and lowest at RUK08 (2526). NGA08 and RUK07 had comparable counts of 4167 and 4175, respectively. These values were consistent with the observed GYs in the four ENVs, reflecting the significant correlation with GY (r=0.89***). In all ENVs, there was a general decline in KN m^{-2} with PD (Table 3.6).

The MAS08 ENV, with its optimal moisture conditions, showed a significant linear decrease in KN m^{-2} from 4787 to 4043, at a rate of -13 kernels m^{-2} d^{-1}. At NGA08, where drought stress was moderate, no clear trend existed with PD. The lowest values were observed with PD3 (3890 kernels m^{-2}), suggesting that factors such as moisture stress were influencing these values. Neither linear nor quadratic relationships between PD and KN m^{-2} were observed.

A significant PD x maturity interaction for KN m^{-2} was evident at RUK07 and RUK08. Neither linear nor quadratic fits were significant for the early group at RUK07 and for all hybrids at RUK08. Even though KN m^{-2} for early hybrids at RUK07 varied from 4575 to 4135 for PD3 and PD4 respectively, there were no differences among remaining treatments. Kernel numbers for both mid and late hybrids decreased linearly with PD, where the late class responded more strongly at rates of -12 kernels m^{-2} d^{-1} vs. -5 kernels m^{-2} d^{-1} for mid hybrids. The observed responses were similar to those reported for GY.

Table 3.6 The effect of planting date (PD) and hybrid maturity on KN m^{-2} for treatments sown on 4 or 5 PDs at NGA08, RUK08, RUK07 and MAS08; a and b are linear and quadratic regression coefficients, expressed as kernels m^{-2} d^{-1} from PD1.

	NGA08	MAS08	RUK07			RUK08		
			Hybrid maturity					
PD	All	All	Early	Mid	Late	Early	Mid	Late
Kernels m^{-2}								
1	4526	-	4254	4025	4858	3172	2618	2944
2	4195	4787	4396	4096	4578	2796	2253	2062
3	3890	4761	4575	3844	4304	2870	2133	1975
4	3996	4675	4135	3732	4080	2621	2525	3095
5	4127	4043	4478	3615	-	2738	2142	1947
se	179.7	217.7	360.9	360.9	360.9	268.8	268.8	268.8
Significance								
PD	***	***		***			***	
Maturity	NS	NS		NS			NS	
PD*Maturity	NS	NS		***			***	
Regression coefficients								
Linear	NS	**	NS	*	**	NS	NS	NS
a	-	-12.9	-	-5.4	-11.7	-	-	-
Quadratic	NS	NS	NS	-	-	NS	NS	NS
b	-	-	-	-	-	-	-	-
r^2	-	0.33	-	0.50	0.75	-	-	-

RUK08 failed to exhibit a clear pattern of KN m^{-2} by PD across all maturities. Early hybrids showed some stability, particularly between PD2 and PD4 (2621-2870 kernels m^{-2}). However mid and late hybrids produced a significantly higher KN under PD1 and PD4 conditions, reflecting their greater yield potential. The difference between the highest and the lowest values was 19 and 37% for mid and late groups, respectively.

3.4.11 Test weight

Average test weights were highest at NGA08 (72.6 kg hl^{-1}). Respective values for MAS08, RUK07 and RUK08 were 71.8, 70.3 and 70.5 kg hl^{-1}. Across the four ENVs, there was a general decline in test weight with PD. At the same time, PD x maturity interactions existed in all four ENVs. Though weak, there was a positive correlation between test weight and KW (r=0.42***). The relationship was much stronger at MAS08 (r=0.66***) where GY and KW decreases with PD were greatest.

At MAS08, test weights for early hybrids averaged >76.5 kg hl^{-1} for the first three PDs, dropping to 69 kg hl^{-1} under PD5. Mid and late hybrids showed a significant linear response to PD, decreasing by about 0.10 kg hl^{-1} d^{-1} from the initial 73 kg hl^{-1} obtained under PD2 conditions for both classes.

At RUK07, a significant linear relationship between test weight and PD was observed. The rates of test weight decline were significantly higher for early hybrids (-0.12 kg hl^{-1} d^{-1}), compared to mid (-0.09 kg hl^{-1} d^{-1}) and late groups (-0.07 kg hl^{-1} d^{-1}). The initial test weight values for the three groups were 77, 75 and 73 kg hl^{-1}.

At NGA08, a linear decrease of 0.09 and 0.08 kg hl^{-1} d^{-1} from the original 76 and 75 kg hl^{-1} at PD1 was observed for early and late hybrids. The mid group showed a quadratic response, reaching a maximum of 74 kg hl^{-1} with 11 October PD, and finally falling to 68 kg hl^{-1} with December plantings.

At RUK08, even though late hybrids showed a general decline in test weight over time, the response could not be described using either linear or quadratic relationships. Test weight values ranged from 73 to 71 kg hl^{-1} between PD1 and PD4, declining to 68 kg hl^{-1} at PD5. A quadratic response of test weight to PD was evident for early and mid hybrids, resulting in maximum values of 73 kg hl^{-1} predicted to occur if the two hybrid maturities were planted around 20 October.

3.5 DISCUSSION

3.5.1 Grain yield, yield components and grain traits

With the exceptions of RUK08, which was significantly affected by drought stress, and some very late planting treatments, GYs achieved in the experiments were considerably greater than the national average of about 11 t ha^{-1} (MAF, 2008). The general quadratic response in yield to PD for mid and late hybrids under high latitude conditions of Manawatu likely meant that planting too early decreased yields through source limitation attributed to low temperatures and reduced canopy development (Al-Darby and Lowery, 1987; Otegui et al., 1995b). This contrasted with Waikato where mean spring temperatures rose more rapidly, resulting in more favourable conditions for plant establishment and early growth. Other than low spring temperatures, the Manawatu ENV was also characterised by very wet soil conditions during the early spring.

With late planting, lower GYs were most likely due to the grain filling phase coinciding with diminishing temperature and radiation levels. Similar results have been reported under high latitude conditions of Northern Europe where adverse conditions occur during late grain filling conditions (Ruget, 1993). Effects of latitude are generally more pronounced towards the end of the season as weather conditions deteriorate, resulting in a reduction in RUE (Andrade et al., 1993a) and slowed grain growth due to low IPAR and temperature (Ruget, 1993). The effects were thus more evident in Manawatu where average radiation and mean temperature during the second half of grain filling in PD5 were 11 MJ m^{-2} d^{-1} and 14.8^{0}C, vs. 20 MJ m^{-2} d^{-1} and 18.1^{0}C experienced with PD1. Mean temperatures below 16^{0}C can decrease RUE in maize (Wilson et al., 1995). Low temperatures during grain filling can also cause photoinhibition (van Hasselt and van Berlo, 1980) and reduce photosynthetic activity (Duncan and Hesketh, 1968; Long et al., 1983; Smillie et al., 1988; Ying et al., 2000).

In 2006/07 (typical season), late hybrids of maize significantly outyielded earlier hybrids when planted early, and vice versa under delayed planting conditions. Compared to their later maturing counterparts, lower yields in early hybrids, particularly when sown early in the season, are usually due to source limitation caused by smaller LA, lower daily IPAR and cooler temperatures (Stone et al., 1999). The smaller ear size also means that under optimum conditions, early hybrids are also sink-limited. In

Waikato, flowering dates of all hybrids, particularly the early group, coincided with the highest irradiance levels just after 22 December (summer solstice), which should have resulted in the greatest assimilate flux to the ear. Due to their larger LA (see section 5.4.10, Chapter 5), bigger sink size and longer grain filling duration, late hybrids would have accumulated more IPAR plant^{-1}, resulting in higher rates of DM accumulation compared to early hybrids.

Across all ENVs, early hybrids yielded consistently over all PDs, suggesting that early hybrids had an appropriate source-sink balance for stable yields, but that they failed to fully exploit the additional growth conditions that were available when planted early. Source limitation was observed by Otegui and Melón (1997) who reported limited LA elasticity in early hybrids. When planted early, short duration hybrids should therefore be planted at higher densities to compensate for the lower LAI levels and the genetic limitations to maximum ear size. Later hybrids however, responded to a longer growing season with greater GY when sown early. Hybrid choice should therefore be based on a capability to fully exploit the potential growing ENV for its whole duration (Capristo et al., 2007).

The effects of late planting were greater for late compared to early hybrids. Under stress conditions caused when grain filling coincides with a period when demand of kernels exceeds assimilate supply, kernels compete for those assimilates, resulting in kernel abortion, especially among tip kernels, and in shrivelled grain (Gambín et al., 2008). Due to their early flowering, shorter grain filling duration and smaller sink size, grain filling in early hybrids is more advanced, reducing GY response to the more moderate degree of assimilate starvation. The longer duration of late hybrids also exposes them for more time to adverse conditions, thereby amplifying yield decline. For these reasons KN and KW were also more stable in early, than in mid and late hybrids.

The risk of late season frost must be considered when planting is delayed. While long duration hybrids can be grown in Waikato, frost is a major risk in this region that averages 11 ground frosts between April and May, compared to only five in Manawatu (NIWA, 2001). This was evidenced by the late planting treatment at RUK07 which was frost damaged on 29 May before reaching maturity. Unless late hybrids are planted by mid October, they should be replaced by earlier maturing hybrids to minimise risk of autumn frost and also reduce potential of higher artificial grain drying costs (also see Table 6.6 and Table 6.13, Chapter 6).

The weak association between GY and PD at RUK08 indicated that yield variation was influenced more by water stress than PD. The general linear decline in GY with PD under these conditions as well as at NGA08 reflected a growing water deficit for late PD treatments. Early planted treatments would have developed a well established deep root system by January (driest month) allowing them to access residual moisture from depth. Unlike late PDs, early planted maize also completed a significant part of their life cycle before water stress became severe. The observed GY response to PD at RUK08 and NGA08 was therefore confounded by drought effects. This highlights one of the challenges when agronomic field experiments are being used to make crop management decisions.

Drought effects were more apparent at RUK08 than NGA08 (see Plate 3.4). This was due to differences in soil water holding capacity. For instance, using data from PD1 and PD2, while volumetric water contents at RUK08 (top 1 m) varied significantly during the season, falling from 26% on 28 February to 12% on 17 March, changes at NGA08 were negligible, where on average, 21, 23 and 21% volumetric soil water contents were recorded on 9 and 28 February and 17 March (data not shown). For both NGA08 and RUK08, at least 40 mm of rainfall fell around the 28 February sampling compared to almost no rain for other sampling times.

At RUK08, the positive attributes of rainfall events during flowering on GY were more apparent largely because of failure of the sandy soil to store water for long term crop use under drought conditions (Swain and Scotter, 1988). Due to similarity in yield performance between hybrid maturities in this ENV, there were no advantages in planting late hybrids other than for risk management. Since the adjustment of PD to synchronise water stress sensitive stages with periods of adequate moisture levels cannot be foreseen at planting time, on soils likely to experience water deficit (e.g., shallow sands), it may be strategic to plant different hybrid maturity mixes on the same date to reduce stress risk at flowering.

Plate 3.4 Crop status for PD5 at RUK08 (top) and NGA08 (bottom) on 25 March 2008.

Kernel number plant^{-1} (or m^{-2}) is the major driver of GY. The strong correlation between KN m^{-2} and GY (r=0.9***) agrees with other reports in the literature (e.g., Otegui et al., 1995a; Bolaños and Edmeades, 1996). However, a higher correlation between GY and KN vs. KW was expected since KN is generally more variable than KW and readily responds to varying environmental and management factors at flowering, especially in older hybrids (Borrás et al., 2009).

Kernel number plant^{-1} and m^{-2} usually reflect assimilate availability. At RUK08, the lowest KN were obtained when either rainfall or irradiance levels around flowering were low. PD3, which only received a total of 3.8 mm rainfall and averaged 25 MJ m^{-2} d^{-1} solar radiation 1 and 2 wk either side of flowering, and PD5 which received more rainfall (23 mm) but lower irradiance (18 MJ m^{-2} d^{-1}), had the lowest KN. On the other hand, PD4 and PD1 with more rainfall (>20 mm) and radiation (>24 MJ m^{-2} d^{-1}), had the highest KN. Increased KN therefore reflected the greater flux of assimilate to the ear at flowering time. A direct positive influence of IPAR on kernel set around silking is also reported in literature (Kiniry and Knievel, 1995; Andrade et al., 2000).

Despite the challenging environmental conditions at RUK08, KW was generally stable across PDs, with the exception of PD5 which had significantly smaller kernels because of temperature limitations during the last half of grain filling. Kernel weight is more strongly conserved than KN in response to varying environmental conditions (Westgate et al., 1997; Boomsma et al., 2009; Borrás et al., 2009). Gambín et al. (2008) thus found that while enhanced CGR kernel^{-1} increased KW in sorghum, this was not the case in maize since maximum kernel size was defined primarily during the lag phase of grain filling.

The highest test weights were observed under early planting conditions, after which a reduction equivalent to approximately 0.1 kg hl^{-1} d^{-1} ensued, causing the test weight of some treatments to fall below the minimum acceptable industry standard of 67 kg hl^{-1} (Grain Trade Australia, 2004). Influences of environmental conditions on test weight have been documented by Robutti (1995) and Lee et al. (2007). Early hybrids generally had higher test weights than later hybrids, resulting in more rapid decline in test weight with PD in the early group.

A positive correlation between test weight and KW, though not supported by other reports in the literature (e.g., Lee et al., 2007; Sandhu et al., 2007), was likely due to the more regular shape and complete filling of larger kernels, resulting in tighter and more uniform packing compared to the smaller irregular kernels. Despite the relationship, test weight was not greatly affected by those factors that influenced KW (e.g., water stress). This agrees with Sala et al. (2007b) who found that, unlike KW, restricting kernel expansion during grain filling did not affect test weight.

Drought and late planting generated similar changes in GY and yield components of early hybrids, suggesting that strategies that mitigate the limited source and sink capacities of early hybrids should help reduce effects of both stresses and enhance yields under optimum conditions. For example, sink limitation due to small ears in early hybrids (Westgate et al., 1997; Sarlangue et al., 2007) can be ameliorated by increasing planting densities. Sarlangue et al. (2007) also reported that early hybrids, when compared to late hybrids, exhibited a greater response in total biomass and HI, to increases in plant densities. Conversely, later hybrids, because of the greater number of potential grain filling sites per plant and their larger physical size, had lower HI at higher densities due to barren plants.

3.5.2 Total aboveground biomass and harvest index

In general, total aboveground biomass responded to PD and ENV in a similar manner to GY. This was expected since the two are not independent of each other as aboveground biomass is the sum of grain and stover yields. The decrease in biomass with PD, particularly for mid and late hybrids, was an indication of the greater impact of late planting on late maturing hybrids, especially under diminishing IPAR and temperature conditions. As with GY, total biomass for early hybrids was stable across PDs, a result that could also be attributed to an appropriate balance between source and sink.

The quadratic response of total biomass to PD across most ENVs was largely due to decreased LA in early PD treatments (see section 5.4.10, Chapter 5) which was caused by low temperatures during early growth and was one of the causes of reduced CGR (see section 4.4.2, Chapter 4). Lower biomass yields with delayed planting, particularly at MAS08, can be attributed to reductions in IPAR and RUE due to lower radiation levels and temperature, which consequently result in poor grain filling. Reduced LA expansion lowers IPAR (Muchow and Carberry, 1989), while the low mean temperatures during grain filling under late planting conditions ($<16^0$C) likely affected grain filling by reducing RUE (Wilson et al., 1995).

In the Waikato ENVs where autumn temperatures did not decrease as fast as in Manawatu, the decline in HI with PD observed in late hybrids was likely due to higher early season temperatures enhancing vegetative growth (see section 5.4.6, Chapter 5) while low temperatures and reduced IPAR during grain filling both reduced grain content somewhat. Early hybrids, because of their shorter duration and lower LAI (see section 5.4.10, Chapter 5), produced less biomass than late hybrids, even when conditions were conducive for production of more biomass (also see section 4.4.2, Chapter 4, for comparison of preflowering CGRs of different hybrid maturities). This could be considered low biomass plasticity (Major et al., 1991; Sarlangue et al., 2007). However, the smaller sink size also meant that assimilate demand met supply, resulting in reasonable grain fill, stable yields and consequently, stable HI values.

An important future research priority would be to reassess the optimal planting density for short duration hybrids when they are being planted early. Four of the five PD treatments at RUK08 had stable HI values (0.37-0.39). This resembles observations by Tollenaar (1989c) under drought conditions. PD4, however, resulted in a higher HI (0.45). The anomaly was attributed to a significant reduction in non-reproductive plant biomass with PD as moisture conditions deteriorated and temperatures rose above the long term mean prior to flowering. Sensitivity of vegetative growth to temperature effects has also been documented by Stewart et al. (1998a) who also observed significant detrimental effects of temperature variation during vegetative growth. Also, PD4 had the highest GYs which reflected higher precipitation (36 mm) within the critical 30 d period centred on silking (Kiniry and Knievel, 1995) compared to ≤20 mm for other treatments. The observation illustrates the significance of the period surrounding flowering in determining GY. The observed high correlations between HI and KN, barrenness and senescence at 50% grain fill suggested that conditions during early phases of grain filling were more important in determining HI than those coinciding with later stages (Gambín et al., 2008).

3.6 CONCLUSIONS

Maize GY and the associated yield components followed either a linear (Waikato) or quadratic (Manawatu) response to PD. In Waikato, GYs were maximised when planting occurred between 20 September and 13 October compared to 6 November for Manawatu. In Manawatu, planting three weeks earlier than 6 November resulted in yield losses of 14, 12 and 2.5% for early, mid and late hybrids. A two week planting delay after this caused on average, 6% yield reduction across all hybrids. Under higher latitude conditions (Manawatu) grain and total biomass yields responded in a quadratic manner to PD and this was attributed to lower early season temperatures which reduced canopy development and CGR whereas diminishing temperatures ($<15^0$C) and solar radiation (<11 MJ m^{-2} d^{-1}) during grain filling reduced RUE under late plantings. In Waikato, effects were weaker since spring temperatures warmed more quickly while radiation and temperature declines in autumn were more moderate.

In Waikato, HI decline with PD was greater for late than early hybrids and this was most likely due to higher early season temperatures enhancing vegetative biomass growth while low temperatures and IPAR during grain filling induced barrenness, kernel abortion or reduced grain filling more in the late hybrid set. When planted late, the higher HI values observed for early hybrids (vs. late hybrids) was largely due to their less vegetative biomass expansion potential under the warmer late planting conditions. The smaller sink size also meant that assimilate demand was smaller, promoting more complete grain fill and thus, more stable HI values under late plantings.

Based on research presented here, late hybrids should only be planted by mid October in Waikato or early November in Manawatu. Early hybrids produced more stable yields when planted late or under water stress conditions, either matching or outyielding late hybrids. The larger sink size potential means that late hybrids are more prone to unfavourable environmental conditions typical of late planting during grain filling. Late planting of longer duration hybrids may also expose them to late season frosts, especially in high risk areas such as Waikato. Early hybrids, because of their shorter duration and smaller sink size, have smaller assimilate demand, more stable yields, KN and total biomass. However, a smaller source and sink size means that early hybrids cannot fully exploit the potential growing ENV when grown early, which also explains their stable yields across all PDs. Sink and source limitation in early hybrids can however be mitigated by modest increases in planting densities without compromising stability of grain and biomass yields.

In moderate water stress situations, drought generally affected late planted crops more than early sown crops since water stress intensified with time. Effects of extreme droughts masked PD effects and favoured early maturing hybrids compared to late hybrids whose assimilate demands occurred later in the season. In risky ENVs such as those prone to drought (e.g., sandy soils), it may be worth planting different hybrid maturity mixes on the same date to reduce risk of stress at flowering. Early planting should be recommended in ENVs likely to dry out in summer to allow roots to develop to depth before soil water reserves become limiting.

Kernel number, which reflects assimilate availability and is highly correlated with GY, was largely influenced by water and irradiance levels around flowering. A combination of 3.8 mm rainfall and 25 MJ $m^{-2}d^{-1}$ solar radiation or 23 mm and 18 MJ $m^{-2}d^{-1}$, 1 and 2 wk either side of flowering resulted in the lowest KN, while rainfall >20 mm and solar radiation >24 MJ $m^{-2}d^{-1}$ during the same growth stage resulted in the highest KN. Since late planting is usually associated with reduced soil moisture, temperature and radiation during grain filling, early planting is key to improved KN, and consequently, high GY.

CHAPTER 4: THE EFFECT OF PLANTING DATE ON MAIZE PHENOLOGY, THERMAL TIME DURATIONS AND GROWTH RATES

4.1 ABSTRACT

Field experiments were conducted in Waikato and Manawatu over two cropping seasons, differing primarily in rainfall, to establish how planting date (PD) influenced maize (*Zea mays* L.) phenological and growth processes across a range of environmental conditions.

A base temperature of 8^0C (T_b8) adequately estimated thermal time (TT) durations for maize development for the emergence-flowering phase and leaf senescence while T_b0 was more satisfactory for estimating grain filling and drydown. Tassel initiation (TI) was estimated indirectly using:
Leaf number at TI = 0.54 x final leaf number - 1.01 (r^2*=0.67***).*

In Waikato, delayed planting reduced the emergence-flowering duration by -1.1 (^{0}Cd)d^{-1} possibly due to declines in leaf number and phyllochron length, whereas in Manawatu, phyllochron variation (42-50^{0}Cd) increased this duration. Sub-optimal temperatures and radiation under late plantings significantly reduced grain filling. Differences in hybrid maturity were mainly related to variation in the grain filling duration rather than the emergence-flowering duration.

When rainfall between emergence and flowering was ≥234 mm, increases in average daily irradiance (19.5-21.4 MJ m^{-2} d^{-1}) and mean temperature (15-18^{0}C) increased pre-flowering CGR by 1 g m^{-2} (^{0}Cd)$^{-1}$. With late planting, higher pre-flowering radiation (≥21 MJ m^{-2} d^{-1}) and temperatures (≥17^{0}C) increased CGR while low post-flowering radiation (13 MJ m^{-2} d^{-1}) and temperature (15.7^{0}C) reduced CGR. Kernel growth rate (KGR) was more stable across PDs and hybrids when TT was used (0.36-0.38 mg (^{0}Cd)$^{-1}$) vs. days (5-7 mg d^{-1}). Even at relatively low daily irradiances (11 MJ m^{-2} d^{-1}), KGR was not compromised provided temperature was ≥19^{0}C.

More rapid leaf senescence occurred for early and late plantings, and this was attributed to source-sink imbalances caused by assimilate accumulation or shortage. Normal leaf senescence rates were 0.03% $(^{0}Cd)^{-1}$ between anthesis and mid grain-fill, reaching 0.2% $(^{0}Cd)^{-1}$ thereafter. Late planting triggered source limitation that led to assimilate remobilisation (stalk), while early planting promoted net weight gain.

Grain moisture contents at physiological maturity (PM) averaged 30-36%. Higher moistures were observed in late planted and/or source-limited crops. Grain moisture loss rates post PM were adequately predicted using:
*Moisture loss rate = 0.16 * atmospheric relative humidity - 0.03*TT after PM (*R^2=0.88***).

4.2 INTRODUCTION

Maize growth and development in the field are mainly influenced by temperature, radiation, photoperiod and water availability, when nutrients are non-limiting. These factors vary over time, and crops planted at different dates therefore experience contrasting environmental conditions. Among these environmental factors, temperature has the largest influence on crop development as it determines rate of development and duration of phenological phases (Stewart et al., 1998b).

The rate of progress towards a specific development stage (e.g., flowering or PM) varies with temperature, and prediction of important development milestones using real time is of limited usefulness where temperatures vary widely. Thermal time, a means of quantifying rate of development by accumulating the number of degrees above a T_b below which development ceases is therefore preferable. This subject is detailed in Chapter 2. While the advent of TT has been a significant development in predicting calendar dates of key developmental stages, correct choice of T_b is critical. Most investigations of T_b for maize have resulted in a value of 6-8^{0}C (Derieux and Bonhomme, 1982; Warrington and Kanemasu, 1983a,c; Muchow and Carberry, 1989; Ritchie and NeSmith, 1991; Vinocur and Ritchie, 2001) and T_b10, widely used in the US may lead to a significant underprediction of heat units to specific developmental stages in areas of low average temperatures such as NZ.

In order to appropriately position a hybrid within a target ENV, its maturity must be known. Even though the CRM rating system has units of days, it does not equate to absolute physical days to maturity. A system that considers TT requirement to reach specific developmental stages such as silking or PM could help alleviate the shortcomings of the CRM system. Knowledge of TT durations of critical stages of maize development allows a hybrid to be matched to a new ENV for which temperature data are available. Additionally, ability to estimate developmental milestones (e.g., emergence, TI or flowering) helps make informed critical decisions in crop husbandry and harvest prediction that must be taken when selecting hybrids.

While grain crops require kernels to attain full size to give maximum yield, silage maturity occurs when total plant DM is about 85% of the final crop biomass (Bagg, 2001). This stage coincides with 62 to 70% whole plant moisture content (Wiersma et al., 1993; Phipps et al., 2000; Bagg, 2001). Whereas 50% kernel milk line has been considered as the traditional standard to assess the ideal silage moisture range (Crookston and Kurle, 1988), Ma et al. (2006) noted that the method was unreliable, particularly under extreme weather conditions. A more reliable method which takes into account environmental effects is desirable.

Once PM has been achieved, no further changes in grain dry weight occur (Brooking, 1990) and field drydown through grain water loss ensues. Moisture loss rate is more reliant on weather than on genetic or management factors (Schmidt and Hallauer 1966; Hoeft et al., 2000). Knowledge of grain moisture at PM and drydown rates would help simplify prediction of harvest timing and determination of suitability of a hybrid to a new ENV (McPherson and Brooking, 1989). Understanding the basic phenological and growth processes that affect time to maturity, as influenced by variable environmental conditions, is also key to the development of mitigating strategies required to maximise and stabilise yields in cases where planting has been delayed, or where new and untested areas are being sown.

The objectives of this Chapter were to determine:

i. the appropriate T_b for different maize developmental processes under NZ conditions.
ii. how PD affects real time and TT to emergence, TI, anthesis, silking, leaf senescence and PM.
iii. how PD affects whole plant moisture content and grain drydown of hybrids differing in maturity grown under contrasting ENVs.

Like Chapter 3, this paper also seeks to generate data required for development of a decision support tool that will be used to help make specific hybrid x management x environmental decisions. Data from the study will be used to calibrate and validate the phenological and growth sub-models of the CERES-Maize model in Chapter 6.

4.3 MATERIALS AND METHODS

4.3.1 Site and planting details

Weather data, site and planting details and choice of hybrids are fully described in Chapter 3. In brief, weather data were obtained from the nearest NIWA automated weather stations. Additionally, soil temperatures at the 5 cm depth were recorded hourly using “WatchDog 100” (Spectrum Technologies®, Inc.) data loggers. After TI, the loggers were raised 20-75 cm above the ground.

4.3.2 Determination of a suitable base temperature for maize crop development

Base temperatures appropriate for maize in NZ were determined by analyses of TT durations between PD treatments using weather data from RUK07. Base temperature values ranging from 0 to 10^0C were used to calculate TT from planting to emergence; emergence to TI and flowering; and flowering to black layer across the five PD treatments. The value resulting in the lowest coefficient of variation (CV) for each duration was considered the most stable and appropriate T_b for that developmental phase (Bonhomme et al., 1994).

4.3.3 Seedling emergence and tassel initiation

Time to emergence was obtained by recording the number of emerged shoots per 6 m length within the centre two rows of each plot, starting approximately 4-7 d after planting. Emergence was considered as the date when the coleoptiles of 50% of planted seeds had emerged above the soil surface (Otegui et al., 1995a,b).

Time required to reach TI stage at RUK07 and RUK08 was determined for each plot by dissecting 3-4 randomly selected border row plants under a stereoscopic dissection microscope (see Plate 4.1) every 2-3 d, starting immediately after the sixth leaf tip became visible in the whorl. Border rows were initially left unthinned to allow these measurements to be conducted on spare plants. The plants were considered initiated when the growing point on at least 50% of the plants was ≥0.4 mm in length (Siemer et al., 1969; Stevens et al., 1986). After completion of the observations, border rows were thinned to the same stand as the centre rows. The higher population density in the border rows during the first few weeks after the main plots were thinned was not considered to affect the observed plants (Jagtap, et al., 1998).

Plate 4.1 Dissecting a maize plant under a stereoscopic microscope to determine timing of tassel initiation.

Due to the time-consuming nature of the TI determination procedure, actual measurements were only conducted at RUK07 and RUK08. In order to predict TI without dissection in other experiments, the number of visible leaf tips at TI was noted and TI estimated as described in section 4.4.5.

4.3.4 Kernel growth rate during effective grain filling rate

A pilot study was conducted at RUK07 to determine kernel growth rate (KGR) during the effective grain filling stage. Four cobs from border rows were sampled every 21 d during the linear grain filling period, starting approximately 19 d after silking (Brooking, 1990; Maddoni et al., 1998), and ending when the kernel starch milk-line had progressed to the kernel tip. Samples were oven dried to constant weight at 75^0C. Individual KW was obtained by weighing a counted sample of approximately 50 dried kernels from the central part of each of the four cobs (Plate 4.2). These data were used to estimate KGR by fitting a linear regression of KW on TT and on real time.

Plate 4.2 Two dried cobs illustrating kernels removed from the central part of the cob.

4.3.5 Determination of growth genetic coefficients

A low density (4 plants m^{-2}) experiment was established at NGA08 (Plate 4.3), a high yielding Waikato site, to generate hybrid specific genetic coefficient data for use as inputs into the CERES-Maize model using the procedures suggested by Ritchie et al. (1986a). The main purpose of this experiment was to determine maximum grain filling rates under optimum temperature (22-24^{0}C) and solar radiation conditions (>20 MJ m^{-2} d^{-1}) (Wilhelm et al., 1999). Two replications of four rows were planted to coincide with maximum daily temperatures between 20-25^{0}C during grain fill to achieve maximum KN and KW. Potential KN $plant^{-1}$ (G2) and kernel growth rate (G3) for each hybrid were estimated using data from this experiment. Potential KN $plant^{-1}$ was estimated as the maximum obtained from ten randomly selected plants per plot. The ears were manually shelled and kernels counted to establish the KN $plant^{-1}$. Where multiple ears existed, the KN on each ear was recorded separately for purposes of estimating average KN ear^{-1}. For estimating KN $plant^{-1}$, total KN $plant^{-1}$, irrespective of the ear status, was reported.

Plate 4.3 A low density maize plot at NGA08.

To estimate G3, four plants per plot were tagged. Ten kernels from each ear were taken weekly during the effective grain filling stage. Where the plant had multiple ears, only the apical ear was sampled. Husks were gently pulled back on each of the four ears and kernels were removed from the centre part of the ear using a modified screw driver. To minimise desiccation, pest and disease infection, a small amount of vaseline was applied where kernels had been removed. After sampling, the husks were returned and held in place by using a rubber band (Duncan and Hatfield, 1964; Tollenaar and Daynard, 1978a; NeSmith and Ritchie, 1992). Kernels from the four plants were placed in a sealed bag and oven dried at 75^0C to achieve constant weight. Kernel growth rate was estimated by linear regression of KW on TT and real time, d.

Six plants from the low density experiment were randomly selected from each plot for whole plant moisture determination every 7-10 d starting from about 3 wk after silking to PM. The plants were subsampled and oven dried at 75^0C to constant weight. The same procedure was repeated for the second and third plantings at MAS08, where four plants were sampled every 10-12 d. This site was selected due to non-limiting moisture conditions. Whole plant moisture contents at anthesis were estimated from average DM contents at anthesis obtained from RUK07, RUK08 and NGA08 (section 5.4.6, Chapter 5). These data were used to determine silage harvest time for use with the CERES-Maize biomass model outputs as the model is mainly focused on grain and thus, lacks the ability to simulate whole plant moisture content.

4.3.6 Anthesis, silking and physiological maturity

Anthesis and silking dates were recorded when 50% of 40 tagged plants within the centre two rows showed anthers or silks, respectively. Physiological maturity was recorded when ≥50% of the kernels in the central portion of at least two of four randomly selected cobs from border rows showed presence of a black layer at the base of the kernel, indicating termination of kernel biomass accumulation (Daynard and Duncan, 1969; see Plate 4.4).

Plate 4.4 A maize plot at physiological maturity (i.e., 50% kernel black layer).

4.3.7 Crop Growth Rates

Crop growth rates for two developmental periods, (i) emergence to 50% silking and (ii) 50% silking to silage harvest time were computed from the change (delta) in plant dry weight per unit area between the two phenological stages divided by the time elapsed (thermal and real) between these events as follows:

$$CGR = \frac{\delta\ [biomass\ m^{-2}]}{\delta\ [time\ elapsed]}$$

4.3.8 Dry matter remobilisation

Dry matter remobilisation or accumulation during grain filling was calculated as the percentage change in aboveground dry weight between silking and maturity (excluding ear) as follows:

$Remobilisation = \frac{V_{maturity} - V_{silking}}{V_{silking}}$, where $V_{maturity}$ and $V_{silking}$ are non-grain aboveground DM weights at maturity and silking, respectively. A negative or positive result either indicates reserve remobilisation or a net gain in DM accumulation between silking and PM, respectively. Biomass weight at PM was assumed to be equal to biomass at grain harvest.

4.3.9 Leaf senescence

Leaf senescence was estimated at NGA08, RUK07 and RUK08. Average leaf senescence of five consecutive plants per plot was estimated weekly starting at the onset of the linear grain filling period, that is, approximately three weeks after silking, until PM. The senescence process was split into two linear components, approximating to either half of the grain filling stage, in real time, d. The average proportion of senesced LA from the five plants was estimated by visual scores of the leaf fraction that remained green, repeated at 7 d intervals. For each individual leaf, average senesced LA was estimated as the sum of the product of the fraction of the senesced LA and the total area of that leaf when fully expanded. Total senesced plant LA was calculated by summing senesced area of the individual leaves (see section 5.3.5, Chapter 5 for description of LA measurements).

The rate of leaf senescence was calculated by regressing the dead LA on real time (d) and TT (T_b0 and T_b8). Rate of senescence was therefore defined as the % change in green LA $(^0Cd)^{-1}$ (T_b8; see section 4.4.1) relative to maximum LA at silking.

4.3.10 Rate of post-maturity grain drydown

At RUK07, four ears were randomly selected and harvested from the border rows of each plot at PM, hand shelled and the grain bulked to evaluate grain moisture content using a GAC 2100 grain analysis meter (DICKEY-john®, Auburn, IL; see Plate 3.2, Chapter 3). The procedure was repeated every 7 d until the grain had reached approximately 20% moisture content. Rate of drydown was determined by linear regression of the kernel moisture on days or TT (T_b0; see section 4.4.1) after PM. The complete process was only accomplished for the first three planting treatments since grain moisture content remained >25% in the last two plantings because of the decline in seasonal temperatures during drydown.

4.3.11 Data analysis

Data analysis is fully described in Chapter 3. Proc GLM was used to estimate the linear relationships between KGR, CGR and leaf senescence on TT and real time. An ANOVA of the regression slopes was then conducted to establish the effect of PD and maturity on each variable. Multiple-linear regressions were conducted to determine factors that had the most significant influence on plant processes such as rate of grain drydown and aboveground whole plant moisture content. The RSQUARE procedure (SAS Institute, 1995) was then used to select a combination of variables that resulted in the highest R^2. For example, leaf number at TI (data from RUK07) was regressed against final leaf number, TT, photoperiod, real time and actual temperature, to establish the combination resulting in the highest R^2 value. The resultant relationship was then validated against an independent data set from RUK08 through comparison of predicted vs. actual observed data using the root mean square error (RMSE) (see section 5.3.3, Chapter 5) to quantify the variation between the actual and predicted leaf number at TI. Grain drydown rate was regressed on wind speed, cloud cover, relative humidity, solar radiation, sunshine, rain, TT (T_b0 and T_b8), T_{min}, T_{max} and mean temperatures. To determine silage maturity, whole plant moisture DM content data from the low density genotype coefficient experiment and two experiments at MAS08, described in section 4.3.5, was regressed against TT (T_b0 and T_b8) and real time using linear, quadratic or multiple-linear regression, and the Gompertz non-linear function (Emmans, 1981). The Gompertz function is used to describe sigmoidal relationships, typical of grain growth (see section 2.1.1), which is the main growth process occurring during this phase. The established relationship was validated against independent silage harvest data from MAS08, NGA08, RUK07 and RUK08. The Proc RSQUARE Procedure in SAS was also used to establish factors with the largest influence on whole plant drydown. Optimum T_b for each developmental stage was obtained by minimising the CV of estimates for TT durations across different PD treatments.

4.4 RESULTS

4.4.1 Estimation of maize base temperature

Optimum T_b for the durations to observed phenological stages varied from 7.1 - 8.6^{0}C between seedling emergence and flowering (Table 4.1). Based on these results, the widely used T_b8 was considered as adequate to predict all phenological stages other than grain filling. For grain filling, $T_b0.5$ minimised the CV but for simplicity, T_b0 was adopted. Also, T_b0 was used for grain drydown rates (see section 4.4.11) and T_b8 for leaf senescence (see section 4.4.12). Thermal time for total crop cycle duration was thus estimated using a combination of T_b8 (emergence-silking), and T_b0 (grain filling).

Table 4.1 Effect of base temperature (T_b) on the coefficient of variation of thermal time durations of different phenological stages of maize, using data obtained from RUK07. Optimum T_b is shown for each stage.

T_b (^{0}C)	Planting - Emergence	Emergence - Tassel initiation	Emergence - Silking	Emergence - Anthesis	Grain filling
	Coefficient of variation (CV) %				
0	19.7	11.9	9.7	9.1	2.6
6	7.9	6.0	4.8	4.4	5.4
8	7.5	5.3	2.6	2.4	7.9
10	12.1	6.4	3.1	3.5	11.1
Optimum T_b (^{0}C)	**7.1**	**7.9**	**8.6**	**8.3**	**0.5**

4.4.2 Crop growth rate

Crop growth rates for the emergence-silking (CGR_{ES}) and silking to silage harvest time (CGR_{SS}) durations were measured at RUK07, RUK08 and NGA08. Silage harvesting occurred when total plant DM was ~35% (Wiersma et al., 1993), which was usually 10-14 d prior to PM (data not shown). The highest mean CGR_{ES} (21.2 gm^{-2} d^{-1}) was recorded at RUK07, while RUK08 and NGA08 averaged 17.6 and 17.7 gm^{-2} d^{-1}. In TT terms, the respective CGR_{ES} values were 2.21, 1.42 and 1.43 gm^{-2} (^{0}Cd)$^{-1}$. However, CGR_{SS} values were 19.98 (RUK07), 19.25 (NGA08) and 6.55 gm^{-2} d^{-1} (RUK08), while their respective TT values (T_b0) were 1.33, 0.95 and 0.33 gm^{-2} (^{0}Cd)$^{-1}$. When normalised to T_b8 to allow for standardised comparisons with CGR_{ES}, these were 2.04, 1.58 and 0.54 gm^{-2} (^{0}Cd)$^{-1}$. Hereafter, data for CGR_{SS} will only be reported on a T_b0 basis.

When both thermal and real times were considered for CGR_{SS}, only NGA08 showed significant PD x hybrid maturity interactions. However, with CGR_{ES}, significant PD x hybrid maturity interactions were observed in all three ENVs when real time was used, whereas only NGA08 and RUK07 showed significant interactions using TT. Additionally, when CGR_{SS} was considered in real time, values for NGA08 and RUK07 were quite similar whereas when TT was used, CGR_{SS} differed significantly between these sites. For this reason, data will be presented in terms of TT.

PD x hybrid maturity interactions for CGR_{ES} arose in the following manner. A significant quadratic response to PD was observed at NGA08, where mid hybrids attained maximum CGR (1.56 gm^{-2} $(^{0}Cd)^{-1}$) from plantings completed around 6 October compared to 16 and 27 October for early (1.54 gm^{-2} $(^{0}Cd)^{-1}$) and late hybrids (1.71 gm^{-2} $(^{0}Cd)^{-1}$). The lowest average values were obtained from PD5 (1.18 gm^{-2} $(^{0}Cd)^{-1}$). While a linear or quadratic response to PD was not evident for CGR_{SS}, early and late hybrids at NGA08 maximised values under PD1 (1.23 and 1.02 gm^{-2} $(^{0}Cd)^{-1}$ compared to PD3 for mid hybrids (1.15 gm^{-2} $(^{0}Cd)^{-1}$). The least values were obtained at PD5 for early and mid hybrids (0.85 and 0.94 gm^{-2} $(^{0}Cd)^{-1}$), vs. PD4 for late hybrids (0.61 gm^{-2} $(^{0}Cd)^{-1}$). All hybrids showed an unexpected significant decrease in CGR_{SS} under PD2 conditions (see section 4.4.8 for more details about PD2 issues).

At RUK07 early and mid hybrids experienced a significant general linear increase (0.005 gm^{-2} $(^{0}Cd)^{-1}$ d^{-1}) in CGR_{ES} with PD (Figure 4.1a). The initial rates were, respectively, 1.96 and 1.89 gm^{-2} $(^{0}Cd)^{-1}$. Late hybrids, however, showed no clear PD trend, with the lowest value (2.16 gm^{-2} $(^{0}Cd)^{-1}$) attained under PD2 conditions vs. a high of 2.61 gm^{-2} $(^{0}Cd)^{-1}$ under PD4. The remaining PD treatments ranged from 2.22 to 2.43 gm^{-2} $(^{0}Cd)^{-1}$. Unlike CGR_{ES}, on average, at RUK07 late hybrids had significantly lower CGR_{SS} (1.01 gm^{-2} $(^{0}Cd)^{-1}$) than early (1.16 gm^{-2} $(^{0}Cd)^{-1}$) and mid hybrids (1.21 gm^{-2} $(^{0}Cd)^{-1}$). Despite a general increase in CGR_{SS} between PD1 and PD2 (Figure 4.1b), the linear relationship showed a better fit than the quadratic equation, resulting in a decline of about 0.006 gm^{-2} $(^{0}Cd)^{-1}$ d^{-1} of planting delay across all hybrid maturities.

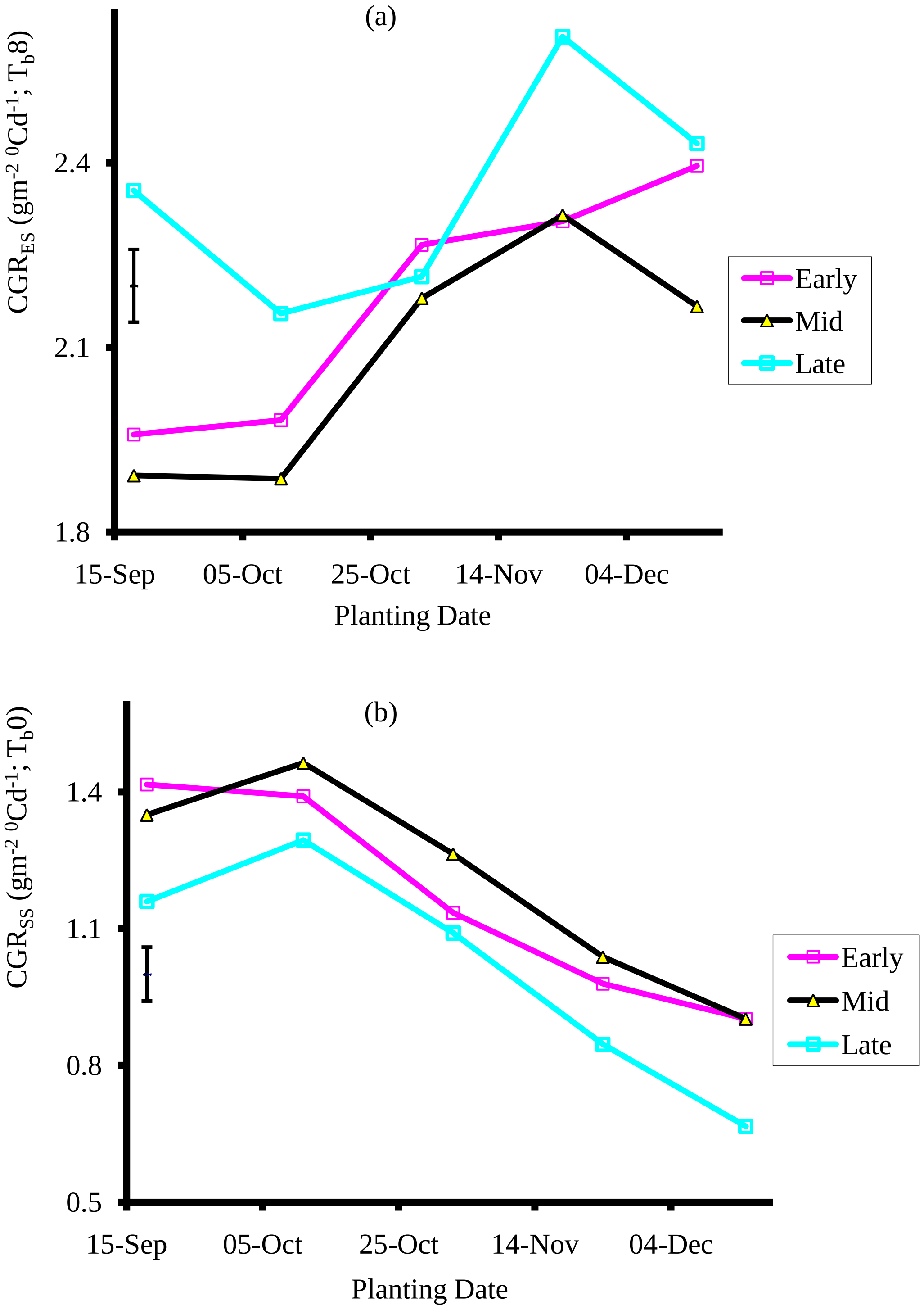


Figure 4.1 Crop growth rates during the (a) emergence-silking period (CGR$_{ES}$) and (b) silking-silage harvest time (CGR$_{SS}$) for RUK07 over five planting dates. The vertical line bars show standard errors (±se) across treatment means.

At RUK08 CGR$_{ES}$ decreased linearly with PD at 0.004 gm^{-2} (^{0}Cd)$^{-1}$ d^{-1}. The highest rates of 1.52 gm^{-2} (^{0}Cd)$^{-1}$ were obtained with early planting compared to 1.2 gm^{-2} (^{0}Cd)$^{-1}$

for PD5 that was severely affected by drought. Even though PD significantly affected CGR_{SS} at RUK08, where PD1 recorded the highest rates (0.46 gm^{-2} ($^0Cd)^{-1}$), and PD3 the lowest (0.20 gm^{-2} ($^0Cd)^{-1}$), the remaining PD treatments ranged between 0.3 and 0.34 gm^{-2} ($^0Cd)^{-1}$ and the inconsistency in PD trend was attributed to drought.

Across ENVs and hybrid maturities, compared to CGR_{SS}, CGR_{ES} was weakly correlated with KN ($r \leq 0.44$***), proportion of senesced LA at maturity (r=-0.47***) and with grain and silage yields (r=0.51***). Among ENVs, the only notable correlation of CGR_{ES} was with SY at NGA08 and RUK08 (r=0.68***). However, correlations between CGR_{ES} and GY were positive (r=0.61***) at NGA08 but negative (r=-0.39*) at RUK07. Across sites, CGR_{SS} was highly correlated with KN ($r \geq 0.78$***), grain and silage yields ($r \geq 0.83$***), senesced LA at anthesis or maturity ($r \leq -0.63$***), assimilate remobilisation (r=-0.61***), HI (r=0.81***) and KW (r=0.62***).

4.4.3 Kernel growth rate during linear grain filling

Using real time, there was a significant interaction between PD and hybrid maturity on KGR (Table 4.2). Kernel growth rates for early and late hybrids decreased linearly with PD from the initial 7.1 and 6.2 mg d^{-1}. On the other hand, rates for mid hybrids initially increased with PD, attaining a maximum growth rate of 7.2 mg d^{-1} under the PD3 treatment. By PD5, growth rates for the three maturities had dropped to between 4.8 and 5.1 mg d^{-1}. However, when TT (T_b0) was used, KGR was found to be independent of PD and maturity, averaging 0.37 mg ($^0Cd)^{-1}$. Use of TT to estimate KGR across the five PD treatments resulted in a CV of 2.2% vs. 12.5% for real time.

The follow-up low density experiment planted at NGA08 under PD3 environmental conditions resulted in moderately higher kernel filling rates. Kernel growth rates for early and mid hybrids (TT) were 0.42 mg ($^0Cd)^{-1}$, while late hybrids averaged 0.37 mg ($^0Cd)^{-1}$. In real time, the respective growth rates were 8.2, 8.2 and 7.3 mg d^{-1}. Similarly, KN $plant^{-1}$ obtained from this experiment were much higher than those reported in section 3.4.8 (Chapter 3). The observed results, which were eventually used for model evaluation are shown in Table 6.4 (Chapter 4).

Table 4.2 Kernel growth rate based on either thermal (T_b0) or real time, d, for RUK07 over 5 planting dates; se is standard error across PD treatments for all hybrids.

	Method			
	Thermal	Real time		
		Maturity		
PD	All	Early	Mid	Late
	mg (^{0}Cd)$^{-1}$		mg d^{-1}	
1	0.38	7.13	6.94	6.20
2	0.38	6.50	7.07	6.03
3	0.37	6.27	7.17	5.45
4	0.37	5.68	6.05	4.88
5	0.36	4.98	5.14	4.75
se	0.087	0.309	0.309	0.309
	Significance			
PD	NS	***	***	***
Maturity	NS	NS	NS	NS
PD*Maturity	NS	*	*	*

4.4.4 Thermal time from planting to emergence

On average, a greater TT duration from planting to seedling emergence was observed at MAS08 (79^{0}Cd) compared to the three Waikato sites which ranged between 67 and 70^{0}Cd. Of the four ENVs, only MAS08 showed a significant PD x maturity interaction for this duration. For example, late hybrids emerged quicker under PD4 treatment (62^{0}Cd) compared to early and mid classes (68^{0}Cd). While this difference was statistically significant, the magnitude was small in real time (<1 d) and was therefore not pursued further.

In Waikato (NGA08, RUK07 and RUK08), emergence was more rapid in the very late plantings compared to early plantings. For example, at RUK08 TT requirement fell from 74 to 56^{0}Cd for PD1 vs. PD5. Thermal time requirement for seedling emergence decreased linearly with PD at rates of 0.15, 0.18 and 0.22 (^{0}Cd)d^{-1}, respectively for NGA08 (r^2=0.53***), RUK07 (r^2=0.68***) and RUK08 (r^2=0.79***).

4.4.5 Predicting time of tassel initiation

In the absence of dissection data, findings from this research showed that final leaf number was the best predictor of TI, using the equation: *Visible leaf tip number at TI =*

0.54 x final leaf number - 1.01 (r^2=0.67***). Across all ENVs, NGA08 had the highest average thermal requirement to reach TI (361^0Cd) while RUK07, RUK08 and MAS08 recorded 338, 347 and 340^0Cd. When only common hybrids were compared at all sites, MAS08 had the largest TT requirements (354^0Cd), compared to RUK07 (325^0Cd), RUK08 (331^0Cd) and NGA08 (347^0Cd). In real time, these differences were quite small, being less than 2 d.

At the drought stressed RUK08 ENV, significant PD x maturity interactions for TT to TI occurred (Table 4.3). Significant linear declines in TI TT duration with PD were observed for early (-0.6 (^{0}Cd)d^{-1}), mid (-0.8 (^{0}Cd)d^{-1}) and late (-0.9 (^{0}Cd)d^{-1}) hybrids. Despite all maturities revealing a significantly lower TT requirement under PD4, mid hybrids displayed the largest decline between PD3 and PD4 (14%, Table 4.3). This resulted in mid hybrids reaching TI at almost the same time as early hybrids under PD4 (294 vs. 282^0Cd).

Table 4.3 Thermal time requirement from emergence to tassel initiation for NGA08, RUK07, MAS08 and RUK08 over 4 or 5 planting dates (PDs); se is standard error across PD treatments for all hybrids.

	NGA08	RUK07	MAS08	RUK08		
	Hybrid maturity					
PD	All	All	All	Early	Mid	Late
	^{0}Cd					
1	370	334	-	346	378	422
2	351	344	329	337	369	416
3	359	356	325	313	341	359
4	336	335	329	282	294	325
5	389	322	378	312	341	371
se	8.3	11.0	6.9	9.0	9.0	9.0
	Significance					
PD	***	***	***	***	***	***
Maturity	NS	NS	NS	*	*	*
PD*Maturity	NS	NS	NS	***	***	***

At MAS08, NGA08 and RUK07, there was no clear trend of TT to TI with PD. Across these ENVs, the largest variation among PDs was recorded at NGA08 (336 (PD4) vs. 389^0Cd (PD5)). In real time, both treatments required 25 d to attain TI. Average photoperiod lengths prior to TI for the two PDs were comparable (14.8 and 14.6 h, respectively). The respective average leaf numbers were also similar (18.4 vs. 18.5; see section 5.4.8). At RUK07 a maximum duration to TI of 356^{0}Cd occurred under PD3, whereas the highest TT requirement to TI was evident under PD5 conditions at MAS08. At RUK08, a significant correlation between mean soil temperature around TI and TT for the emergence-TI phase (r=-0.53***) was observed. Across all ENVs, TT to TI was highly correlated with TT from emergence to anthesis (r=0.84***), and with final leaf number (r=0.67***; see section 5.4.8, Chapter 5).

4.4.6 Thermal time from emergence to silking

All hybrids at RUK07 and NGA08 responded similarly to PD irrespective of maturity (Table 4.4). At RUK07 the thermal requirement to silking decreased linearly by 1 (^{0}Cd) d^{-1} (r^2=0.39***). At NGA08, a weak quadratic response to PD (r^2=0.2*) was observed. Duration from emergence to silking decreased linearly up to PD4 (-1.1 (^{0}Cd)d^{-1}, r^2=0.30**) before increasing at PD5 to reach magnitudes similar to the first PDs.

Table 4.4 Thermal time (T_b8) requirement from emergence to silking for MAS08, NGA08, RUK07 and RUK08 over 4 or 5 planting dates (PDs); se is standard error across PD treatments for all hybrids.

	NGA08	RUK07	MAS08			RUK08		
			Hybrid maturity					
PD	All	All	Early	Mid	Late	Early	Mid	Late
			^{0}Cd					
1	881	860	-	-	-	849	887	938
2	866	862	676	721	783	837	868	944
3	838	837	692	720	757	801	853	889
4	813	820	699	739	776	773	816	884
5	868	773	769	826	865	794	815	873
se	3.0	4.6	8.1	5.7	5.7	7.7	7.7	7.7
			Significance					
PD	***	***	***	***	***	***	***	***
Maturity	***	**	*	*	*	**	**	**
PD*Maturity	NS	NS	**	**	**	*	*	*

At MAS08 there was a general tendency for an increase in TT to silking with PD. Early hybrids required 13% more TT (7 d) to attain silking at PD5 compared to PD2, though trends with time were inconsistent. However, a quadratic regression fit was observed with late (r^2=0.97***) and mid hybrids (r^2=0.95***). Based on the regression estimates, TT requirement to silk decreased to reach minimum levels between 1 and 4 November, before reaching a maximum with the 10 December plantings.

At RUK08, similar to RUK07 observations, all hybrids revealed a significant linear response to PD, resulting in TT reductions. Early hybrids had the lowest response rates (-0.83 (^{0}Cd)d^{-1} **) compared to mid and late hybrids (-0.93*** and -0.91 (^{0}Cd)d^{-1} **).

4.4.7 Anthesis-silking interval

Significant interaction effects between maturity class and PD for ASI were evident at RUK08. While no trend in ASI with PD was observed across maturities, the late group had on average, longer ASIs (12^{0}Cd; 0.9 d) compared to early (7^{0}Cd; 0.5 d) and mid hybrids (3^{0}Cd; 0.3 d). On the other hand, PD effects on ASI were significant at RUK07 and NGA08, where values across PDs ranged from 5 to 19^{0}Cd (0.5-1.8 d) and 8 to 15^{0}Cd (0.7-1.1 d) for the two ENVs. In all three ENVs, there was no clear trend of ASI with PD.

Across the three ENVs where both silking and anthesis were measured (NGA08, RUK07 and RUK08), there was a strong correlation between silking and anthesis TT durations (r=0.96***). Thermal time to anthesis was more strongly associated than TT to silking with leaf number (r=0.75*** vs. 0.57***), TT to TI (r=0.84*** vs. 0.68***) and TT to PM (r=0.46*** vs. 0.09^{NS}).

4.4.8 Thermal time from silking to PM, and grain moisture at PM

The duration of grain filling, measured from 50% silking to the stage when 50% of kernels exhibited black layer, was more stable across PDs when T_b0 was used rather than T_b8 or real time. Though significant, differences in grain filling durations using T_b0 were usually small. In all ENVs, there were significant maturity x PD interactions on grain filling duration.

At MAS08, grain filling duration was more stable across PD treatments for the early hybrids (1180-1205^{0}Cd) compared to mid and late hybrids which ranged from 1177-1388^{0}Cd and 1234-1408^{0}Cd (Table 4.5). The mid and late groups showed a significant quadratic response to PD and the highest thermal requirement for grain filling was estimated to occur by planting on the 31st October (r^2=0.96***) or 8 November (r^2=0.87**), PDs which coincided with the highest GYs (see section 3.4.2, Chapter 3). Early hybrids at RUK08 also showed a similar response to PD, demonstrating maximum duration of grain fill when planted on 26th October (r^2=0.93***). Other than the mid and late (MAS08) or early hybrids (RUK08), there were no significant linear or quadratic relationships between grain filling duration and PD for all other maturities or ENVs. The shorter grain filling duration observed under PD2 at NGA08 was due to plants senescing earlier than expected. While NGA08 experienced some drought stress, efforts to establish what caused this response (e.g., presence of a hard pan or a high soil bulk density that exacerbated drought stress effects) proved inconclusive. In all ENVs, grain filling duration, particularly for late, and to a smaller extent, mid hybrids, was generally shortest under late planting conditions (PD5).

Table 4.5 Thermal time requirement from 50% silking to physiological maturity (50% black layer) for MAS08, NGA08, RUK07 and RUK08 over 4 or 5 planting dates (PDs); se is standard error across PD treatments for all hybrids.

	MAS08			NGA08			RUK07			RUK08		
	Hybrid matuity											
PD	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late
	^{0}Cd											
1	-	-	-	1185	1243	1355	1231	1248	1322	1025	1148	1297
2	1204	1353	1317	1138	1226	1344	1171	1250	1333	1105	1274	1365
3	1201	1388	1408	1212	1284	1379	1154	1238	1283	1169	1231	1304
4	1205	1311	1367	1231	1315	1387	1162	1297	1357	1112	1141	1120
5	1180	1177	1234	1196	1264	1321	1228	1259	-	892	1120	1321
se	28.2	19.9	19.9	21.4	21.4	21.4	20.0	20.0	20.0	22.9	22.9	22.9
	Significance											
PD		***			***			***			***	
Maturity		NS			*			*			***	
PD*Maturity		***			***			***			***	

Significant correlations between grain filling TT duration and KW (r=0.51***), KN plant^{-1} (r=0.33***), LAI (r=0.50***) and leaf number (r=0.49***) were observed over all ENVs. A stronger relationship between grain filling duration and KW was however observed for mid and early hybrids (r=0.70***) compared to late hybrids (r=0.43*). A relationship with KN was only evident for early (r=0.50**) and mid hybrids (r=0.58***). MAS08, a higher latitude ENV with optimum moisture levels, was the only ENV to show a significant correlation between grain filling duration and GY (r=0.79***).

At RUK07, there was a significant interaction between hybrid maturity and PD on grain moisture content at PM (Table 4.6). While early hybrids showed a consistent increase in grain moisture at PM (30-36%) for PD1 to PD5, both mid and late hybrids revealed no particular relationship between grain moisture and PD.

Table 4.6 Grain moisture (%) at black layer for RUK07 over 5 planting dates (PDs); se is standard error across PD treatments for all hybrids.

	Hybrid Maturity		
PD	Early	Mid	Late
		%	
1	29.5	31.0	32.6
2	31.5	34.0	35.7
3	35.2	36.2	35.7
4	35.2	34.5	33.7
5	36.1	36.9	-
se	0.32	0.32	0.32
		Significance	
PD	***	***	***
Maturity	***	***	***
PD*Maturity	***	***	***

All hybrids attained PM at lower grain moistures when planted early. With early planting, early maturing hybrids also tended to reach 50% black layer at lower moisture contents than later hybrids. Overall, grain moisture content at PM was inversely correlated to grain test weight (r=-0.79***) and KW (r=-0.55**).

4.4.9 Thermal time for total crop cycle duration

Total crop cycle duration (Table 4.7) will only be briefly discussed here as it is the sum of TT to silking and silking to PM, both of which have already been described. For the Waikato ENVs, the drought-affected RUK08 ENV had the shortest TT durations, averaging 2030^{0}Cd across all hybrids, compared to NGA08 (2125^{0}Cd) and RUK07

(2091^{0}Cd). When standardised to the same set of hybrids, MAS08 had the greatest crop duration (2098^{0}Cd) vs. NGA08 (2058^{0}Cd), RUK07 (2033^{0}Cd) and RUK08 (1956^{0}Cd). As with grain filling duration, a significant PD*maturity interaction for total TT was evident across all ENVs. In the Waikato ENVs, where all entries were uniform, early hybrids averaged 1951^{0}Cd compared to 2077 and 2219^{0}Cd for mid and late hybrids.

Table 4.7 Thermal time requirement from emergence to physiological maturity for MAS08, NGA08, RUK07 and RUK08 over 4 or 5 planting dates (PDs); se is standard error across PD treatments for all hybrids.

	MAS08			NGA08			RUK07			RUK08		
	Hybrid matuity											
PD	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late
	^{0}Cd											
1	-	-	-	2024	2122	2281	2045	2114	2222	1874	2035	2236
2	1880	2074	2100	1959	2089	2256	1989	2109	2241	1942	2142	2309
3	1893	2107	2165	2010	2120	2259	1952	2074	2160	1969	2084	2193
4	1904	2050	2143	1993	2124	2257	1953	2108	2216	1885	1958	2003
5	1948	2003	2099	2025	2117	2241	1955	2025	-	1686	1935	2195
se	24.7	17.5	17.5	20.7	20.7	20.7	22.8	22.8	22.8	17.5	17.5	17.5
	Significance											
PD		***			***			***			***	
Maturity		*			**			*			**	
PD*Maturity		***			**			***			***	

4.4.10 Whole plant moisture content post anthesis

A study conducted to establish the moisture content in whole plant aboveground biomass showed that TT (T_b0) was less variable than real time. When independent data of silage harvest DM contents from NGA08, MAS08, RUK07 and RUK08 (n=330) were used to validate predicted values obtained using the TT relationships, TT reduced RMSE by ≥24% relative to real time. Multiple regressions consisting of combinations of TT, T_{min}, T_{max}, mean temperature, solar radiation, sunshine, rainfall and wind speed had no significant advantages over TT. Thermal time was thus considered adequate to estimate whole plant moisture content between anthesis and silage harvest time.

Mean whole plant moisture contents across all hybrid maturities ranged between 82 and 85% at anthesis. In NZ, SY is usually referenced in DM terms rather than moisture content, and for consistency, DM content as a percent of total fresh weight (i.e., 100 - % moisture content) will be used hereafter.

When the linear, quadratic and Gompertz equations were compared for their ability to predict silage drydown using TT, there were no differences between linear and quadratic functions. For simplicity, testing the quadratic method was thus discontinued. Using linear regression, rates of DM gain (silage drydown) between silking and silage harvest time for the early, mid and late hybrids were 0.021, 0.019 and 0.019% (^{0}Cd)$^{-1}$. The respective rates in real time were 0.41, 0.37 and 0.36% d^{-1}.

Across all treatments and models, a significant deviation of predicted vs. observed values was noticed when silage was harvested at ≥40% DM, under-estimating the observed DM values by either 11% (linear equation) or 20% (Gompertz function). When all data with DMs ≥40% were eliminated from the analysis, the Gompertz function had a greater improvement in DM predictions, resulting in a RMSE of 3.51%, compared to 4.02% for the linear equation.

Significant deviations (overprediction) between observed and predicted DM values were also noticed for crops planted after 22 November at RUK07 (PD4 and PD5). Average T_{min} between anthesis and silage harvest time for these treatments were <8^{0}C (see section 3.4.1, Chapter 3). Whereas DM estimates derived from the Gompertz model (Table 4.8) were within 10% of the observed values, variations due to linear regression averaged 19%. When these data were removed from the analysis, there was a significant improvement in RMSE for the linear regression (3.16%) whereas the Gompertz function only improved marginally to 3.27%, showing the superiority of the latter under cool conditions. At RUK08 and NGA08, where temperatures were at least 2.5^{0}C higher than long term averages, whole plant DM content at silage harvest for the late planted treatments was adequately estimated by both models. Due to its superiority under a wider range of conditions, the Gompertz model was therefore considered more robust than the linear and quadratic models, and adopted for use in this study.

Table 4.8 The Gompertz equations and statistical parameters used to estimate whole plant dry matter content (%) on thermal time (TT, (T_b0) in ^{0}Cd) between anthesis and physiological maturity for three hybrid maturities, using data from the low density experiment (NGA08) and MAS08.

Equation	Maturity*	a_0	b_0	b_1	P	n
$DM = a_0 * exp(-exp(-b_0 *(TT-b_1)))$ where a_0, b_0 and b_1 are Gomertz coefficients and TT is thermal time (T_b0)	Early	21274.6	4.5E-05	42473.6	***	20
	Mid	225.6	3.4E-04	2834.5	***	20
	Late	7528.5	2.4E-05	71310.1	***	12

* Early = 38P05 and 38H20; Mid = 36B08 and 36M28; Late = 34D71 and 34P88.

4.4.11 Grain drydown post PM

A pilot study conducted at RUK07 to determine the rate of grain drydown post PM showed that, of the factors considered to have potential significant influence on the drydown process (mean daily wind speed, cloud cover, mean daily relative humidity, daily global solar radiation, daily rainfall, daily T_{min}, T_{max} and mean temperatures, daily average TT and hours of daily sunshine), drydown was satisfactorily predicted using only relative humidity and TT with the relationship: *Rate of moisture loss* d^{-1} *(%) = 0.16 * RH% - 0.03 * TT*, where RH is average daily atmospheric relative humidity, %, and TT is average daily thermal time (T_b0). Table 4.9 shows the combined and individual relationships for the three hybrid maturities. The combined multiple regression equation (i.e., use of a single equation for all hybrids) resulted in very small differences among hybrid maturity classes, and was therefore adopted.

Table 4.9 Multiple regression equations and statistical parameters describing rates of grain moisture loss vs. thermal time (TT, (T_b0) in ^{0}Cd) and relative humidity (RH%) using data from three planting date treatments at RUK07, expressed as % moisture loss d^{-1}.

Equation	Maturity	a	b	c	P	R^2	n
*Moisture loss = b*TT + c*RH%* *a = intercept*	Early	29.3±0.96	-0.035±0.0044	0.226±0.0630	***	0.80	36
	Mid	30.6±0.63	-0.031±0.0023	0.157±0.0290	***	0.90	43
	Late	29.5±0.60	-0.033±0.0017	0.175±0.0212	***	0.94	42
	Combined	30.1±0.39	-0.031±0.0013	0.159±0.0157	***	0.88	121

4.4.12 Leaf senescence

A bilinear relationship between leaf senescence and TT, consisting of a marginal linear increase during the first half of grain filling (using real time, d), followed by a rapid increase in senescence during the last half (phase two) was observed (Figure 4.2). In TT, the first phase of senescence constituted 70% of the total grain filling duration at RUK07 and 60% at RUK08 and NGA08, where drought stress accelerated leaf death. As senescence data was not recorded during phase one at RUK07, the rate of senescence was extrapolated from silking to the start of phase two, assuming 0% senescence at silking.

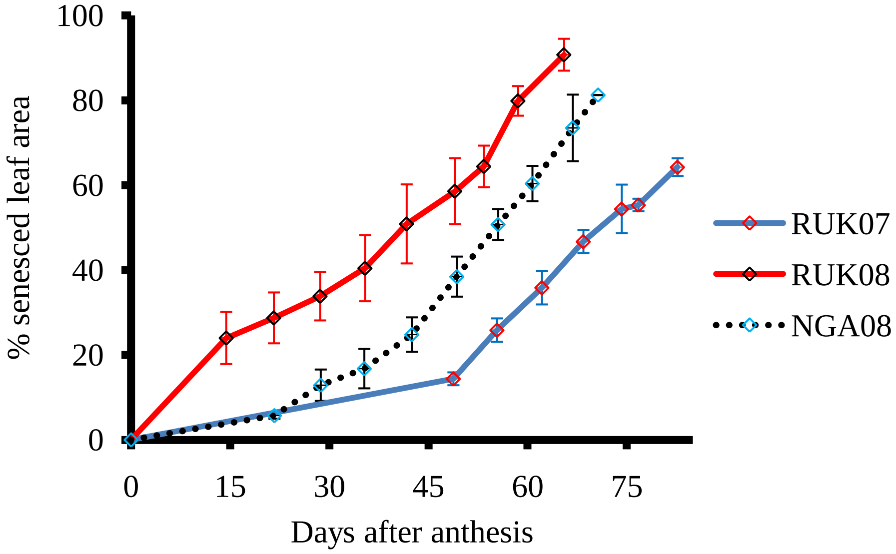


Figure 4.2 Senesced leaf area (%) for RUK07, RUK08 and NGA08 across 3 hybrid maturities and 5 planting date treatments between silking and physiological maturity. The vertical line bars denote the standard error (±se) of the mean for each treatment.

Leaf senescence rates during phase one were significantly higher at RUK08 (0.09% $(^0Cd)^{-1}$) compared to RUK07 (0.03% $(^0Cd)^{-1}$) and NGA08 (0.04% $(^0Cd)^{-1}$). On average, at RUK07, only 14% of the total LA had senesced by the beginning of phase two and the senesced LA increased to 57% by the end of phase two (PM). In other ENVs, changes in senesced LA between beginning and end of phase two varied from 18 to 67% (NGA08) and 37 to 88% (RUK08). On average, RUK07 phase two senescence rates (0.19% $(^0Cd)^{-1}$) were significantly higher than NGA08 and RUK08, both averaging 0.16% $(^0Cd)^{-1}$). Despite their higher phase two rates, plots at RUK07 possessed the most green LA at PM.

Averaged over PDs, by the end of phase one, early hybrids at NGA08 had significantly less senesced LA (8%) vs. mid (21%) and late hybrids (24%). At RUK08, the senesced LA at the end of the first phase for early hybrids varied from 20-50% compared to between 30 and 45% in mid and late hybrid classes. PD4, which received 18 mm of rainfall within a week of flowering, unlike other treatments which were drier, experienced the lowest phase one senescence rates (0.03% (^{0}Cd)$^{-1}$) while PD5 recorded the largest (0.15% (^{0}Cd)$^{-1}$). However, PD4 had significantly higher rates during phase two than the rest of the treatments, rates which were similar to those observed for phase two at RUK07. The respective phase two senescence rates for PD1 to PD5 (RUK08) were 0.17, 0.14, 0.18, 0.22 and 0.11% (^{0}Cd)$^{-1}$.

At NGA08, the respective phase two senescence rates for PD1 to PD5 were 0.13, 0.20, 0.14, 0.17 and 0.16% (^{0}Cd)$^{-1}$. PD2 rates were even higher than for the significantly water stressed RUK08 ENV for both phases one (0.09 vs. 0.03% (^{0}Cd)$^{-1}$ and two (0.2 vs. 0.14% (^{0}Cd)$^{-1}$. As discussed in section 4.4.8, reasons for these unexpected results from PD2 were not established.

At RUK07, while early hybrids also had lower senescence rates than later hybrids during phase one (Figure 4.3), the magnitude was much smaller than in the drought affected sites of RUK08 and NGA08. Similarly, early hybrids had higher senescence rates (0.25% (^{0}Cd)$^{-1}$) than mid and late classes (0.16% (^{0}Cd)$^{-1}$) during phase two of grain filling. Across hybrid classes, PD5 recorded the highest phase two senescence rates (0.28% (^{0}Cd)$^{-1}$), followed by PD4 (0.23% (^{0}Cd)$^{-1}$) and PD1 (0.20% (^{0}Cd)$^{-1}$). PD2 and 3 had the least rates of 0.13 and 0.10% (^{0}Cd)$^{-1}$.

Over all five PD treatments at RUK07, when assessed at PM, early and mid hybrids still possessed 50% of their green LA vs. 40% for the late group (Figure 4.3). At NGA08, the three hybrid maturities ranged from 25-40% of green LA at PM, while the average proportion of green LA at that stage in the RUK08 ENV under more severe drought was about 10% across all treatments.

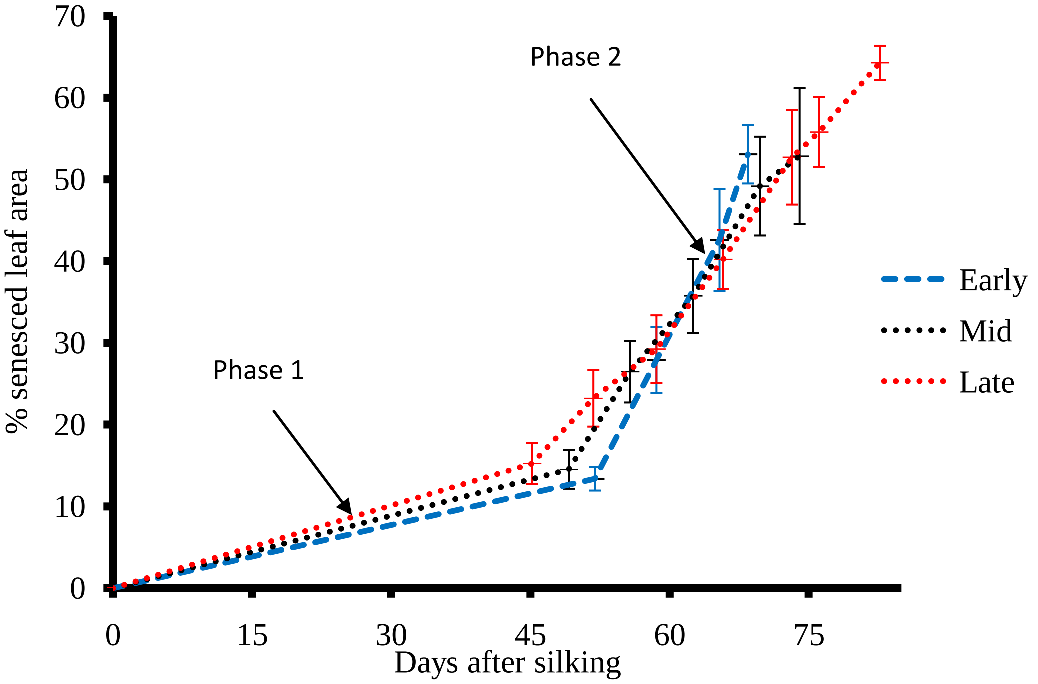


Figure 4.3 Senesced leaf area (%) for 3 hybrid maturities across 5 planting date treatments at RUK07 from anthesis to physiological maturity. The vertical line bars denote the standard error (±se) of the mean for each treatment.

In the initial stages, senescence progression was from bottom leaves towards the ear leaf (EL). As the crop approached PM, leaf senescence also occurred from the top to bottom leaves, resulting in the central part of the plant (leaves around the ear) remaining green for the longest time.

Across ENVs, negative correlations were evident between % senesced LA at PM and GY (r=-0.59***), HI (r=-0.69***), KN (r=-0.64***) and KW (r=-0.47***). The respective correlations with senescence during the first phase of grain fill were r=-0.55***, r=-0.77***, r=-0.66*** and r=-0.42***. However, when considered by maturity class, correlations between GY and senescence during either mid grain fill or at PM were only significant for early and mid hybrids (r≤-0.77***). Across ENVs, the respective correlations between senescence at PM and mid grain fill with barrenness were r=0.51*** and r=0.52***.

4.4.13 Dry matter remobilisation

Dry matter remobilisation or accumulation between flowering and PM differed significantly among the three ENVs (RUK07, NGA08 and RUK08). RUK08 had the highest average remobilisation rates, amounting to 15% of the non-grain biomass at 50% silking, vs. 5% for NGA08 and a 6% biomass gain at RUK07. At RUK07 and NGA08, PD and maturity interacted to influence remobilisation.

At RUK08, between PD1 and PD5, non-grain aboveground DM biomass weights ranged from 103 to 132 g plant^{-1} at silking vs. 87 to 118 g plant^{-1} at maturity (Table 4.10). Assimilate remobilisation varied from -9 to -22%, with significantly higher rates observed under very dry conditions during vegetative growth (PD3 and PD4), where individual non-grain plant weights decreased by ≥21%.

Table 4.10 Relative change in stover weight (%) between silking and maturity for RUK08, RUK07 and NGA08 over five planting dates (PDs); se is standard error across PD treatments for all hybrids. Data in parentheses indicate the average vegetative aboveground plant dry weight (g plant^{-1}) at silking.

	RUK08	RUK07			NGA08		
		Hybrid maturity					
PD	All	Early	Mid	Late	Early	Mid	Late
		%					
1	-9(131)	+19(89)	+12(97)	-4(123)	-4(114)	-0.5(121)	+2(129)
2	-10(128)	+4(92)	+20(97)	+16(116)	-6(115)	-6(134)	-5(138)
3	-22(132)	-6(103)	+8(109)	+8(116)	-7(118)	+6(122)	-6(138)
4	-21(111)	+1(105)	+7(114)	-3(134)	-12(106)	-2(103)	-25(148)
5	-11(103)	-6(102)	+7(102)	-	-15(89)	-2(99)	+6(103)
se	3.7	4.5	4.5	4.5	6.9	6.9	6.9
		Significance					
PD	**		**			*	
Maturity	NS		**			NS	
PD*Maturity	NS		**			**	

While remobilisation was evident at NGA08, it was much less than at RUK08. Early hybrids varied from -4 to -15%, whereas mid and late classes ranged from -6 to +6% and -25 to +6%, respectively. At NGA08, PD effects on remobilisation were only significant for late hybrids, where the highest rates (-25%) were observed under PD4. For all maturity classes, the lowest vegetative weights at both silking and maturity were observed under PD5 conditions.

At RUK07 PD affected remobilisation in early and late hybrids only. Mid hybrids averaged +11% net stover weight gain across PD treatments. The early group ranged from -6 to +19% whereas late hybrids varied between -4 to +16%. While the early group had the highest DM gain under PD1, late hybrids experienced the largest gain with PD2 and the most remobilisation (-4%) under PD1. On average, early hybrids had the least accumulation of stover biomass between flowering and maturity.

In all three ENVs, early and mid hybrids showed an inverse relationship between GY and remobilisation (r=-0.55**, r=-0.65**, respectively), indicating that demand for assimilate to fill grain and sustain respiration exceeded the supply from photosynthesis. A weak association between KW and remobilisation existed for mid hybrids (r=-0.49**). Mid hybrids showed a stronger relationship between remobilisation and CGR_{ES} (r=-0.53**), CGR_{SS} (r=-0.87***) and KN (r=-0.67***). The respective correlation coefficients for early and late hybrids were (r=-0.44*; -0.43*), (r=-0.81***; -0.45*) and (r=-0.52**; -0.46*).

4.5 DISCUSSION

4.5.1 Thermal time durations and base temperature estimations

While T_b8 was considered adequate in predicting most of the development processes, T_b0 was more appropriate for grain filling and field drydown. Other reports citing T_b0 for grain filling in maize include Muchow (1990) and Birch et al. (1998c). Superiority of T_b0 over T_b8 during and post-grain filling was likely because the two processes active during those periods involve a component of physical diffusion of sucrose and grain moisture loss (Brooking, 1990). Unlike other processes such as LA expansion which are enzyme mediated (Purdy and Crane, 1967), water loss does not involve enzymes. Enzymes typically respond to temperature in a Q_{10} fashion that implies a base temperature and a sharply curvilinear response to temperature over a narrow range. Drying rate is instead influenced more by physical factors such as pericarp permeability and osmotic diffusion (Crane et al., 1959). Diffusion processes on the other hand tend to be proportional to absolute temperatures and to concentration gradients.

Prediction of the timing of occurrence of TI is a basic requirement of most maize process models since this duration is used to predict final leaf number and is key to estimating planting-to-flowering durations. The indirect method for estimating TI (see section 4.4.5) established in this study provides a simple way of determining TI when destructive dissection is not an option. Other researchers have predicted TI to occur at 0.4 x seedling emergence to silking TT duration (Bonhomme et al., 1991). This relationship was evaluated using data from the current study, and was not adopted because it accounted for less variability in TI than a relationship associated with final leaf number (r^2=0.50, vs. 0.67). Additionally, leaf number was considered more readily observable, unequivocal, stable, easily measured and less prone to error than TT. A linear relationship established by Hunter et al. (1974) which also depends on final leaf number (*TI = 0.44 x final leaf number - 1.95*) under-predicted leaf number at TI. This relationship was established using older hybrids and it appears necessary to modify the equation using data from current maize hybrid genetics.

The observed variations in TT durations between emergence and TI among PDs (Table 4.3) possibly suggest that T_b8 may still be too high for this interval, or that photoperiod sensitivity differed among the maturity classes of hybrids. However, even though TT from emergence to TI differed among PDs under non-limiting moisture conditions, the variation around the mean was quite small and considered inconsequential. Photoperiodic effects were also not considered to have influenced hybrids differently among PDs due to the narrow range in daylengths observed across PDs. Moreover, modern temperate hybrids are generally not very photosensitive (Bonhomme et al., 1991).

The inverse relationship between TT for the emergence-TI interval and soil temperature immediately prior to TI in the water stressed ENV was consistent with other research (Breuer et al., 1976; Warrington and Kanemasu, 1983c). The relationship was, however, non-existent in ENVs where moisture was not limiting, suggesting that increasing levels of water stress may have triggered this response. Dry conditions appear to have increased soil temperatures by 1-3^0C for RUK08 vs. RUK07 and it seems likely that the higher temperatures hastened progress to TI by reducing leaf numbers (section 5.5.4.1, Chapter 5), in turn decreasing the duration from emergence to TI. Earlier PD treatments, which were least stressed, had the most number of leaves compared to the last two which received the least amount of rainfall. The reduction in leaf numbers at RUK08 may also reflect a sensing of impending drought that resulted in increased rates of progress towards TI. Decrease in leaf number under drought stress prior to TI has also been reported elsewhere in literature (Jordan, 1983; NeSmith and Ritchie, 1992). The shorter thermal duration from emergence to TI under dry warm conditions, however, depend on the severity of the water stress. For instance, Abrecht and Carberry (1993) reported up to a 4 d delay in time to TI under severe drought stress.

The emergence-flowering duration, which also includes the TI period, is considered here to allow for comparisons with other reports. The average linear decrease in the emergence to flowering duration with delayed planting observed in the Waikato ENVs (-1.1 (^{0}Cd)d^{-1}) falls within the -0.7 to -1.1 (^{0}Cd)d^{-1} range reported by Nielsen et al. (2002), using T_b10. The response of the emergence-flowering duration to PD in the current study was most likely due to variations in leaf number and phyllochron lengths (see sections 5.4.8 and 5.4.11, Chapter 5). Drought was not considered to have significantly influenced silking duration, since anthesis, which is generally not responsive to drought (Bolaños and Edmeades, 1993b), usually occurred within a day of silking. Increased leaf numbers and/or phyllochron delayed flowering, since emergence-silking duration is directly proportional to both variables. Under optimum conditions, TT between emergence and silking can therefore be estimated accurately from total leaf number and phyllochron.

Unlike the Waikato ENVs, MAS08 exhibited a general increase in the duration from emergence to flowering with delayed planting, which concurs with earlier studies on older and possibly more photosensitive hybrids in Canada (Daynard, 1972). This delay in development was largely attributed to a significant increase in phyllochron from 42 to 50^{0}Cd between PD1 and PD5 (see section 5.4.11, Chapter 5). Due to the narrow photoperiod range, daylength was not considered to have played a significant role in the present study, though it would have greater influence on leaf number here than in the lower latitudes of the Waikato ENVs. Over all PD treatments, during the last week prior to TI, when photoperiod is known to delay TI in photosensitive maize hybrids (Kiniry et al., 1983b), daylength ranged from 14.2-14.8 h in Waikato and 14.8-15.1 h in Manawatu. Even though higher temperatures just prior to TI for late planting treatments (e.g., 18.7 vs. 14.1^{0}C) reduced leaf numbers (see section 5.4.8, Chapter 5), temperature effects were larger on phyllochron than leaf number, resulting in longer emergence-TI durations. Warrington and Kanemasu (1983c) showed that between 15 and 25^{0}C, leaf number had a curvilinear response to temperature, whereby the lowest numbers were observed at 18^{0}C (see section 5.5.4.1, Chapter 5, for a more detailed discussion). Larger phyllochron values under warmer conditions have also been cited by Tollenaar et al. (1984; 19-29^{0}C) and Padilla and Otegui (2005; 12-26^{0}C).

Flowering date is a very obvious indicator of overall crop maturity and is expected to be significantly correlated with leaf number and TT duration to TI and maturity. This was the case in the present study. The higher correlations observed between these three traits and anthesis vs. silking were due to the greater sensitivity of silking to environmental stress (Bolaños and Edmeades, 1993b). Anthesis is therefore a more reliable indicator of the flowering growth stage than is silking in maize. Anthesis-silking interval will not be discussed here since the values obtained, even under drought conditions, were not considered large, and correlations between ASI and yield traits were generally non-significant.

Under non-stressed conditions, grain filling TT durations were generally consistent across PD treatments, especially in Waikato. In Manawatu, a higher latitude ENV where environmental conditions vary significantly between early spring and late autumn, a quadratic response was observed with PD for mid and late hybrids. Similar observations have also been reported under some USA conditions (Nielsen, 2002), further evidence that grain filling duration was not necessarily dependent on temperature alone (Stewart et al., 1998a,b). The latter reported that environmental factors directly affected assimilate availability. For instance, drought or reductions in IPAR and temperature had a significant influence on filling duration. This was evidenced by low KW and KN observed under shorter grain filling durations, which is consistent with assimilate deprivation (Wardlaw, 1972; Stewart et al., 1998a,b).

The higher correlation between grain fill duration and KW vs. KN suggests source limitation during the latter parts of grain filling (Borrás et al., 2004). Drought stress was more pronounced in late hybrids, and these showed an association between duration of grain filling and KW, but not KN. Possible reasons why later hybrids were affected more by stress are discussed in sections 3.5.1 and 3.5.2 (Chapter 3).

In all ENVs the main differences in lifecycle duration between hybrid maturity classes principally reflected variation in grain filling duration. This was evidenced by the higher correlation between the total crop cycle (emergence-PM) and the grain filling durations (r=0.87***) compared to the emergence to silking duration (r=0.56***). While these findings concur with results observed in the temperate areas of Argentina (Capristo et al., 2007), they contradict other reports from studies of diverse maize hybrids grown under varying daylength and temperatures that suggest that variation in the emergence-flowering duration explained the majority of hybrid maturity differences (Derieux and Bonhomme, 1982; Major et al., 1983). This disparity could be due to possible errors associated with T_b assumptions used in these other studies. For instance, while emergence-silking duration for early hybrids was 11% less than for late hybrids, differences in grain filling duration were larger using T_b0 (16%) than T_b8 (13%). Differences may also reflect the fact that hybrids did not differ markedly in duration or photoperiod sensitivity, and that daylengths among PDs and ENVs were fairly similar.

4.5.2 Crop growth rate

Crop growth rates in the current study were reported in TT rather than real time, a contrast with most reported literature (e.g., Andrade et al., 1999; Borrás et al., 2007). Use of TT removes artifacts caused by differences in temperature and rate of growth. For instance, at RUK07, the PD1 emergence-flowering duration averaged 108 d, vs. 75 d (PD4) and 67 d (PD5), while the total biomass yields at silking were reasonably similar among PDs (see section 5.4.6, Chapter 5).

The observed increase in CGR_{ES} with late planting, particularly at RUK07, was attributed to high RUE, high IPAR (Cirilo and Andrade, 1994a) and near-optimal temperatures for growth between emergence and flowering. Average daily irradiance for the period increased linearly with PD from 19.5 to 21.5 MJ m^{-2} d^{-1} between PD1 and 4, before dropping to 21.2 MJ m^{-2} d^{-1} for PD5. At the same time mean temperatures increased from 14.4 to 17.7^0C between PD1 and PD5.

In contrast to CGR_{ES}, the general decrease in CGR_{SS} with PD, particularly in the absence of water stress, was attributed to a linear decline in radiation from 20.4 (PD1) to 13.0 MJ m^{-2} d^{-1} (PD5). Kiniry and Knievel (1995) showed that KN, which is determined by CGR (Andrade et al., 1999), was linearly related to IPAR. The higher mean temperature regimes between anthesis and silage harvest time for early plantings (18.7 vs. 15.7^0C) also would have contributed to higher CGR_{SS} through increased RUE as observed by Wilson et al. (1995), who reported low RUE if mean temperatures dropped below 16^0C.

Even though mean temperature and radiation levels for NGA08 and RUK08 were at least 1^0C and 1.5 MJ m^{-2} d^{-1} greater than RUK07, CGR_{ES} rates were 35% less. A similar trend was also observed with CGR_{SS}, where mean temperature and radiation for the two ENVs were at least 1.5^0C and 2.5 MJ m^{-2} d^{-1} higher than RUK07. This was attributed to the effects of water stress. On average, RUK07 received 234 mm rainfall during the emergence-flowering period across the five PD treatments vs. 112 mm for the other two ENVs. The significant decrease in CGR_{SS}, particularly for RUK08, was largely due to lower rainfall during the anthesis to silage maturity period (50 mm) vs. RUK07 (140 mm) negating any direct effect of higher temperature and radiation levels on CGR.

Reduced CGR under water stress conditions have also been reported by Pandey et al. (2000) and Sangakkara et al. (2004). Similarly, Edmeades (1972) reported that, provided water was not limiting, timing of maximum CGR was governed by trends in temperature and radiation.

The strong correlation between CGR_{SS} and GY compared to CGR_{ES} was most likely because sink size is largely determined during and after flowering (Andrade et al., 2000). Additionally, light interception is also more complete during grain filling and thus, higher correlations between CGR_{SS} and yield components are likely as the latter is directly related to IPAR (Kiniry and Knievel, 1995). Post-flowering conditions also have a large bearing on kernel abortion and grain filling (Schussler and Westgate, 1991). Crop growth rate between silking and silage maturity therefore determines GY and its components, as evidenced by the high correlations with GY, HI, KW and KN. Crop growth rate between emergence and silking is however influenced by rate of LA expansion or the speed of canopy closure, directly affecting vegetative biomass. The positive correlations of CGR with KN and green LA are consistent with other findings in literature. For example, Andrade et al. (1999) observed an increase in KN m^{-2} from 1000 to 3500 when CGR increased from 12 to 25 $gm^{-2}\ d^{-1}$ during flowering.

Averaged across ENVs, under cool, early planting conditions, late hybrids had significantly higher CGR_{ES} than early and mid hybrids. This could be due to greater IPAR as a result of quicker canopy closure in late hybrids (see section 5.5.4.2, Chapter 5), or it could reflect higher temperatures experienced by later hybrids immediately prior to flowering. In contrast, the CGR_{ES} of early hybrids were equal to or greater than late hybrids under late planting conditions (warm). Similar results have been observed in sweet corn by Garcia et al. (2009) who concluded that since silking occurred earlier in early hybrids, mean temperatures encountered in late plantings were higher compared with later flowering hybrids.

4.5.3 Estimation of post-anthesis whole plant DM content

Despite existence of other models for predicting whole plant DM content such as FOPROQ (Hermann et al., 2005), the Gompertz model was considered adequate due to its reasonable accuracy (particularly under cool conditions) and simplicity. Root mean square error values for estimated vs. observed values for the Gompertz model were less than 10% of the measured DM content and also, calculations can be easily done using an Excel® spreadsheet. Even though the Gompertz model resulted in significant errors when DM contents were ≥40%, this was not considered as a limitation to its use since the recommended range for silage harvest window is 32-38% whole plant DM (Wiersma et al., 1993; Phipps et al., 2000; Bagg, 2001).

The model will be used in conjunction with the CERES-Maize model to estimate silage maturity since the latter lacks the ability to estimate moisture content in its biomass subroutine (see section 6.3.2, Chapter 6). Superiority of the Gompertz model, which is a sigmoid function, over linear regression in determining DM content, is consistent with the kernel growth rate being curvilinear, consisting of a lag phase, which is immediately followed by linear growth, and eventually, a slow down towards maturity (e.g., Yoshida, 1981; also see section 2.1.1).

Other than its ability to predict DM content for silage harvest scheduling, the established model can also be used as a decision support tool to select a hybrid that fits the time frame which suits the grower's conditions. Though widely used, estimating DM content using real time was the least accurate, largely because of variations in temperature conditions. This was evidenced at RUK07 (typical seasonal temperature conditions), where, depending on PD, late hybrids took 54-82 d to reach silage maturity.

4.5.4 Effective grain filling and field drydown

Once kernel set has been determined, KGR and grain filling duration are the two factors that determine yield in grain crops. This study revealed that KGR during the effective grain filling stage was stable across different hybrid maturities and PDs when reported in TT rather than the more commonly reported real time (e.g., Cirilo and Andrade, 1996; Borrás et al., 2009). Similar findings have been noted by Maddoni et al. (1998). Yield differences among hybrids are therefore largely determined by grain filling duration, as observed at MAS08 where growing conditions were non-limiting (r=0.79). Variations in KGR using real time were largely due to effects of temperature variation on crop development.

The observed rates of individual kernel filling of 0.36-0.38 mg (^{0}Cd)$^{-1}$ are slightly higher than the 0.3 mg (^{0}Cd)$^{-1}$ recorded elsewhere (Tollenaar and Bruulsema, 1988; Melchiori and Caviglia, 2008) using T_b0. Using T_b8, at temperatures >19^{0}C and high irradiance, KGRs of 0.46-0.67 mg (^{0}Cd)$^{-1}$ across a range of different sized kernels have been reported by Maddoni et al. (1998), while Wilhelm et al. (1999) observed a KGR of 0.55 mg (^{0}Cd)$^{-1}$ under a 25/20^{0}C day/night glasshouse temperature regime. When normalised to T_b0, these rates are less than findings from the current study and may help explain the higher average GYs (>13 t ha^{-1}, see section 3.4.2, Chapter 3) vs. <10 t ha^{-1} recorded in Argentina by Melchiori and Caviglia (2008).

When temperatures were around 19^{0}C, KGR was maintained at high levels even when irradiance was as low as 11 MJ m^{-2} d^{-1}. This was consistent with findings by Daynard et al. (1969) that variations in IPAR did not affect KGR provided temperatures were near optimal since stalk remobilisation could provide a reserve of assimilates required for grain filling during periods of reduced photosynthesis. The observed higher remobilisation levels, particularly under later planting conditions were consistent with this finding.

The slightly higher KGRs (0.37-0.42 mg (^{0}Cd)$^{-1}$) observed under low planting rates (<4 plants m^{-2}) agree with the report of Cirilo and Andrade (1996), who noted that grain filling rates were directly dependent on temperature and assimilate availability. It is however surprising that these rates were not considerably higher than those from crops planted at much greater planting densities as reported in section 4.4.3. This could reflect the genetic limitation of the hybrid set (Reddy and Daynard, 1983), but is also likely due to inherent limitations to rates of transfer of assimilate to the endosperm by diffusion in the placental area of the kernel (Borrás et al., 2009). Lower planting rates decrease competition for radiation (Andrade et al., 1993b) and soil moisture. When converted to real time, the rates (7-8 mg d^{-1}) resemble reported values of 6-10 mg d^{-1} (Jones and Simmons, 1983; Ritchie et al., 1986a; Wilhelm et al., 1999).

The observed grain moisture contents at PM (30-36%) fall within the ranges reported in literature (Carter and Poneleit, 1973; Cavalieri and Smith, 1985; Sala et al., 2007a). Kernel black layer formation at maturation marks termination of DM accumulation and the beginning of grain drydown. Moisture content at PM therefore influences harvest timing as well as potential artificial grain drying costs. Higher grain moisture contents at PM under late plantings agree with those reported in source-deficient and/or cooler conditions (Sala et al., 2007a) and were most likely due to environmental conditions that slowed or terminated filling rather than hybrid factors. Since grain filling involves progressive displacement of water through DM accumulation (Borrás et al., 2009), premature termination of grain filling results in kernels with higher moisture contents. Source limitation under the late planting conditions was evidenced by the general reduction in KW and in grain fill duration as discussed in section 4.5.5. The lower moisture at PM exhibited by early vs. late hybrids under early plantings has been reported elsewhere and could be associated with more complete filling because of their shorter effective grain filling duration (Cross, 1981). It also supports the observation that short duration hybrids are usually sink-limited when planted early (see section 3.4.9, Chapter 3).

The inverse relationship observed between grain moisture at PM and test weight has also been reported by Cross and Kabir (1989). Poorly filled grain generally constitutes lower test weights due to low endosperm density. Selection of hybrids with lower grain moisture at PM would therefore likely result in lower harvest moistures and high test weight grain, reducing grain drying and storage costs as well as improving grain quality.

Despite the range of environmental and hybrid specific factors that determine field drydown rates (Hunter et al., 1979; Cross, 1985), grain moisture losses post-PM were adequately predicted using temperature and atmospheric relative humidity alone. This corroborates findings by Hoeft et al. (2000) that kernel moisture loss was more reliant on weather than genetic factors within a rather narrow range of Corn Belt hybrids. Schmidt and Hallauer (1966) also showed that at >30% kernel moisture, moisture loss rate was dependent on air temperature, whereas at <30%, relative humidity was the more important of the two. Ability to accurately estimate moisture loss rate using such a small set of parameters would provide growers with a simple but accurate and practical tool for selecting the best hybrid x ENV combinations required to increase profitability through minimising artificial grain drying costs.

Even though different hybrids showed some variation in drying rates, the magnitude of the differences was considered negligible among this hybrid set, and was consistent with studies showing comparable rates across a range of temperate hybrids (Hunter et al., 1979; Cavalieri and Smith, 1985). Despite other research showing significant genotype x ENV interactions (e.g., Magari et al., 1997), the current findings imply that under the study conditions and the set of hybrids tested, a single equation was adequate to predict drydown for all hybrids. Whereas cool temperatures during grain drying may influence the observed relationship, as observed with silage drydown, the inclusion of relative humidity will likely reduce the magnitude of error.

4.5.5 Leaf senescence and assimilate remobilisation

Drought accelerates the death of lower leaves, and because it intensifies with time, at any single developmental stage it will affect late hybrids more than early hybrids sown on the same date. This was particularly apparent at RUK08. High senescence levels (up to 50% of total LA) were observed under drought conditions during the first half of grain filling (phase one of leaf senescence). Similar results have also been reported by Muchow and Carberry (1989). The generally lower senescence rates obtained with early hybrids relative to later hybrids in phase one, particularly under drought conditions reflect their ability to avoid stress due to their shorter duration.

Planting date *per se* did not have any effect on senescence during phase one senescence, and this was likely because both temperature and radiation declined only during the later phases of grain filling. Despite the generally higher rates of senescence during the second part of grain filling (phase two), early hybrids maintained the highest proportion of green LA by PM, even under optimal conditions, suggesting a better balance between source and sink. This could also signify sink size limitations. Accelerated leaf senescence in dry soils is usually a symptom of N or water deficits, resulting in leaf N remobilisation to supply the growing kernels (Wolfe et al., 1988b; Bänziger et al., 2002).

Under drought conditions (NGA08 and RUK08), the lower senescence rates in phase two were a result of the high rates of phase one senescence, which were induced by water stress at these locations. RUK07 experienced a normal senescence pattern throughout the whole season, whereas drought-accelerated senescence was apparent at NGA08 and RUK08. The normal pattern of foliar senescence therefore calls for low rates in phase one, followed by rates that are at least five-fold greater during phase two. At RUK07 the onset of phase two occurred when only 14% of the LA was senesced, vs. 37% at NGA08. A similar response was also evident at RUK08 where PD4, which experienced precipitation during flowering, resulted in low senescence rates during phase one whereas phase two rates surpassed all other treatments and resembled RUK07 rates. It therefore appears that under normal situations, senescence rates during phases one and two are respectively, 0.03 and ~0.2% (^{0}Cd)$^{-1}$. The delayed onset of rapid senescence at RUK07 and the high proportion of green LA at the end of grain fill compared to the other ENVs, particularly RUK08, meant that photosynthesis was likely maintained at high rates over an extended duration during grain filling in this ENV.

The negative correlation between senescence rate and GY was due to reduced assimilate supply for grain growth, and concurs with other research associating decreased grain fill duration with leaf defoliation (Sala et al., 2007b). Conversely, the positive relationship between barrenness and senesced LA is analogous to reports of leaf senescence under excess assimilate accumulation situations resulting from reduced grain set (Sadras et al., 2000). Either oversupply of carbohydrates in the leaf or shortage of leaf N, water deficits or shading can accelerate senescence (Tollenaar and Daynard, 1982; Wolfe et al., 1988b; Uhart and Andrade, 1995). These factors may explain the higher senescence rates observed under early (PD1; sink-limited) and late planting (PD4 and 5; source-limited) at RUK07. Lower temperatures experienced with early planting tend to affect biomass accumulation by altering leaf expansion which reduces IPAR (Muchow and Carberry, 1989) and assimilate flux, while decreased temperatures at the end of grain filling under late planting conditions would slow grain growth and/or photosynthesis (Cirilo and Andrade, 1996). Both scenarios would therefore create an imbalance between the sink-source relationships.

The poor correlation between leaf senescence and GY for late hybrids compared to early and mid hybrids could be due to the larger biomass of the former, which could provide a bigger assimilate reserve for use in situations where LA is limiting. Alternatively, assimilate remobilisation from stalks may be greater in late hybrids, a phenomenon common with older germplasm (Tollenaar and Aguilera, 1992) and associated with increased stalk lodging. This was however not the case in this study where late hybrids generally had the least remobilisation rates. The higher remobilisation rates in early hybrids, in contrast to findings reported by Capristo et al. (2007) could be attributed to the smaller LA (see section 5.4.10, Chapter 5) and biomass (section 5.4.6, Chapter 5) leading to reduced ability to store enough assimilates for supply during periods of high photosynthetic demand.

The bottom followed by top leaves senescence pattern observed towards the end of grain filling is quite normal, and has also been reported by Thiagarajah et al. (1981) and Valentinuz and Tollenaar (2004). Even though no clear explanation of why top (younger) and bottom leaves die before the central leaves exists in literature, Wolfe et al. (1988b) reported increased occurrence of the phenomenon under water and N stress. It is therefore highly probable that under stress, the plant will sacrifice all other leaves and maintain the largest leaves, which also happen to be closest to the sink, for continued assimilate export.

The significantly high DM remobilisation rates observed during grain filling under drought conditions reflect a severe source limitation induced by water stress. Elsewhere, the net gain in stover weight between silking and maturity experienced under early planting and optimal moisture conditions was an indication that assimilate supply exceeded requirements for grain growth. Conversely, the lower stover weight gain under late planting conditions for the non-water stressed situations was likely due to remobilisation occurring during the later parts of grain filling as photosynthetic activity decreased due to diminishing radiation and temperature levels and the demands of a large sink (Daynard et al., 1969).

Significant correlations between remobilisation and senesced LA signified source limitation during grain filling. Since source capacity is dependent on photosynthetic activity and assimilate availability (Uhart and Andrade, 1991; Rajcan and Tollenaar, 1999), reduction in LA would promote increased remobilisation during grain filling. This is supported by the inverse relationships between remobilisation and HI, CGR, KW and KN. Under non-drought conditions the levels of remobilisation were quite modest and consistent with the stalk assimilate reserves serving as a buffer against occasional assimilate shortages during periods of low photosynthetic activity.

4.6 CONCLUSIONS

Across PDs, the narrow photoperiod range (≤0.6 h) resulted in no measurable differences in hybrids' responses to daylength. Planting delay in Waikato reduced TT to silking by -1.1 (^{0}Cd)d^{-1}, possibly due to leaf number and phyllochron variation. In Manawatu, an increase in phyllochron with PD (42-50^{0}Cd) resulted in an opposite response. The emergence-anthesis duration was more strongly associated with leaf number, TI and PM than the emergence-silking phase, mainly because of the sensitivity of the silking process to stresses. Anthesis is therefore a more stable indicator of flowering. While the emergence-silking TT was usually longer than the grain filling duration, most of the variation in total growth cycle duration among maturity classes was associated with differences in the grain filling duration. This was especially apparent when T_b0, rather than T_b8 was used. Grain filling duration was more responsive to variation in environmental conditions (IPAR, temperature and drought) than the emergence-flowering duration. Due to bigger sink sizes and thus, larger assimilate demands, long duration hybrids were more prone to source limiting conditions, resulting in greater reductions in grain fill duration or in KW. While PD had no influence on total crop cycle duration in TT *per se,* shortest intervals were obtained under stressful situations. Even though TT is generally considered stable when predicting maize development, phyllochron, source-sink balance and leaf number, all of which vary with PD, significantly influenced crop cycle duration.

Across all ENVs, late (vs. early) hybrids had higher CGR_{ES}, particularly under early planting, possibly due to quicker canopy closure and greater IPAR. Late hybrids are therefore most suited to early plantings, unless planting densities of early hybrids planted early are substantially increased. When planted late, early hybrids' CGR_{ES} either equalled or surpassed late hybrids. Late hybrids had less CGR_{SS} than earlier hybrids especially in late plantings and this was attributed to differences in mean temperatures during grain filling, affecting hybrids of varying cycle durations differently. Drought stress effects were more apparent under late planting conditions where CGR_{ES} values were as low as 1.2 vs. 2.3 gm^{-2} (^{0}Cd)$^{-1}$ for the same period when soil water status was adequate. Drought impact was generally higher for CGR_{SS}, resulting in up to 74% reduction in growth rates compared to 35% for CGR_{ES}.

Effective KGRs (0.36-0.38 mg $(^0Cd)^{-1}$) were higher than those reported in the literature, which helps explain the observed high average GYs (≥13 t ha^{-1}). At ≥19^0C, IPAR levels as low as 11 MJ m^{-2} d^{-1}, common under late PDs, did not affect KGR as assimilate supply during periods of reduced photosynthesis was likely met through stalk remobilisation. Lower or negative stover weight gains observed under late planting and drought conditions were due to remobilisation during grain filling caused by decreased photosynthetic activity as a result of diminishing radiation and temperature levels.

Direct effects of water stress or reduced assimilate supply for kernel growth under drought or late planting situations increased leaf senescence, which consequently reduced GY. When moisture conditions were adequate, particularly around flowering, leaf senescence followed a bilinear trend, proceeding at 0.03% $(^0Cd)^{-1}$ between flowering and mid grain fill, increasing to 0.2% $(^0Cd)^{-1}$ thereafter. Under drought conditions, senescence rates were much higher during early stages (0.09%) but slightly less than normal rates during the latter stages of grain filling (0.16%). Leaf senescence was also more rapid in barren plants possibly due to excess assimilate accumulation exacerbated by reduced grain set. Senescence was thus greater under early or late plantings, and this was attributed to sink-source imbalance. The shorter cycle duration and smaller sink size for early hybrids meant that under late planting or drought conditions, they had lower foliar senescence rates than later hybrids during phase one of senescence. While early hybrids had a generally higher rate of phase two senescence, they maintained a higher proportion of green LA at PM, implying either a better sink-source balance or limited sink size.

Grain moisture at PM ranged from 30-36%, with lower values recorded for early vs. late plantings. Late planting or stress conditions influenced source availability by shortening grain filling duration, resulting in higher kernel moisture. Since PM marks termination of grain filling and the beginning of grain drydown, moisture content at PM determines harvest time. To estimate field grain drydown, use of a minimum set of parameters (temperature and relative humidity) and a single equation across a range of hybrids, as suggested in this study would help simplify the ability for growers to select the best hybrid-ENV combination that suits their conditions.

CHAPTER 5: THE EFFECT OF PLANTING DATE ON MAIZE SILAGE YIELD AND QUALITY, LEAF PRODUCTION AND LEAF AREA DISTRIBUTION.

5.1 ABSTRACT

Four field experiments were established in Waikato and Manawatu over two years to determine planting date (PD) influence on silage yield (SY), quality and phenology of seven maize (*Zea mays* L.) hybrids. Silage yield response to PD was best described using quadratic regression models. Optimum PD was later in Manawatu (23rd October) than Waikato, where highest yields were obtained with 9-15 October plantings. In Manawatu and Waikato, planting 2 or 3 wk either side of the optimum PD, respectively, reduced silage yields by <5%. In Waikato, optimum PD for a warmer than average spring (+1^{0}C) was 1-2 wk earlier. With late planting, low yields were attributed to decreased temperatures (<15^{0}C) and radiation (<17 MJ m^{-2} d^{-1}) during grain filling. Due to more rapid autumn temperature and radiation declines in Manawatu, yield loss beyond optimum PD was greater (-183 kg ha^{-1} d^{-1} (0.6%); r^2=0.81***) than Waikato (-50 to 85 kg ha^{-1} d^{-1} (0.3%); r^2≥0.67***). Silage quality was highest for plantings before 6 November, dropping thereafter with harvest index. Silage yield had the greatest influence on predicted milk yield ha^{-1} (r=0.92***) whereas milk yield t^{-1} of silage was largely determined by starch (r=0.93***), acid detergent fibre (r=-0.81***) and neutral detergent fibre (r=0.77***).

At 11 plants m^{-2}, yields for early hybrids showed little response to PD, suggesting that higher densities may be required under early and optimum PDs. Between 13 and 19^{0}C, higher temperatures reduced leaf number by 0.1 leaves ^{0}C^{-1} whereas mean temperatures <17^{0}C and ≥20^{0}C reduced LAI. Phyllochron values were generally higher (47^{0}Cd) than those reported elsewhere. Soil temperature >22^{0}C, low radiation (≤17 MJ m^{-2} d^{-1}) and low precipitation (≤30 mm) between emergence and tassel initiation increased phyllochron to 51^{0}Cd.

Total plant leaf area was predicted as: *Leaf Area=((Area of largest leaf*8.18)-0.59)+0.03* Total leaf number; (R^2=0.95***).* The largest leaf on the plant ranged from one immediately above to two below the ear. The Gompertz function was used to

estimate visible leaf tip number from fully expanded leaves as follows: _Leaf tip=23.0*exp(-exp(-0.175*(fully expanded leaf number-4.8))); (_r^2_=0.998***)._ To predict phyllochron, bilinear regression of leaf tip appearance on thermal time improved estimates from the linear model by 50%.

5.2 INTRODUCTION

Maize silage is of major importance to the NZ Dairy Industry where 5.6 million cows are milked on 1.5 million ha of land to produce about 15 billion litres of milk every year (DairyNZ, 2009). Even though the dairy farming system is mainly grass based, the intensive production system and the continued demand for milk means that supplementary feeding from other sources such as maize silage plays a pivotal role in meeting winter and spring feed deficits. The common pasture rotation system in NZ thus includes maize silage as a supplement (Macdonald et al., 1998). Inclusion of maize silage in a grass based system has been found to increase feed intake, milk yield and milk protein levels (O'Mara et al., 1998; Phipps et al., 2000).

In NZ, maize silage is grown either on- or off-farm depending on individual situations. Growers are usually faced with the difficult task of selecting hybrids that would maximise SY and quality. Concurrently, the hybrid choices should fit within their farming systems such that harvesting is completed either in time for autumn grass planting or before the first killing frost. However, environmental factors such as temperature, radiation and water vary in a random manner around their seasonal mean trends, resulting in uncertainties in crop production.

There is need to quantify SY and quality responses of different maize hybrid maturities planted at variable times under a range of NZ ENVs. Environmental interactions with crop growth and development must be considered, since they influence crop cycle duration as well as yield and quality. For instance, if IPAR levels per plant around flowering are low, HI may be significantly reduced due to barrenness, consequently affecting silage quality (Sheaffer et al., 2006).

Silage quality is also affected by seasonal differences in temperature and soil water (Deinum and Bakker, 1981; Struik, 1983) as well as genotype (Deinum & Struik, 1989; Graybill et al., 1991). The maturity stage at harvest also affects silage quality, with total DM levels between 30 and 35% considered as the ideal balance to maximise both yield and quality (Wiersma et al., 1993; Phipps et al., 2000). Wiersma et al. (1993) noted that silage quality was inversely related to maturity stage at harvest and attributed this to grain content. Although research showing a high correlation between grain content and silage quality exists (e.g., Cox et al., 1994), this relationship has not been observed in the cooler climates of Europe and Canada (Dhillon et al., 1990).

Even though maize silage has mainly been adopted by dairy farmers for its bulk, energy content and ease of feeding, higher quality hybrids have also been developed to increase milk production (Darby and Lauer, 2002). Metabolisable energy (ME), ADF, NDF and digestible NDF (dNDF) contents are some of the parameters used for assessing the nutritive value of feed and forages (Wolfrum et al., 2009). Whereas ADF is a measure of the content of cell walls which are slowly digested, NDF represents the total cell wall content (i.e., the ADF fraction plus hemicellulose). On the other hand, dNDF constitutes the fibre that is not excreted in faeces. Both ADF and NDF contents are reported as percentages but for purposes of this discussion, they will largely be referred to as either ADF or NDF.

While individual quality parameters in isolation can provide an indicator of silage quality, their effects on cow performance may be strongly influenced by interactions with other factors. MILK2006 (Shaver et al., 2006), a model which predicts milk yield from a combination of feed quantity and quality factors has been developed to provide a useful and simple tool that helps farmers make informed feed decisions. The model removes the complexities arising from interactions between the ENV and plant parameters that determine quality.

Radiation interception is largely determined by LAI (Muchow, 1988; Andrade et al., 2000), leaf angle and vertical distribution of LA (Sivakumar & Virmani, 1984). Leaf area index is in turn influenced by plant density, leaf number and size while leaf number and size are influenced by genotype, N, water, temperature and photoperiod (Muchow and Carberry, 1989). Due to its influence on biomass accumulation and yield, LAI is a critical parameter in crop simulation models (Ritchie and NeSmith, 1991).

Leaf area can be measured directly using digital electronic area meters such as LI-3000C. Indirect methods based on the product of leaf length and width (Dwyer & Stewart, 1986) or area of the largest leaf (Elings, 2000), are also used. The latter may require a larger sample size to obtain acceptable accuracy (Francis et al., 1969). Leaf area calculations based on length and width of individual leaves utilise a coefficient originally established by Montgomery (1911) and recently validated (e.g., Birch et al., 1998a; Elings, 2000). Leaf area measurements are laborious and time consuming and the method used depends on the required accuracy and availability of equipment and time.

Phyllochron (or the time between successive leaf appearances) is used to predict canopy production as well as crop development. Crop models such as CERES-Maize use leaf number and phyllochron to predict flowering time. Phyllochron is based on the appearance of visible leaf tips rather than fully expanded leaves. However, data on fully expanded leaves are more often collected than the former. Leaf tips can be indirectly estimated from fully expanded leaf number up to leaf tip 10 using the relationship:
*Fully expanded = 0.7*visible leaf tip number - 1* (Hardacre and Turnbull, 1986).

In chapters 3 and 4, effects of PD on GY, development rates and source-sink relations were described. This chapter describes how environmental factors (temperature, radiation, photoperiod and water), as dictated by PD, interact with hybrid maturity to influence plant growth (e.g., leaf growth functions) and SY and quality. Alternate methods to simplify routine phenology measurements which are used in deterministic crop simulation models such as CERES-Maize (e.g., estimation of total LA or leaf tips) are also described.

5.3 MATERIALS AND METHODS

5.3.1 Background

Site and planting details are described in detail in Chapter 3. In summary, four replicated experiments were conducted over two seasons at Rukuhia Research Station in 2006 (RUK07), and 2007 (RUK08), Ngaroto Research Station in 2007 (NGA08) and Massey University in 2007 (MAS08). Massey University is located in Manawatu, which is 400 km south of the other sites in Waikato, and is characterised by a shorter growing season. Hybrids planted at each site, weather data collection and experimental design have also been described in Chapter 3.

5.3.2 Photoperiod sensitivity

Photoperiod sensitivity was considered as the difference in TT from emergence to TI divided by the hours by which photoperiod exceeded 12.5 h in the period 4-7 d before TI (i.e., $[\frac{\delta\, TT}{\delta\, photoperiod\ at\ TI} - 12.5\ h]$) (Kiniry et al., 1983a). Photoperiod was estimated using the Martindale Centre Photoperiod Calculator (Lammi, 2008). Effective photoperiod is usually estimated as the time between successive civil twilight hours (Bonhomme et al., 1994). Civil twilight begins in the morning and ends in the evening when the centre of the sun is 6^0 below the horizon and marks the point at which twilight illumination is sufficient, under good weather conditions, for terrestrial objects to be clearly distinguished without the aid of artificial lighting.

5.3.3 Leaf number, visible leaf tip appearance and fully expanded leaves

Before the first leaf had senesced, ten plants in the centre two rows (five consecutive plants per row) were tagged by cutting the tip of leaf 5 (see Plate 5.1), considering the leaf with the characteristic rounded tip as leaf one rather than the coleoptile. Leaf 10 was also tagged as soon as it appeared. Tagged leaves were used as reference points for convenient and accurate counting of leaf number after the lower leaves had senesced.

At RUK07, the total number of leaf tips visible from outside the whorl (see Plate 5.2) and the number of fully expanded leaves (visible ligule) were recorded every 3 or 6 d, respectively, from seedling emergence until flag leaf emergence. For management reasons, both leaf tips and fully expanded leaves were recorded every five to six days at RUK08 and NGA08, while at MAS08 they were recorded every 10-12 d.

Plate 5.1 A maize plant showing a tagged leaf tip for use as a reference point.

Plate 5.2 A maize plant showing a leaf tip emerging from the whorl.

Leaf appearance rate was determined by linear regression of leaf number on cumulative TT (T_b8) between appearances of the first to final leaf. A combination of soil (before TI) and air temperatures (after TI), was used to calculate TT for leaf appearance (see section 3.3.3, Chapter 3 for details of TT calculations).

Bilinear functions were also explored to determine rates of leaf tip emergence in response to TT, considering the interval up to 90% of total leaf number (leaf 15-18, depending on hybrid) as one linear segment and the remaining leaves as the second linear segment. To determine the best method for predicting leaf development at different stages of leaf production, the bilinear function was compared against the linear regression between leaf one and the appearance of the final leaf using the RMSE to quantify the variation between models. Root mean square error was used as a goodness-of-fit indicator between measured and predicted values and was calculated as:

$RMSE = \sqrt{\frac{1}{\mathrm{n}}\sum(\mathrm{yi} - \mathrm{\hat{y}i})^2}$, (Willmott, 1982; Potter and Williams, 1994)

where y_i is the measured value, $\hat{y}_i$ is the estimated value of the dependent variable, and n is the number of observations. Small RMSE values indicate high accuracy of the estimated value to predict the actual value of the variable.

Despite the ease of obtaining leaf tip data, it has limited use in the literature compared to fully expanded leaf number. The relationship between visible leaf tips and fully expanded leaf number was thus estimated using data from RUK07 and validated for its adequacy using data from MAS08, NGA08 and RUK08.

5.3.4 Plant and ear height

Average plant height for the 10 tagged plants in the centre two rows were measured as the distance between the ground level and the flag leaf collar soon after anthesis (Lizaso et al., 2005). Node position of the primary ear (leaf number and distance from the ground) for the 10 plants was also recorded. Average internode length was estimated as a ratio of plant height to total leaf number minus six, (i.e., $[\frac{Plant\ height\ (cm)}{Total\ leaf\ number - 6}]$), based on the assumption that the first six internodes do not expand during vegetative growth (Morrison et al., 1994).

5.3.5 Leaf Area Index

At anthesis, four consecutive plants originally tagged for leaf appearance observations were selected for LA measurements in each plot. The length (from ligule to leaf tip) and width (the widest portion of the leaf blade) of each green leaf were measured at RUK07. Individual LA was estimated as the product of leaf length and maximum breadth, adjusted by a constant coefficient as follows:
*LA = length * maximum width * 0.75 (*Montgomery, 1911; Muchow and Davis, 1988; Elings, 2000).

Leaf area per plant was calculated by summing the individual LAs. Leaf area index for each plot was calculated as the average plant LA divided by the average land area occupied by a single plant. Due to the cumbersome nature of the LA measurements, multiple linear regression analysis was conducted to establish the relationship between the total LA per plant and other associated variables (e.g., EL or largest LA, total leaf number, plant height etc.) for PD1, PD3 and PD5 at RUK07. Using independent data sets from PD2 and PD4, validity of the established relationship was tested against the measured LA data using RMSE to quantify the variation between the actual and predicted LA. The validated relationship was then used to estimate total plant LA at RUK08, NGA08 and MAS08.

5.3.6 Total biomass at 50% anthesis

Total aboveground biomass at 50% anthesis was only measured in the Waikato ENVs. Biomass yield was estimated from a bordered area of 1.5 m^2 (4 rows x 0.76 m x 0.5 m length) at RUK07 and RUK08. At NGA08, only the two central rows were harvested (0.76 m^2). Plants were cut at ground level and separated into leaf, stem, tassel and ear components. Fresh weights of each component were recorded immediately and oven dried to constant weight at 75^0C.

5.3.7 Silage Yield

A bordered area of 7.6 m^2 (2.5 m x 0.76 m x 4 rows) was hand-harvested for silage at approximately 35% DM content at RUK07. Harvested areas for the other sites were 9.8 m^2 (3.5 m x 0.7 m x 4 rows), 5.9 m^2 (3.9 m x 0.76 x 2 rows) and 11.9 m^2 (3.9 m x 0.76 m x 4 rows) for MAS08, NGA08 and RUK08, respectively. To accurately determine harvest time, plants from the border rows were periodically sampled and oven dried to determine DM content, starting when kernels from the centre of the ear had reached about 50% milk line (Wiersma et al., 1993; Ma et al., 2006; also see Plate 5.3). Prior to harvest, total number of plants per plot, number of barren, and root and stalk lodged plants were counted.

Plate 5.3 A maize crop ready for silage harvesting.

Plants were cut at ground level and weighed immediately. Six plants were randomly selected as a subsample for DM and quality analysis. The six plants were mulched into a homogenous sample using a modified chipper shredder (Plate 5.4). A 1 kg subsample from the mulched biomass was oven dried to constant weight at 75^0C to estimate silage DM. A further 1 kg subsample was collected for silage quality determination. The sample was sent to the laboratory for near-infrared spectroscopy (NIRS) using the Pioneer® World Forage NIRS calibration (Welle et al., 2003). The calibration equation allows prediction of silage quality composition based on its NIRS spectrum. Near-infrared spectroscopy analysis was performed to analyse the following parameters: starch, crude protein (CP), ADF, NDF, dNDF, ash and soluble sugars. The samples were initially oven dried at 62^0C overnight and ground to pass through a 1 mm screen.

Plate 5.4 A modified chipper shredder used to mulch sample plants for dry matter subsampling.

Based on SY and NIRs trait values, milk yield was estimated using MILK2006, the decision support software developed at the University of Wisconsin (Shaver et al., 2006). MILK2006 uses silage quality composition to estimate potential milk yield t^{-1} of silage fed (milk t^{-1} index) and also calculates potential milk yield ha^{-1} of harvested maize silage (milk ha^{-1} index) largely based on SY. Milk ha^{-1} index measures the relative response of milk yield per unit area of silage production. Hereafter, the milk t^{-1} index and the milk ha^{-1} index will simply be referred to as milk t^{-1} or milk ha^{-1}. To estimate the milk yields, MILK2006 utilises silage moisture content and DM yield (tons ha^{-1}), CP, starch, fat, ash, NDF and dNDF contents.

5.3.8 Data analysis

Data analysis methods and assumptions were as reported in Chapter 3. Proc GLM of SAS was used to estimate the relationships between biomass yields and quality traits, LAI, leaf number and plant height and associated components by linear regression on PD or TT. Leaf emergence data (tip and fully expanded) were regressed on TT to estimate rate of leaf emergence. Leaf tip data for RUK07 were regressed against fully expanded leaf data using either linear regression or the Gompertz function (Emmans, 1981). The resultant relationships were then validated against MAS08, NGA08 and RUK08 data using RMSE as described in section 5.3.3. Linear vs. bilinear TT estimations for leaf tip appearance were also compared using RMSE. Multiple linear regressions were conducted to estimate total plant LA from area of the largest leaf or the ear leaf (EL), total leaf number plant^{-1} and plant height. To quantify effects of environmental factors on leaf number, multiple linear regressions against average mean soil and air temperature, solar radiation between emergence and TI, and photoperiod 1-5 d prior to TI on leaf number were also conducted.

Only results that are significant at $P<0.05$ level are discussed. The following notation *, ** and *** is used to illustrate significance at $P<0.05$, $0.001<P<0.01$, and $P<0.001$ respectively, while NS refers to $P\geq0.05$.

5.4 RESULTS

5.4.1 Weather summary

Mean monthly weather data are described in Chapter 3. Despite the higher radiation levels during early developmental stages for late plantings, early PDs generally accumulated more total radiation between emergence and flowering due to slower development under the lower temperature conditions (Table 5.1). At RUK07, for example, average planting to flowering duration for PD1 was 108 d vs. 67 d for PD5. Other than RUK07 where December night temperatures were abnormally low (Table 3.1, Chapter 3), a steady increase in mean temperature for PD1 to 5 characterised all ENVs. Table 5.2 illustrates average daylength and air temperature 1-5 d prior to TI for each PD. There was comparatively little variation in daylengths (≤0.6 h) among PDs in all ENVs. Plantings at MAS08, NGA08 and RUK08 were characterised by considerable drought in summer and were also dominated by higher than normal spring and summer temperatures.

Table 5.1 Total solar radiation and mean temperature between emergence and flowering (maize) across planting date treatments for MAS08, RUK07, RUK08 and NGA08.

	Solar Radiation				Mean Temperature			
	RUK07	MAS08	NGA08	RUK08	RUK07	MAS08	NGA08	RUK08
PD	MJ m^{-2}				^{0}C			
1	2130	-	1952	1971	14.4	-	15.2	15.2
2	1923	1696	1730	1788	15.3	15.7	16.2	16.3
3	1792	1585	1607	1638	16.0	16.8	17.3	17.4
4	1632	1530	1469	1507	16.9	17.8	18.7	18.8
5	1440	1593	1480	1465	17.7	18.1	19.4	19.4

Table 5.2 Average daylength and mean air temperature for 1-5 d prior to tassel initiation for 4 or 5 planting date treatments at MAS08, RUK07, RUK08 and NGA08.

	Daylength				Mean air temperature			
	RUK07	MAS08	NGA08	RUK08	RUK07	MAS08	NGA08	RUK08
PD	h				^{0}C			
1	14.2	-	14.3	14.3	15.5	-	15.0	15.2
2	14.6	14.8	14.5	14.6	13.6	14.1	14.9	15.3
3	14.8	15.0	14.7	14.7	14.7	17.2	18.3	18.0
4	14.7	15.1	14.8	14.8	14.0	17.3	18.4	19.2
5	14.5	14.9	14.6	14.6	20.0	18.6	20.1	20.1

5.4.2 Silage yield

Highest SYs were obtained at MAS08 (Table 5.3), which experienced above average mean summer temperatures (+1^{0}C) and adequate water supply through the application of 178 mm of supplementary sprinkler irrigation in addition to 414 mm of rainfall received between October and April. The lowest yields were recorded at RUK08, under severe drought.

Table 5.3 Silage dry matter yields for NGA08, RUK08, RUK07 and MAS08 across planting dates (PDs); se is standard error over PD treatments for all hybrid maturities.

PD	MAS08	NGA08	RUK08	RUK07		
	Hybrid maturity					
	All	All	All	Early	Mid	Late
	kg ha^{-1}					
1	-	24639	18498	22928	23508	25107
2	30092	24400	17440	22176	24268	26214
3	29025	24596	16219	21951	23444	24500
4	27838	21237	15086	22026	23116	23758
5	22496	19537	13808	21345	20977	20862
se	658	329	382	684	684	684
	Significance					
PD	***	***	***		***	
Maturity	NS	NS	NS		NS	
PD*Maturity	NS	NS	NS		**	

RUK07, a typical Waikato season, was the only ENV that exhibited a significant PD x maturity interaction for SY. At RUK07, while early hybrids yielded similarly across PDs, a quadratic response to PD was obtained for mid (r^2=0.74**) and late hybrids (r^2=0.79**). Maximum predicted yields were obtained by planting on the 9th and 15th October, respectively. Yields were generally higher for later hybrids under early planting but as planting was delayed, the yield gap between the hybrid maturities narrowed (Figure 5.1a). Once past the optimum PD, linear yield reductions of 47 (mid) and 77 kg ha^{-1} d^{-1} (late; $r^2 \geq 0.8$**) were observed.

Quadratic regression also explained the yield response to PD of all hybrid maturities at both MAS08 (r^2=0.91***) and NGA08 (r^2=0.64***; Figure 5.1b). Optimum PDs were estimated to occur on 2 and 23 October at NGA08 and MAS08, respectively. Planting past the estimated optimum PD resulted in linear yield losses of 85 (r^2=0.67***) and

183 kg ha^{-1} d^{-1} (r^2=0.81***) for NGA08 and MAS08. At RUK08 where moisture stress was most pronounced, planting delay resulted in a linear yield decrease of 56 kg ha^{-1} d^{-1} (r^2=0.76***; see Figure 5.1b)

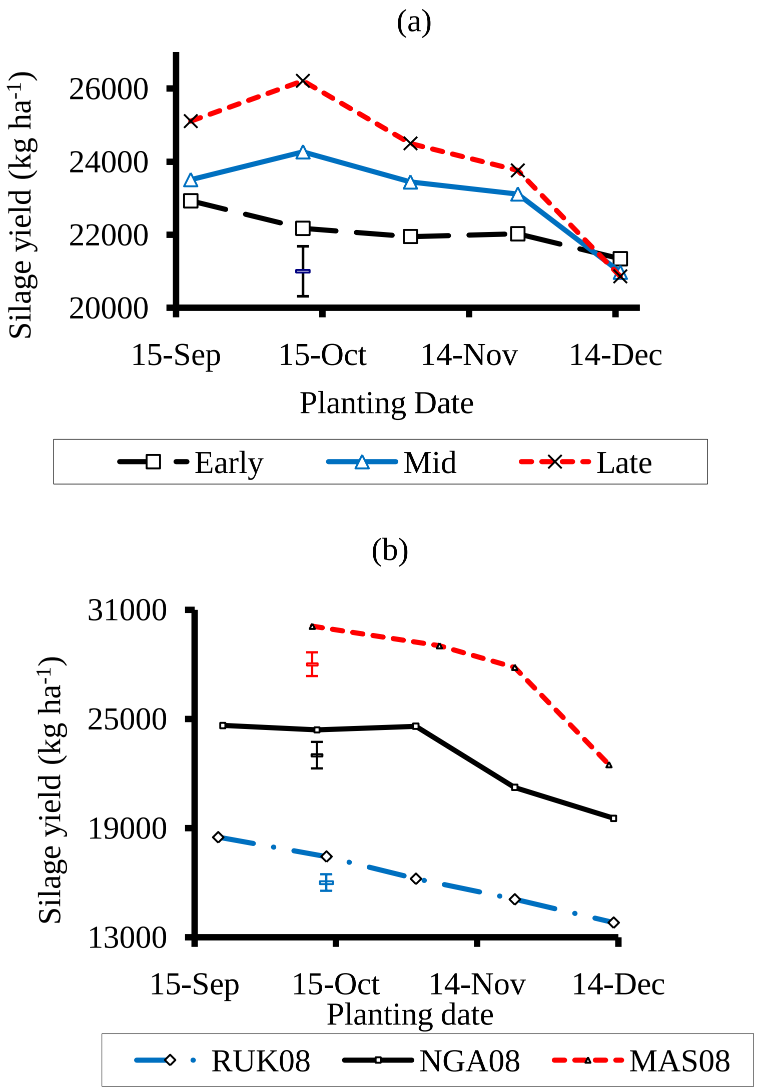


Figure 5.1 Silage dry matter yields as affected by PD and hybrid maturity at a) RUK07 and (b) RUK08, NGA08 and MAS08. The vertical bars show standard error (±se) across treatment means.

Across all sites, positive correlations were observed between SY and GY (r=0.87***) and total aboveground biomass at maturity (r=0.94***). In the water stressed ENVs (RUK08 and NGA08) SY was negatively correlated with senescence at maturity (-0.57***).

5.4.3 Silage quality traits

Silage quality traits were estimated at RUK07, NGA08 and MAS08. The highest average CP levels were recorded at MAS08 (7%) vs. NGA08 (6.4%) and RUK07 (6.5%). The effect of PD on CP was only significant at NGA08 where PD1 had the lowest CP (5.9%) vs. 6.7% for PD5 and an average of 6.5% for the remaining treatments.

In general, high starch contents were recorded under early planting treatments while late planting resulted in the lowest values. The highest starch levels (29%) were observed at RUK07 and MAS08, both of which experienced no water stress, compared to 26% at NGA08 (Table 5.4). At RUK07 and MAS08, a significant PD x maturity interaction for starch existed. In both ENVs, mid hybrids maximised starch content under the first planting and had the lowest values under the last two PD treatments. Conversely, for late hybrids, starch content responded in a quadratic manner with PD, resulting in the highest values (>31%) when planted on 3 November (MAS08) or 24 October (RUK07). For early hybrids, with the exception of PD2 at RUK07, which was considered an outlier as the low values could not be explained, the lowest starch contents were observed at PD5 while early planting provided conditions for the highest starch values.

Table 5.4 Predicted silage starch content averaged over 4 or 5 planting dates (PDs) at NGA08, RUK07 and MAS08; se is standard error across PDs for all hybrid maturities.

	RUK07			MAS08			NGA08
	Hybrid maturity						
PD	Early	Mid	Late	Early	Mid	Late	All
	%						
1	31.8	31.3	27.6	-	-	-	22.2
2	25.8	30.4	30.4	32.4	35.0	29.7	28.8
3	32.8	28.5	31.9	-	34.7	30.9	28.1
4	30.1	27.4	27.0	28.2	26.2	30.0	25.5
5	27.8	27.4	25.5	25.8	26.7	22.5	23.7
se	1.33	1.33	1.33	1.63	1.15	1.15	0.95
	Significance						
PD		**			***		***
Maturity		NS			*		NS
PD*Maturity		**			**		NS

Delayed planting at MAS08 resulted in linear decreases in starch content of 0.12% d^{-1} (r^2=0.99***) and 0.18% d^{-1} (r^2=0.7***) for early and mid hybrids, respectively. At NGA08, which experienced moderate drought stress, the highest levels of starch were obtained with 31 October planting (>28%) while 22 and 24% starch were recorded under PD1 and 5, respectively.

The highest average NDF values were obtained at NGA08 (45%) compared to 43% for MAS08 and RUK07. As with starch content, RUK07 and MAS08 showed significant PD x maturity interactions for NDF. At RUK07, NDF ranged from 42 to 48% across maturity and PD treatments, with NDF in late hybrids responding quadratically to PD. The lowest NDF values were attained with 19 October plantings (r^2=0.72*). MAS08 however had much wider ranges of 40-49%, 36-48% and 39-50% for early, mid and late hybrids. In general, the highest values were observed under late planting. As at RUK07, late hybrids showed a quadratic response of NDF to PD, yielding the lowest NDF values when planted on 25 October, unlike mid hybrids that increased linearly by 0.24% d^{-1} (r^2=0.89) when planting was delayed past PD1. At NGA08, NDF ranged from 43 to 50% and highest values were observed under both early and late planting. The lowest values of 43% were recorded for 12 November planting (r^2=0.61***).

Digestible NDF was significantly higher at RUK07 and MAS08 (44.5%) than NGA08 (43.7%). While late hybrids had the least dNDF at RUK07 and NGA08, at MAS08, early hybrids had the lowest dNDF values (42%). At MAS08 and RUK07, the highest dNDF values were observed under early plantings, unlike NGA08 where early PDs were exposed to hot dry conditions during growth. The general pattern for dNDF in the absence of drought was therefore a decline with PD.

In general, ADF content increased with PD. As with other quality traits, significant PD x maturity interactions for ADF were observed at RUK07 and MAS08. At RUK07, all hybrids had the lowest ADF under PD1 conditions. Between PD1 and PD5, early and mid hybrids marginally increased, respectively, from 20 and 23% to 25.5%. The ADF of late hybrids ranged between 25.5-26.4% from PD1 to PD4, before increasing to 30% under PD5. Delayed planting resulted in a linear increase (0.04% d^{-1}; r^2>0.42*) in ADF for early and late hybrids. At MAS08, the lowest ADF values (21%) were generally obtained under the first two plantings. PD5 had the highest ADF, particularly for early

(30%) and late hybrids (29%). Late hybrids showed a quadratic response of ADF to PD. The lowest values were recorded for 29 October plantings (r^2>0.94***) whereas ADF in mid hybrids increased linearly at 0.16% d^{-1} after PD1. Acid detergent fibre content was significantly higher at moderately water stressed NGA08 ENV (26.4%) than RUK07 (25.3%) and MAS08 (24.9%). NGA08, which exhibited a quadratic response to PD, recorded the highest ADF with PD1 (28.5%) compared to between 25.2 and 26.7% for the remaining PD treatments. The lowest ADF values were obtained with 13 November planting. Overall, ADF values paralleled NDF (r=0.91***) whereas an inverse relationship existed between ADF and starch (r=-0.76***).

In the absence of drought, SY was weakly correlated to ADF (r=-0.56***), NDF (r=-0.59***), dNDF (r=0.33*), starch (r=0.47**) and CP (r=0.47***). Table 5.5 illustrates the correlation coefficients for quality traits against HI, SY and predicted milk yield across all ENVs.

Table 5.5 Correlation coefficients for silage quality traits vs. silage yield and harvest index (HI) at NGA08, RUK07 and MAS08. Only values with P<0.01 are presented. NS refers to not significant at P<0.01.

	Silage yield	HI	ADF	NDF	dNDF	Starch
Silage yield	-	-	-	-	-	-
HI	NS	-	-	-	-	-
ADF	-0.39	-0.61	-	-	-	-
NDF	-0.38	-0.50	0.91	-	-	-
dNDF	NS	0.56	-0.75	-0.60	-	-
Starch	0.39	0.42	-0.76	-0.81	0.31	-
CP	NS	0.32	-0.58	-0.55	0.59	0.48

5.4.4 Milk t^{-1} index

MILK2006 (Shaver et al., 2006) was used to generate milk t^{-1} largely using the silage quality traits presented above. Milk t^{-1} can be considered as a surrogate for silage quality, as reflected by the high correlations with quality traits compared to SY (Table 5.5). Significantly higher values were obtained at MAS08 (1658 kg t^{-1}) and RUK07 (1640 kg t^{-1}) vs. NGA08 (1547 kg t^{-1}). Though not necessarily significant, earlier hybrids generally resulted in more milk t^{-1} across ENVs (data not shown).

A significant maturity x PD interaction for milk t^{-1} existed at RUK07 and MAS08 (Table 5.6). At NGA08, like starch, highest milk t^{-1} values were observed with plantings conducted around 2 November while the lowest values were obtained under PD1 (1482 kg t^{-1}) followed by PD4 (1521 kg t^{-1}) and PD5 (1531 kg t^{-1}).

Table 5.6 Predicted milk t^{-1} from silage for RUK07, NGA08 and MAS08 over 4 or 5 planting dates; se is standard error across PD treatments for all hybrid maturities.

	RUK07			MAS08			NGA08
	Hybrid maturity						
PD	Early	Mid	Late	Early	Mid	Late	All
				kg t^{-1}			
1	1768	1745	1610	-	-	-	1482
2	1606	1650	1647	1683	1802	1674	1600
3	1701	1626	1672	-	1807	1716	1600
4	1710	1619	1537	1611	1581	1699	1521
5	1591	1607	1509	1510	1594	1562	1531
se	32.1	32.1	32.1	42.1	29.8	29.8	24.8
				Significance			
PD*Maturity		*			**		NS
Maturity		***			NS		NS
PD		***			***		***

A linear response of milk t^{-1} to PD was evident for mid hybrids at MAS08 (-5 kg t^{-1} d^{-1}; r^2=0.72**) and RUK07 (-1 kg t^{-1} d^{-1}; r^2=0.46*) whereas a quadratic response was observed for late hybrids at MAS08 (r^2=0.75*). At RUK07, late hybrids resulted in significantly less milk t^{-1} than early and mid hybrids. Across all ENVs and hybrid maturities, there was a significant drop in milk t^{-1} with very late planting (i.e., PD4 or PD5, depending on ENV and hybrid maturity).

5.4.5 Milk ha^{-1} index

Milk ha^{-1} was more strongly associated with SY than quality factors (data not shown). The highest average milk ha^{-1} values were obtained at MAS08 (39815 kg ha^{-1}) compared to 34360 and 32189 kg ha^{-1} for RUK07 and NGA08, respectively. As with SY, PD x hybrid maturity interaction effects for predicted milk ha^{-1} were only observed at RUK07. At both MAS08 and NGA08 there was a highly significant quadratic response of milk ha^{-1} to PD (r^2=0.87***; r^2=0.63***, respectively; Figure 5.2a). The highest amount of milk ha^{-1} was obtained by planting on 15th October (NGA08) or 22nd October (MAS08), coinciding with the dates that maximised SY. At RUK07, late hybrids also showed a quadratic response of milk ha^{-1} to PD, initially increasing from 36745 kg ha^{-1} to reach 39147 kg ha^{-1} under PD2 before eventually decreasing to 28584 kg ha^{-1} for PD5 (r^2=0.88***; Figure 5.2b).

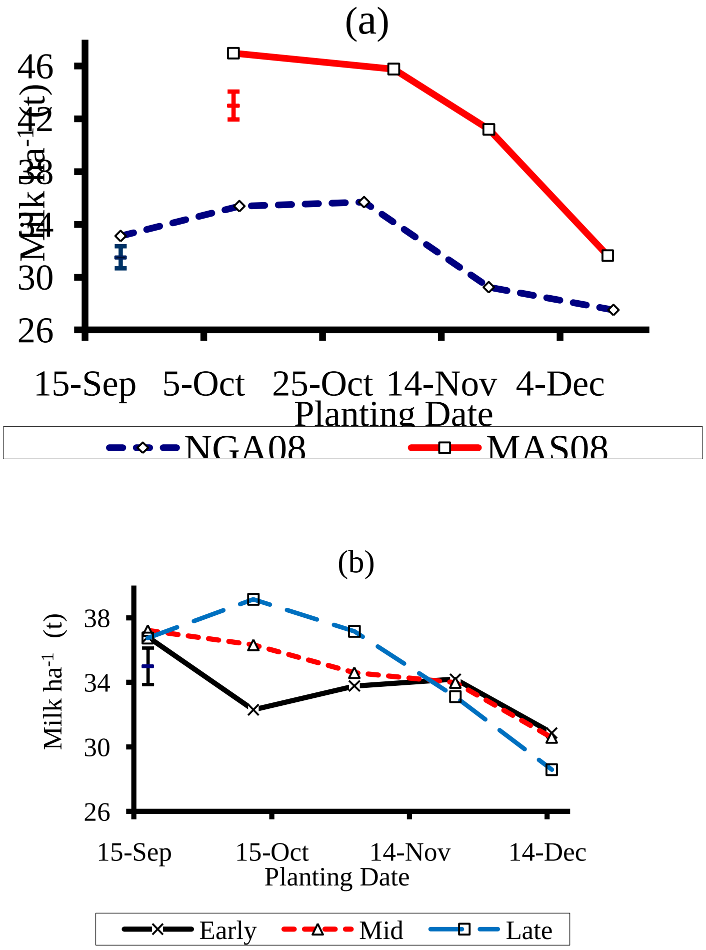


Figure 5.2 Milk ha^{-1} (MILK2006) at (a) NGA08, MAS08 and (b) RUK07 over 4 or 5 planting dates. The vertical bars show standard errors (±se) across treatment means.

The predicted PD to maximise milk ha^{-1} at RUK07 for late hybrids was 11 October. However, a linear trend was observed with mid hybrids (-71 kg ha^{-1} d^{-1}, r^2=0.77***). Even though a high value was observed under PD1 with early hybrids (36820 kg ha^{-1}), unlike mid and late hybrids, there were small variations across PDs thereafter (30860 - 34198 kg ha^{-1}). As planting was delayed, early and mid hybrid classes outperformed late hybrids for milk ha^{-1}.

Over all ENVs, starch content had the most significant influence on milk t^{-1} (r=0.92***), while SY was the largest determinant of milk ha^{-1} (r=0.93***).

5.4.6 Total biomass yield at anthesis

The highest average biomass yields at anthesis were obtained at NGA08 and RUK08 (12952 and 13028 kg ha^{-1}). Both these sites experienced above average summer temperatures (+1.5^{0}C) compared with the more normal conditions of RUK07 (11565 kg ha^{-1}; Table 5.7) (Also see section 3.4.1, Chapter 3).

Significant PD x maturity interactions on biomass were observed at RUK07 and NGA08 where almost all maturities displayed a quadratic response to PD. At NGA08, a quadratic response of biomass yield to PD was observed for early (r^2=0.83**) and late hybrids (r^2=0.63*). Maximum yields were observed with 16 (>13900 kg ha^{-1}) and 27 October plantings (>15500 kg ha^{-1}) for early and late hybrids, respectively. The lowest yields of 10615 and 10874 kg ha^{-1} were observed under PD5 for early and late hybrids. Biomass at anthesis for mid hybrids declined linearly from approximately 14000 kg ha^{-1} with early planting, reaching 10392 kg ha^{-1} at PD5 (-39 kg ha^{-1} d^{-1}; r^2=0.66**).

At RUK07, biomass at anthesis in early hybrids increased linearly between PD1 and PD4 at 21 kg ha^{-1} d^{-1} (r^2=0.56*) from 9800-11722 kg ha^{-1} before falling slightly thereafter. Conversely, late hybrids showed significantly higher biomass at anthesis under PD4 plantings (14129 kg ha^{-1}) compared to the rest of the PD treatments. With mid hybrids, biomass at anthesis was highest under PD3 (11521 kg ha^{-1}) and PD4 (11953 kg ha^{-1}).

Table 5.7 Total aboveground biomass yields at 50% anthesis for NGA08, RUK08 and RUK07 over 5 planting dates (PDs); se is standard error across PD treatments for all hybrid maturities.

	RUK08	RUK07			NGA08		
	Hybrid maturity						
PD	All	Early	Mid	Late	Early	Mid	Late
	t ha^{-1}						
1	14.16	9.80	10.02	12.97	13.48	12.78	13.32
2	13.77	10.27	10.16	12.22	13.59	14.15	14.52
3	14.19	11.50	11.52	12.17	13.98	12.86	14.72
4	11.96	11.72	11.95	14.13	12.58	10.88	15.56
5	11.07	11.41	10.78	12.85	10.62	10.39	10.87
se	0.403	0.449	0.449	0.449	0.563	0.563	0.563
	Significance						
PD	***		***			***	
Maturity	NS		*			NS	
PD*Maturity	NS		*			***	

At RUK08 biomass at anthesis declined with PD from about 14000 kg ha^{-1} for PD1-3, to 11065 kg ha^{-1} at PD5, falling at a rate of -39 kg ha^{-1} d^{-1} (r^2=0.44***). Across ENVs, biomass at anthesis was positively correlated with LAI (r=0.67***) and plant height (r=0.55***).

5.4.7 Plant height

Plants were tallest at NGA08 and RUK07 (2.4 m) relative to RUK08 and MAS08 (2.2 m). Planting date x maturity interaction for plant height existed in all Waikato ENVs. Under the RUK07 ENV, all hybrid classes showed initial linear height increases of 9 (r^2=0.92***), 10 (r^2=0.54*) and 8 mm d^{-1} (r^2=0.92***) for early, mid and late hybrids between 18 September and 24 November plantings, followed by a decrease of 2-4% for later plantings. When the linear response was computed for PD1 to PD5, the rate of increase was between 6-7 mm d^{-1} for early (r^2=0.92***), mid (r^2=0.44*) and late hybrids (r^2=0.77***). At MAS08, plant height increased linearly with planting delay at a rate of 3 mm d^{-1} (r^2=0.21*).

At NGA08, where growth occurred under hot, dry conditions, plants were much shorter when planted late. The height of early hybrids responded to PD in a quadratic manner

(r^2=0.84**), and tallest plants were predicted to occur with a 6 October planting. A linear decline in plant height (-7 mm d^{-1}) was observed with planting delay for both mid (r^2=0.43*) and late hybrids (r^2=0.89***) in this ENV.

At RUK08, which like NGA08, also experienced hot dry conditions during stem elongation, there was a negative response of height to PD for early (-6 mm d^{-1}; r^2=0.68**), mid and late hybrids (-7 mm d^{-1}; r^2=0.58* and 0.94***, respectively).

5.4.8 Leaf number

Across ENVs, the average leaf number was highest at NGA08 (18.7) and RUK08 (18.6). RUK07 averaged 18.4 leaves across treatments while MAS08, which had an earlier set of hybrids, had the lowest total leaf number (17.9). Leaf number was associated with TT from emergence to TI (r=0.67***) and TT from emergence to anthesis (r=0.75***), both of which are a reflection of maturity. Maturity x PD interactions for leaf number were significant in all ENVs but NGA08.

At NGA08, PD had a highly significant effect on leaf number, with the highest numbers obtained under PD1 (19.1) and PD2 (18.9) conditions (Table 5.8). The lowest values were recorded in the fourth and fifth plantings.

At MAS08, both mid and late hybrids showed significantly higher total leaf numbers with the first planting, relative to later plantings. The last two plantings had the least number of leaves. The early group however had a significantly lower leaf number under PD4 compared to the other plantings. Reasons for the anomaly could not be established and may simply have been due to sampling error.

Under RUK07 conditions, even though the hybrid maturities differed somewhat for when leaf number was maximised (e.g., PDs 3 and 4 for early, PDs 2, 3 and 4 for mid, and PDs 2 and 4 for late hybrids), PD1 and PD5 generally had the least leaf numbers. Under the RUK08 ENV, which experienced increasing temperatures associated with dry conditions, both early and mid hybrid classes resulted in the highest leaf numbers under PDs 1-3 and least under PDs 4 and 5. Leaf numbers of late hybrids declined linearly with PD at -0.06 leaves wk^{-1} from a high at PDs 1 and 2.

Table 5.8 Total leaf number for RUK07, NGA08, RUK08 and MAS08 over 4 or 5 planting dates (PDs); se is standard error across PD treatments for all hybrid maturities.

	NGA08	MAS08			RUK07			RUK08		
					Hybrid Maturity					
PD	All	Early	Mid	Late	Early	Mid	Late	Early	Mid	Late
1	19.1	-	-	-	17.6	17.5	19.5	18.1	18.4	20.2
2	18.9	16.9	19.3	19.1	17.7	18.3	20.1	18.3	18.4	20.1
3	18.7	17.0	18.4	18.3	18.4	18.3	19.7	18.3	18.2	19.8
4	18.4	16.3	18.1	18.0	18.1	18.2	20.2	17.8	17.6	19.5
5	18.5	16.7	18.1	18.0	17.3	17.2	18.7	17.6	17.7	19.1
se	0.30	0.97	0.69	0.69	0.67	0.67	0.67	0.61	0.61	0.61
					Significance					
PD*Maturity	NS		***			***			***	
Maturity	NS		NS			NS			NS	
PD	***		***			***			***	

Analysis of mean soil and air temperatures (from emergence to TI and 1-5 d prior to TI), photoperiod (1-5 d prior to TI) and solar radiation effects on leaf number showed that average air temperature between emergence and TI was the only factor with a significant effect on leaf numbers across all ENVs (r=-0.21*). When separated by ENV, it was only RUK07 where air temperature was not significantly correlated with leaf number. The largest temperature effects were observed at MAS08 (r=0.39**). Photoperiod did not influence leaf number (Chapter 4).

An increase in mean air temperature between emergence and TI within the range of 13 and 19^0C reduced leaf numbers by about 0.1 leaves $^0C^{-1}$. The largest leaf number responses were experienced at MAS08 where average temperatures ranged between 13-17^0C, compared to NGA08 and RUK08 which ranged from 16-19^0C. When air temperature 1-5 d before TI was considered, effect on leaf number was only observed at MAS08 (-0.3 leaves $^0C^{-1}$; r=0.49*). While leaf number is itself a reflection of hybrid maturity, response of different hybrid maturities to temperature was similar.

5.4.9 Leaf area distribution

To alleviate the arduous nature of manually measuring total plant LA, the established relationship between area of the largest leaf and total plant LA was considered an adequate predictor of total plant LA (R^2=0.97***, RMSE=0.021 m^{-2}, mean=0.62 m^{-2};

Figure 5.3). The data from all PD treatments at RUK07 were then merged and used to predict LA for RUK08, MAS08 and NGA08 using:

LA = LLA x 8.18 - 0.59 + 0.03 x LN (R^2*=0.95***, n=54)*

where *LA* = total plant leaf area; *LLA* = area of largest leaf; and *LN* = total leaf number.

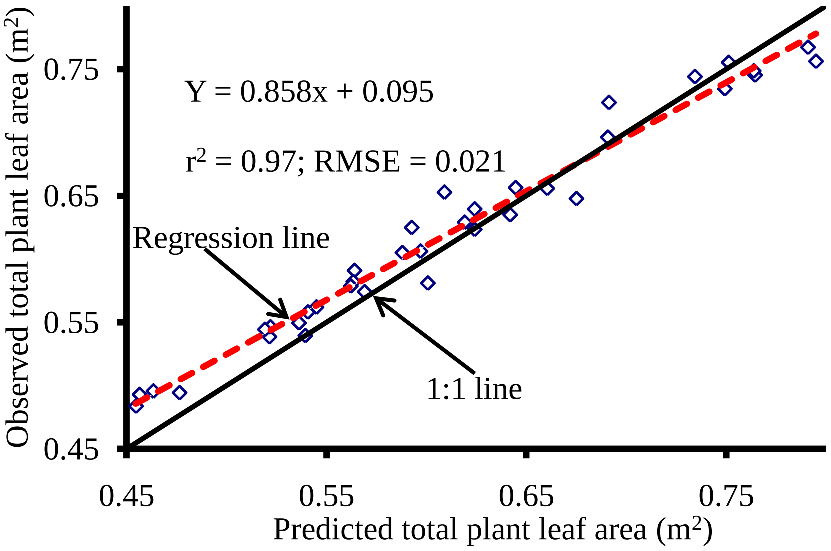


Figure 5.3 Comparison of actual and predicted total plant leaf area using independent data from RUK07 (PD2 and PD4).

To further enhance the process of LA measurement, methods that simplify identification of the largest leaf on a plant were pursued. Average positions for the largest leaf at the three ENVs ranged from leaf 10 to 14, depending on hybrid maturity, for example, the largest leaf occurred at lower nodal positions in early hybrids (Figure 5.4).

A bell shaped function adequately described the relationship between individual LA and its position on the plant (Figure 5.4). Individual plant LA was similar among all hybrids for at least the first 10 leaves, after which later hybrids had bigger leaves at any given leaf position and more leaves than earlier hybrids.

Using data from RUK07, the position of the largest leaf on a plant was also regressed against total leaf number to derive the relationship:

*Largest leaf = 3.68 + 0.46*LN* (RMSE=0.84; r^2=0.64***).

Validation against independent data from MAS08, NGA08 and RUK08 resulted in over-prediction of the position of the largest leaf by an average of 3% (RMSE=0.82). When the largest leaf position was less than 11 (18% of sample, n=242) the equation over-predicted leaf position by about 1.5 leaves. Under-estimation by the same magnitude was observed in situations where the largest leaf was situated on nodes >13 (13% of sample). When these data were excluded from the analysis, model accuracy was increased by >30% (RMSE=0.55).

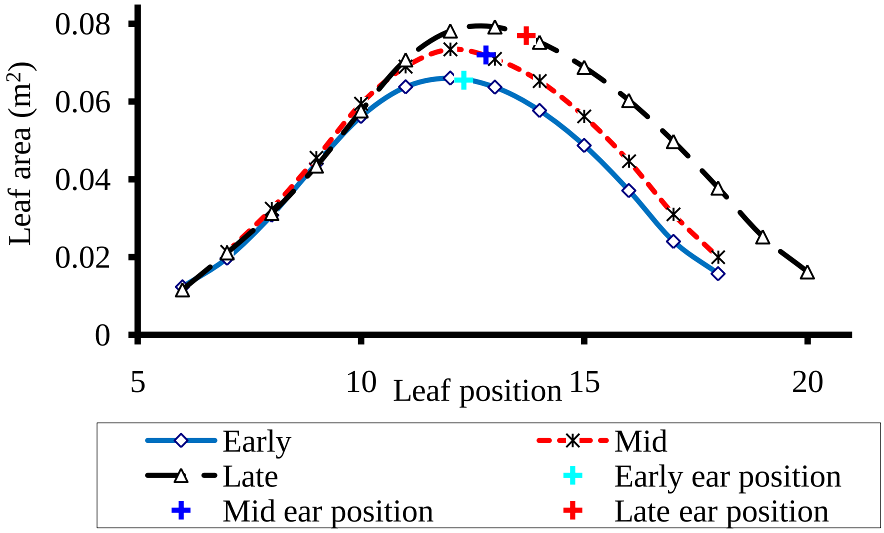


Figure 5.4 Leaf area distribution by hybrid maturity class and leaf position in the RUK07 ENV, averaged over 5 planting date treatments.

Based on field observations, the largest leaf across all hybrids was generally around the ear. Over all ENVs, 46% of the sampled plants (n=330) had the largest leaf situated immediately below the ear (EL-1) while 20% of the plants had the EL as the largest. There was a P=0.98 chance that the largest leaf was one of four leaves around the ear (i.e., EL-2, EL-1, EL and EL+1). Also, 98% of the sample from these ENVs had the ear on leaf number 12, 13 or 14. Based on these findings, a method involving measuring the area of the four leaves around the ear was adopted, in favour of the derived equation which was accurate for only 69% of the tested data.

5.4.10 Leaf Area Index (LAI)

There were significant differences in LAI at anthesis among all four ENVs, with mean values varying from 6.9 (NGA08), 6.7 (RUK08), 6.5 (RUK07) and 6.4 (MAS08). The mean air temperatures during the leaf expansion periods for the four ENVs across the PD treatments ranged from 17.1 (RUK07), 18.0 (MAS08), 18.6 (NGA08) and 18.7^{0}C (RUK08). The inclusion of earlier hybrids in the Manawatu ENV was largely responsible for the lower LAI values at MAS08.

In general, LAI showed a quadratic response to PD, resulting in the lowest values obtained with either early or late planting (Table 5.9). Over all sites, plants with more leaves generally had higher LAI (r=0.59***). While no interactions existed across all ENVs, PD had a significant impact on LAI in all ENVs except MAS08. At RUK07, PD4 had the highest LAI (7.1) while PD1 had the least LAI (6.1) compared to an average of 6.5 for PDs 2, 3 and 5.

Table 5.9 Leaf area index (LAI) at NGA08, RUK08, RUK07 and MAS08, over 4 or 5 planting dates (PDs); se is standard error across all hybrids or maturities. Figures in parenthesis refer to mean temperatures (^{0}C) during leaf expansion for the respective treatment.

PD	NGA08		RUK08		RUK07		MAS08	
1	6.7	(16.9)	6.1	(16.9)	6.1	(15.8)	-	-
2	7.1	(18.1)	7.0	(18.2)	6.5	(16.1)	6.2	(17.2)
3	7.5	(18.8)	7.4	(18.8)	6.5	(16.9)	6.4	(17.9)
4	7.1	(19.4)	6.9	(19.5)	7.1	(17.7)	6.6	(18.3)
5	6.0	(19.9)	5.9	(19.9)	6.5	(18.8)	6.3	(18.7)
se	0.27		0.29		0.20		0.22	
Significance	***		***		***		NS	
Maturity								
Early	6.4		6.1		6.0		6.1	
mid	6.5		6.3		6.2		6.4	
Late	7.7		7.5		7.4		6.6	
se	0.45		0.48		0.33		0.42	
Significance	NS		NS		NS		NS	
PD*Maturity								
Significance	NS		NS		NS		NS	

A significant quadratic response of LAI to PD was observed at NGA08 (r^2=0.30**) and RUK08 (r^2=0.33**) where LAI was maximised by planting between 28 and 31 October (i.e., around PD3). The low r^2 value suggests that LAI was largely determined by factors other than PD effects (e.g., water stress). Under both ENVs, PD5 had the smallest LAI, followed by PD1. Despite RUK08 experiencing significant drought stress, the effects of water stress, particularly for PD1 to PD4, were not very evident during the leaf expansion phase. Precipitation received during the pre-flowering phase was 121, 74, 72, 69 and 47 mm for PD1 to PD5, respectively.

5.4.11 Rate of leaf emergence/phyllochron

Phyllochron (see Plate 5.2) varied significantly among ENVs, averaging 48.9, 48.3, 46.7 and 45.3^{0}Cd for NGA08, RUK08, RUK07 and MAS08. There were no differences between NGA08 and RUK08. Consequently, data for the two ENVs were combined and renamed WKT08 (Table 5.10). While there were no PD x maturity interactions for it across ENVs, phyllochron was significantly influenced by PD.

Table 5.10 Phyllochron values for WKT08, RUK07 and MAS08 over 4 or 5 planting dates (PDs); se is standard error across PD treatments for all hybrid maturities.

	WKT08	RUK07	MAS08
PD		^{0}Cd	
1	47.7	48.3	-
2	48.7	46.7	41.7
3	50.8	47.2	44.8
4	46.7	45.5	44.9
5	49.2	45.9	50.0
se	1.01	1.10	1.91
		Significance	
PD*Maturity	NS	NS	NS
Maturity	NS	NS	NS
PD	***	***	**

In WKT08, the largest phyllochron was observed at PD3 (50.8^{0}Cd), followed by PD2 (48.7^{0}Cd) and PD5 (49.2^{0}Cd). The smallest phyllochron occurred at PD1 (47.7^{0}Cd) and PD4 (46.7^{0}Cd).

In contrast, at RUK07, PD1 (48.3^{0}Cd) and PD3 (47.2^{0}Cd) had the largest phyllochron whereas PD4 and 5 had the least, averaging 45.7^{0}Cd. At MAS08, phyllochron was lowest under PD2 conditions (41.7^{0}Cd) and highest (50^{0}Cd) for PD5. In general, phyllochron was largest during the hot conditions of WKT08 and lowest for the early planted crops at MAS08 (42 vs. $>46^{0}$Cd).

Even though rate of leaf tip appearance is generally considered to be linear with TT throughout the whole leaf emergence phase, the linear model revealed a significant change in slope during the appearance of the last 10-15% of leaf tips, suggesting that a bilinear model could more accurately describe the trajectory of leaf tip appearance. The first three leaves were produced very rapidly whereas the last 10-15% of leaves required an average of 2.5 times the TT of the main body of emerging leaves.

A comparison between a linear model based on the whole leaf emergence duration (Y1) vs. a bilinear model (Y2 and Y3) using a data set for an early maturing hybrid from RUK07 as an example, is illustrated in Figure 5.5. Based on the observed field data, leaves ≤17 and >17 were considered to constitute the two linear segments.

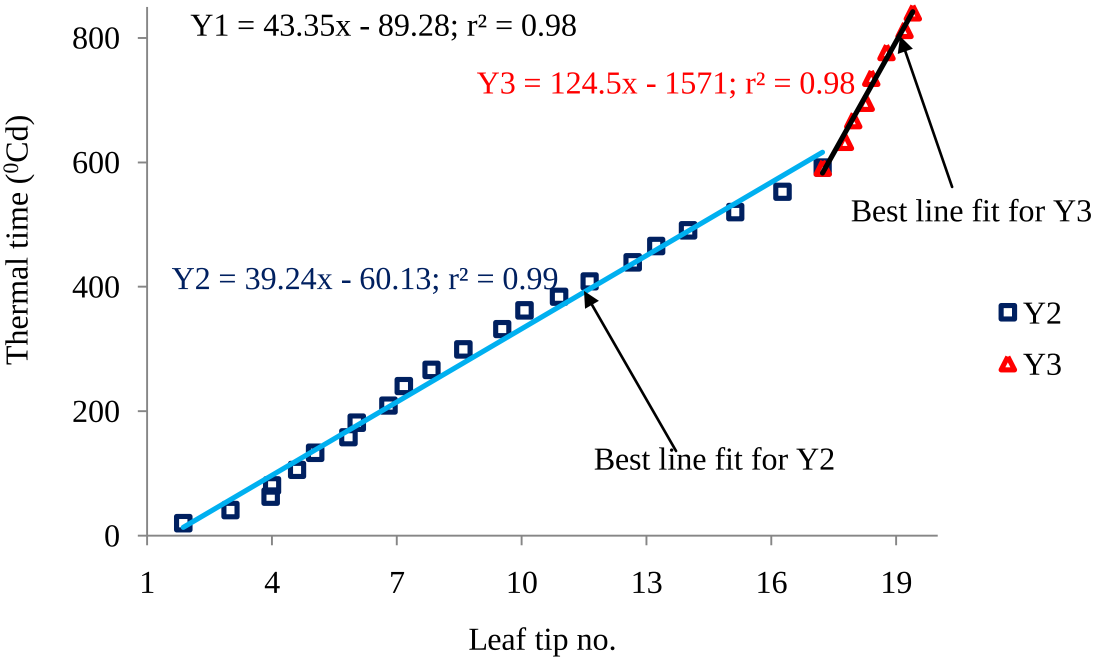


Figure 5.5 Comparison of phyllochron estimation based on a linear (**Y1**) and bilinear model split into two parts (**Y2**) ≤17 leaves (i.e., up to 90% of total leaf number) and (**Y3**) >17 leaves (i.e., the last 10-15% of the total leaf number). Blue squares and red triangles respectively represent the two linear phases of the bilinear models, Y2 and Y3, of leaf emergence. Combination of red triangles and blue squares constitute the linear model, Y1.

The bilinear model predicted TT for leaf emergence more accurately than the linear model, reducing RMSE from 31.2 to 15.8 (mean=394.8). Both models predicted earlier leaf emergence (≤10) with reasonable accuracy (see Table 5.12). However, the linear model significantly under-predicted thermal requirement for appearance of the last leaves. When the data were analysed on a hybrid x hybrid basis, in days, errors due to the linear model ranged from -14 to +5 d vs. -1 to +5 d for the bilinear model.

5.4.12 Estimation of leaf tip counts from fully expanded leaves

To predict leaf tip number where only fully expanded leaf number (leaf collar) data exist, the relationship obtained from RUK07, *Leaf tip = 2.13 + 1.32 x leaf collar* (r^2*=0.98***)*, was validated using independent data from MAS08, NGA08 and RUK08 (RMSE=0.63, mean=10.2; n=1820). The model was considered robust only up to <17 leaf tips (or less for hybrids with fewer leaves), systematically overestimating leaf tip number for the last 2-3 leaves, due to their higher TT requirements for emergence.

Due to deficiencies of the linear function to predict leaf tip number from full leaves, particularly at >17 leaves, the Gompertz function was also fitted to the RUK07 data. Throughout the whole trajectory of leaf tip appearance, the model improved the regression fit (RMSE=0.50, vs. 0.63 for the linear regression) (Figure 5.6; Table 5.11).

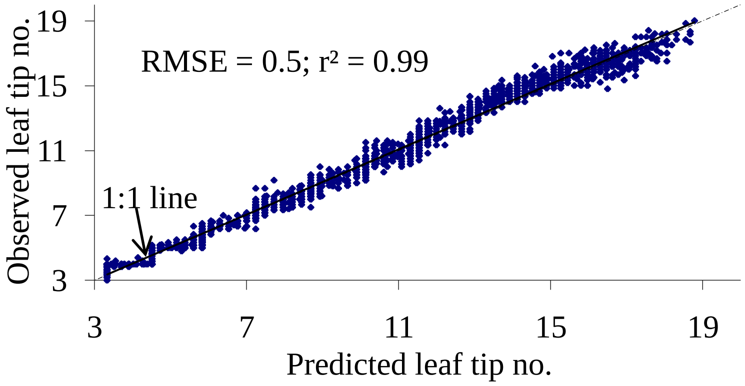


Figure 5.6 Observed leaf tip number (MAS08; NGA08; RUK08) vs. predictions based on RUK07 data using the Gompertz model.

By combining data from the four ENVs, the following relationship was obtained using the Gompertz function:

*Leaf tip = 23.0*exp(-exp(-0.175*(leaf collar-4.8)))* (r^2*=0.998***, n=2923).*

Table 5.11 compares performance of linear vs. Gompertz functions in predicting leaf tip number, when the fully expanded leaf number is known. While both models resulted in reasonably accurate estimations when the fully expanded leaf number was ≤6, prediction power of the Gompertz function was superior at higher expanded leaf number positions.

Table 5.11 Comparison of actual vs. predicted visible leaf tips from fully expanded leaf numbers for 7 maize hybrids in 4 environments using linear or non-linear (Gompertz) models.

	Actual	Linear model	Gompertz model
		Leaf tip no.	
Full leaf no.			
2	4.5	4.7	4.4
4	7.2	7.4	7.1
6	10.0	10.0	10.1
8	13.1	12.6	12.9
10	15.7	15.2	15.3
12	16.9	17.8	17.2
13	17.7	19.1	18.1

For purposes of this study, the Gompertz function was adopted due to its superiority in estimating visible leaf tip numbers where only fully expanded leaf data were available.

5.5 DISCUSSION

5.5.1 Total DM yield at flowering

Provided water was not limiting, DM yields at flowering averaged about 50% of the total final biomass (see section 3.4.3, Chapter 3). However, the ratio of biomass at flowering to final biomass for late planted treatments was usually higher and this was largely due to the greater radiation levels for the emergence-flowering vs. flowering-PM durations (see Table 5.1 and Table 3.2, Chapter 3, for the comparisons). This subject has been discussed in greater detail in Chapter 3. In drought situations however, the proportion was much higher (up to 0.9) depending on drought timing and severity. Kernel abortion was usually higher in water stressed crops, reducing total DM yield. Drought stress also influenced the ratio through stalk remobilisation, necessary to provide assimilates to the growing kernels during periods of limited photosynthesis.

Under adequate moisture conditions, vegetative biomass was usually highest for later planted crops and this was attributed to the higher cumulative IPAR during vegetative growth since biomass accumulation and intercepted radiation are highly correlated (Monteith, 1977; Kiniry et al., 1989). Significant biomass reductions have also been reported in wheat at reduced light interception levels during vegetative growth (Badarrudin et al., 1999). For water stressed conditions, the observed linear decline in total biomass at flowering with delayed planting was consistent with pre-anthesis drought effects reducing cell expansion and elongation as evidenced by smaller leaves, shorter plants and decreased internode lengths.

While biomass yields at flowering were maximised with 16 and 27 October plantings at NGA08 for early and late hybrids respectively, the optimum date was at least 3 wk later for late hybrids under cooler conditions (RUK07). NGA08 experienced higher average temperatures (+1.5^{0}C) and solar radiation (+2 MJ m^{-2} d^{-1}) than RUK07 during the November growing phase. In cooler seasons therefore, maximum biomass at flowering is more likely to occur with later plantings than in normal or warmer seasons. Similar findings have been documented by Capristo et al. (2007), who also attributed higher biomass of later hybrids to the longer emergence-flowering duration and the greater quantity of radiation intercepted. The observed relationship between DM yields and

LAI imply that conditions that favoured increased vegetative growth also encouraged leaf expansion.

5.5.2 Silage DM yield

Under optimum environmental conditions, the response of SY to PD (26-23 t ha^{-1} between PD1 and PD4) differed from the average total biomass at flowering that increased with PD from 11-12.6 t ha^{-1} for the same period. The observed quadratic response of SY to PD under non-water stress conditions is widely reported in literature (e.g., Johnson and Mulvaney, 1980) and was consistent with the recorded GY response (see section 3.4.2, Chapter 3). Silage yield response was therefore largely driven by the grain component rather than stover *per se*. Yields were maximised by planting earlier in ENVs characterised by warmer (Waikato) than cooler (Manawatu) springs, in agreement with Lauer et al. (1999) and Darby and Lauer (2002). Low spring temperatures, consistent with early planting particularly in cooler regions, impede biomass accumulation (Muchow and Carberry, 1989), consequently decreasing yields. This also explains seasonal differences in optimum PD for SY within similar regions (e.g., NGA08 vs. RUK07) where the latter averaged 14^{0}C vs. 17^{0}C (NGA08) for the TI-flowering duration for the first planting. The respective soil temperatures between emergence and TI were 14.8 and 15.6^{0}C rising by about 1 and 2^{0}C, respectively for October plantings. RUK07 thus experienced a cooler spring than NGA08. Similar explanations also apply to observed differences in biomass yield at flowering.

Low SYs (<21 t ha^{-1}) observed under late planting situations were largely due to low temperature (<15^{0}C) and radiation levels (<17 MJ m^{-2} d^{-1}) during grain filling (Table 5.1). Photosynthetic activity in tropical C4 grasses is negatively affected by temperatures <15^{0}C (Long, 1983). For example, Vietor and Musgrave (1979) observed a 269% higher photosynthetic rate at 30^{0}C vs. 15^{0}C. Elsewhere, Tollenaar (1989b) reported a 40% reduction in leaf photosynthetic rate when night temperature decreased from 15 to 11^{0}C. Silage yield decline in plantings after the optimum PD was much higher (double) in Manawatu (-0.6% d^{-1}, i.e., -183 kg ha^{-1} d^{-1}) than Waikato (-0.3% d^{-1}, i.e., -85 kg ha^{-1} d^{-1}). This was consistent with the greater rate of decline in temperature and radiation level in Manawatu (Table 3.1 and Table 3.2, Chapter 3), which likely accentuated the presence of source limitations during grain filling (Andrade et al., 1993a).

The ENV with the lowest spring temperatures (RUK07) was also the only one to show maturity x PD interactions for SY, where both mid and late hybrids showed a quadratic yield response while early hybrids yielded similarly across PD treatments. This could have been due to the smaller sink size of early hybrids (Capristo et al., 2007) and a well balanced source-sink ratio, both of which have already been discussed in sections 3.5.1 and 3.5.2 (Chapter 3). In brief, stress situations have less impact on early than late hybrids which have bigger sinks and thus greater assimilate demand. Also, the different life cycle lengths mean that critical stages of development occur at different times, differentially affecting yields. For instance, when planted late, long season hybrids had a greater proportion of their life in the period of diminishing radiation and temperature vs. early hybrids planted at the same time. Conversely, early hybrids were sink-limited under optimum conditions (e.g., early PDs).

The planting densities used for early hybrids (11 plants m^{-1}) may have been too low for the early plantings where their LAI was about 20% lower than late hybrids. To maximise yields under these conditions, long maturing hybrids should therefore be planted instead (Lafitte and Edmeades, 1997; Bruns and Abbas, 2006). Alternatively, densities for early hybrids should be increased by a further 10% at least.

Despite PD playing a part, the observed linear SY decreases at RUK08 (similar to biomass response at flowering) were confounded by the growing impact of drought stress on late planted crops as the soil water reservoir was depleted by evapotranspiration. Reports of low biomass yields due to delayed planting under drought stressed situations are also extensively cited in literature (e.g., Gheysari et al., 2009). Even though SY was negatively correlated with barrenness and leaf senescence in the water stressed ENVs, drought rather than barrenness or staygreen was considered to have influenced yields. Barrenness and senescence were both increased by drought stress. Water stress reduced LAI (see section 5.4.10) and possibly RUE, thereby decreasing photosynthetic capacity and thus low yields. Due to confounding effects of water stress at RUK08, it was impossible to quantify PD effects on SY.

5.5.3 Silage quality and predicted milk production

Whereas some quadratic responses to PD were observed for ADF, NDF and starch contents, silage quality was generally highest under early planting conditions (PDs 1-3). The small variation in CP (6-7%) among treatments could be due to the generally low protein content of maize silage, which is normally <8% (Graybill et al., 1991; Darby and Lauer, 2002; Lawrence et al., 2008). Consequently, maize silage is considered as an energy rather than protein source for livestock. Similarly, Graybill et al. (1991) also noted that while PD had a significant effect on ADF and NDF, it did not influence CP. Analogous results have been documented by Lawrence et al. (2008). Even though CP was positively correlated with the estimated milk yield, the impact of variation in CP was much smaller than that of starch, ADF and NDF. The observed starch levels fell within the 26-37% reported in literature (Bal et al., 1997; Bal et al., 2000; Weiss and Wyatt, 2000). Similarly, ADF and NDF values were consistent with those reported by other researchers (Phipps et al., 2000; Weiss and Wyatt, 2002; Lawrence et al., 2008).

The lower starch contents at the drought stressed ENVs were consistent with reduced grain fill caused by water stress and evidenced by low HI values (see section 3.4.4, Chapter 3). All hybrids generally had significantly less DM yield, quality (i.e., low starch and high ADF and NDF), milk t^{-1} and milk ha^{-1} when planted late as observed in other research that showed silage quality reduction when HI was low (e.g., Graybill et al., 1991; Coors et al., 1997; Wiatrak et al., 2004). Moss et al. (2001) also showed that good growing conditions (e.g., high fertilizer levels) increased quality by lowering ADF. High starch and low NDF contents in maize silage significantly improve food intake and milk yield (Phipps et al., 2000).

Effects of reduced grain filling on silage quality were evidenced by the negative correlations between HI and ADF (r=-0.61) or NDF (r=-0.5). Cox et al. (1994) also observed higher correlations between HI and ADF (r=-0.79) or NDF ($r \leq -0.82$). When analysed on an ENV basis, MAS08, whose average HI values declined from 0.57 to 0.48 for late plantings (see section 3.4.4, Chapter 3), had much higher correlations between HI vs. ADF, NDF or starch (<-0.69) than the other ENVs where HI values ranged from 0.49-0.52 (NGA08) and 0.5-0.54 (RUK07).

Similarity of milk ha^{-1} and SY responses to PD (quadratic) was evidence that the milk yield per unit area from silage was determined mainly by SY since both are quantity measures. This contrasts with predicted milk t^{-1}, a quality measure, which was more responsive to total starch levels and to a lesser extent, ADF and NDF. Similar observations have been made by Sheaffer et al. (2006). The deviation in the response of milk t^{-1} from either linear or quadratic responses to PD concurs with Deinum and Bakker (1981) who observed differences in forage quality between environments differing on soil and water conditions. They concluded that silage quality was largely determined by the prevailing environmental conditions (e.g., temperature, moisture and irradiance). For instance, on average, NGA08 which received 117 mm total rainfall during grain filling resulted in a predicted 100 kg milk t^{-1} less than MAS08 and RUK07 that received >220 mm during the same period (see Table 3.2, Chapter 3). The differences in some hybrid maturity group responses to PD within both the Manawatu and Waikato regions are analogous to findings by Nafziger (1994) who also concluded that silage quality varied with season. Since hybrids varying in maturity reach developmental milestones at different times, variation in weather can also be expected to influence them differently.

The PD required to maximise milk ha^{-1} generally coincided with that of maximum SY, or was slightly later. Despite the strong relationship between SY and milk ha^{-1}, maturity responses to PD were more apparent for milk yield than SY. For example, at RUK07, the rate of decrease in milk ha^{-1} past optimum PD to maximise milk yield was significantly larger for late (-164 kg ha^{-1} d^{-1}***) than mid (-71 kg ha^{-1} d^{-1}***) and early hybrids (-45^{NS} kg ha^{-1} d^{-1}), while SYs were more stable among maturity classes. Larger effects on milk ha^{-1} were likely because the parameter is determined by both quality and yield factors, resulting in additivity of the effects. Larger milk ha^{-1} declines with delayed planting have also been observed by Darby and Lauer (2002) in cooler vs. warmer ENVs. Quality responses to PD were also more apparent in late hybrids (Table 5.4), particularly if grain filling occurred under declining environmental conditions.

5.5.4 Canopy development

5.5.4.1 Plant height, total leaf number and phyllochron

Plant height was largely related to internode length rather than internode numbers (equal to final leaf number) *per se*. This finding contradicts other published research suggesting a strong correlation between plant height and leaf or internode number (e.g., Yamaguchi, 1974; Robertson, 1994). Late planted crops were generally taller likely due to higher temperatures and radiation which increased growth rate and internode elongation. The positive correlation between height and biomass DM at flowering imply that conditions that promoted vegetative DM (e.g., adequate soil water) also increased elongation.

Across ENVs, delayed planting resulted in internodes elongating by between 0.4 and 0.5 mm d^{-1} under optimum conditions, and decreasing by the same magnitude under water stress conditions. Reductions in internode length and plant height by as much as 50% have also been reported by Robertson (1994) under water stress. This is consistent with findings that leaf and stem elongation are among processes most sensitive to drought (Westgate and Boyer, 1985; Kiziloglu et al., 2009). Higher internode elongation rates with PD at RUK07 vs. MAS08 were likely due to a larger mean temperature variation for the emergence-flowering durations (14-18^{0}C for early vs. late planting) compared to 16-18^{0}C for MAS08. Low night temperatures also appeared to have negatively affected elongation for early plantings at RUK07. For example, 40% of the nights under PD1 at RUK07 experienced night temperatures of <8^{0}C compared to 24% for the first PD at MAS08.

The lower average plant height and total leaf number for MAS08 was largely due to the differences in hybrid sets since the late hybrid group for Waikato were not planted in Manawatu. Late maturing hybrids have more leaves (Warrington and Kanemasu, 1983c) and are larger than earlier maturing hybrids, as evidenced by their larger total biomass DM. However, the inverse relationship between internode length and leaf number (across hybrid maturity classes) was also evidence that later maturing hybrids experienced a greater degree of drought stress than earlier ones during internode elongation, or that internodes of late maturing hybrids were inherently shorter.

It was impossible to assess whether photoperiod had any effect on leaf number because of the narrow range of daylengths obtained during experimentation and the confounding effects of temperature on leaf number. Temperate hybrids, compared with tropical varieties are either less photosensitive (Bonhomme et al., 1991), or virtually insensitive (Ritchie et al., 1986a), and thus, variation in daylength was not considered an important cause for differences in leaf number and crop duration in this study.

The greater leaf numbers observed under low temperature conditions contradict other research on germplasm which included a number of tropical materials. This showed more leaves under higher mean temperatures varying between 15 and 30^{0}C (Duncan and Hesketh, 1968; Tollenaar et al., 1979). Observations in the present study on Corn Belt and European germplasm are consistent with findings of Warrington and Kanemasu (1983c) who studied germplasm adapted to the central Corn Belt and found that between 15 and 25^{0}C, leaf number responded in a curvilinear manner to temperature, with the lowest numbers obtained at 18^{0}C. It should also be noted that temperature ranges of 13-19^{0}C in the current study were narrower than those covered by the former researchers and the highest temperature (19^{0}C) was close to that for the minimum leaf number reported by Warrington and Kanemasu (1983c). Greater leaf numbers under cooler temperatures have also been documented by Aitken (1977; cited by Tollenaar and Hunter, 1983). The observed decrease in leaf number as mean temperature approached 18^{0}C is thought to reflect a reduced rate of leaf initiation (Warrington and Kanemasu, 1983b).

Phyllochron is used in crop simulation models to predict flowering (i.e., duration between emergence and silking) or to keep track of canopy development. For instance, the product of total leaf number and phyllochron determines the duration between emergence and appearance of the last leaf before flowering. With addition of a small correction needed to grow the tassel from the appearance of the flag leaf to anthesis, this provides a basis for predicting TT from emergence to anthesis in crop models such as CERES-Maize (Jones and Kiniry, 1986). To predict TT requirement for leaf (tip) appearance, the bilinear model resulted in a significant improvement of about 50% (RMSE) in the prediction of phyllochron over the linear regression commonly found in the literature (e.g., Ritchie and NeSmith, 1991; Birch et al., 1998e; Padilla and Otegui, 2005). Failure of the linear model was due to its inability to consider the higher TT requirement for emergence of the last 10-15% of leaves.

Whether a linear or bilinear model should be used depends on the purpose of the study. For example, when measuring LA development over time (i.e., prior to the emergence of the last 10-15% of leaves), based on these data, the linear model would be adequate. In situations where phyllochron is required to estimate flowering for some crop models, the linear model would predict earlier anthesis dates than observed (see Table 5.12). The bilinear model, therefore would predict silking time more accurately, since it considers the higher TT requirements for emergence of the last leaves. Therefore, while the bilinear model could be considered more appropriate where the objective was to estimate flowering, phyllochron values based on linear regressions may continue to play an important role especially in situations where estimations of earlier leaf staging, rather than flowering dates are required.

Table 5.12 Comparison of actual vs. predicted average timing of leaf development stage across 6 hybrids planted at RUK07, in thermal time (TT), using linear and bilinear regression models. Figures in parenthesis refer to differences, in days, between predicted and actual.

	Actual	Linear model	Bilinear model
Leaf no.		^{0}Cd	
5	148	145 (0)	150 (0)
10	383	379 (0)	366 (-1.5)
16	627	662 (+3.5)	640 (+1)
Final leaf	857	773 (-8)	847 (-1)

For purposes of this study, phyllochron values reported in the thesis are based on the linear rather than the bilinear regression since these values were used to evaluate the CERES-Maize model. While the model uses phyllochron and leaf number to estimate silking time, it utilises the following relationship: Leaf number = $\frac{Accumulated\ TT}{(Phyllochron*0.5)+5}$, where Accumulated TT refers to accumulated TT throughout the leaf emergence cycle (Gerrit Hoogenboom, pers. comm., 2007), which itself is not a linear relationship and thus, minimises subsequent errors caused by use of phyllochron values obtained through linear regression.

Other improvements on determining phyllochron include the exponential relationship established by Muchow and Carberry (1989). Even though the formulation has been shown to improve timing of leaf emergence, Wilson et al. (1995) found that under cooler temperatures of NZ, it resulted in the instantaneous production of 2.5 leaves at emergence, resulting in an over-prediction of total biomass accumulation. It is thus recommended that in most other cases, the bilinear model be adopted for use instead.

Phyllochron values in this study (42 to 52^0Cd leaf tip^{-1}), agree with values of between 35 and 50^0Cd observed by Birch et al. (1998e) who used T_b8 with a range of maize hybrids and ENVs. Other published values using T_b8 range from 34 to 45^0Cd, (Hesketh and Warrington, 1989; Kiniry and Bonhomme, 1991; Ritchie and NeSmith, 1991; Otegui and Melón, 1997). Observed values were generally on the higher end of the range found in literature most likely because other research either do not consider leaves throughout the whole pre-flowering phase (e.g., Vinocur and Ritchie, 2001) or use air temperature to calculate phyllochron throughout the whole leaf emergence phase. Similarly, Vinocur and Ritchie (2001) also reported lower phyllochron durations when air temperature was used instead of a combination of soil (prior to TI) and air temperatures (post-TI). Vinocur and Ritchie's average phyllochron length of 52^0Cd was larger than the NZ average of 47^0Cd, and this could be due to the higher mean temperatures of >21^0C vs. 17^0C in the current study (see discussion on temperature effects on phyllochron below). Radiation, also thought to influence phyllochron, was not considered to have caused the difference since it was comparable in both studies.

While significant PD responses to phyllochron were observed, regional (i.e., Manawatu vs. Waikato) and seasonal influences (e.g., RUK07 vs. RUK08) were also apparent. For instance, higher values were obtained in Waikato during the hot dry season of 2007/08 vs. 2006/07 (+1.5^0C warmer, see Table 5.1). Also, Manawatu phyllochron values, particularly for early PDs, were lower than for Waikato. These findings are supported by Birch et al. (1998d,e) and Padilla and Otegui (2005) who recorded higher phyllochron values in warmer climates, evidence that phyllochron may not be constant across ENVs or that T_b8 may be too low for the process. Phyllochron variations across PDs within ENVs have also been observed in wheat (Kirby and Perry, 1987; McMaster et al., 1992).

Though significant, the differences in phyllochron within the Waikato ENVs for 2006/07 (cooler) vs. 2007/08 (warmer) season were small, suggesting reasonably comparable values within the region, compared to Manawatu values. Differences in hybrid sets between Waikato and Manawatu could not have contributed to the lower Manawatu values since analysis based on a common set of hybrids (data not shown) did not alter the result.

Larger phyllochron values were observed when mean soil temperatures were >22^{0}C (data not shown). Soil temperature was however thought to have influenced phyllochron only up to TI, after which leaf emergence was determined by air temperature. Elsewhere, phyllochron variations of 10-15% have been observed at temperatures between 10 and 35^{0}C (Tollenaar et al., 1979; Tollenaar et al., 1984).

Between Waikato and Manawatu ENVs, during the leaf emergence periods, irradiance differences were greater than temperature. Manawatu radiation levels were higher (22-24.5 MJ m^{-2}) than Waikato which averaged as low as 17 MJ m^{-2} d^{-1} for some treatments. This could explain the observed differences, similar to findings by Birch et al. (1998e) and Padilla and Otegui (2005) who reported increased phyllochron under reduced PAR. Birch and co-workers reported an increase in phyllochron of 2-4^{0}Cd MJ^{-1} of reduction in daily PAR, with the effects magnified at higher temperatures.

Because of the narrow ranges of temperature and radiation levels experienced in this study, it was not possible to fully quantify their relationships with phyllochron. In situations where differences in radiation levels were large (e.g., RUK07; 17 vs. 23 MJ m^{-2} d^{-1} for PD1 and PD4, respectively), both mean soil temperature (15 vs. 20^{0}C) and radiation had a significant influence on phyllochron. When considered in isolation, radiation accounted for 66% of the variation in phyllochron compared to 69% for soil temperature.

For treatments that experienced water stress, delayed leaf emergence seemed to have been largely influenced by reduced total precipitation between emergence and TI. For instance, during the dry season of 2007/08, despite PD3 receiving higher average radiation levels than PD4 (+1 MJ m^{-2}) and lower mean temperatures (-1.5^{0}C), larger phyllochron values (51 vs. 47^{0}Cd) were observed. The difference in phyllochron was thus attributed to water stress, where PD3 received 30 mm vs. 60 mm for PD4 in the emergence-TI interval. Of the 30 mm received under PD3, 20 mm fell in the last 5 d prior to TI, suggesting significant deficit during the greater part of the emergence to TI cycle. Increased phyllochron values under pre-flowering moisture stress have also been reported elsewhere in maize (Çakir, 2004) and wheat (Krenzer et al., 1991). Similarly, Leong and Ong (1983) observed smaller phyllochron in irrigated groundnuts (*Arachis hypogaea* L.) compared to unirrigated plants.

In general, fully expanded leaf data are more routinely collected than leaf tips, particularly for purposes of plant growth staging (Ritchie et al., 1986b). Since phyllochron, critical in crop simulation models, is based on leaf tips and not fully expanded leaves, in situations where only fully expanded leaf data are available there is need to convert the data to visible leaf tips. The equation established in this study based on the Gompertz function was considered robust for the morphology and genetics of modern hybrids, and a significant improvement over other published relationships (e.g., Hardacre and Turnbull, 1986). The established equation has the further advantage in that it can be used to estimate the number of leaf tips for the whole duration of leaf tip emergence.

5.5.4.2 Leaf area distribution and LAI

The observed bell shaped response of individual LA to the leaf position on the plant has also been reported by Dwyer and Stewart (1986) who proposed functions to describe the relationship. Differences in the areas of individual leaves among hybrids were mostly expressed within the mid to upper canopy, since lower leaves were similarly sized. Similarity in LA of lower leaves among hybrids of different genetic backgrounds has also been observed elsewhere (Birch et al., 1998a; Birch et al., 2003).

Though differences were not significant at $P<0.05$, the LAI for late hybrids in Waikato was, on average, about 20% higher than early and mid hybrids. The larger size of the upper canopy for later maturing hybrids could have resulted in more IPAR per plant since upper leaves intercept the majority of radiation (Simmons and Jones, 1985). In addition, upper leaves translocate the majority of assimilates to the ear while lower leaves mostly supply the internodes and the roots (Edmeades et al., 1979). Even though yield difference between early and late hybrids is largely attributed to the longer period of interception for the latter, at the individual plant level, more LA could also provide an advantage to later hybrids. On a unit area basis, early hybrids should therefore be planted at higher densities to be able to intercept a similar amount PAR.

Total plant LA was accurately predicted based on the area of the largest leaf and total leaf number. Elsewhere, Valentinuz and Tollenaar (2006) have also used the bell-shaped function and area of the largest leaf to predict total plant LA but observed a consistent under-prediction of LA using this method.

To further simplify the process of LA measurements, an easier way of identifying the largest leaf on the plant was evaluated. Even though the established relationship to identify the largest leaf was quite comparable to that obtained by Stapper and Arkin (1980; *Largest leaf = 3.53 + 0.46 x total leaf number*), some inadequacies were observed with the Stapper-Arkin relationship when leaf position was either <11 or >13. Other equations such as Birch et al. (1998a; *Largest leaf = 0.67±0.01 x total leaf number*) were also considered not sufficiently robust for conditions of this study (RMSE = 0.99). Some established relationships (e.g., Francis et al., 1969; Pearce et al., 1975) have been evaluated by Fakorede et al. (1977) who also observed inadequacies which led them to conclude that the derived coefficients were only adequate for optimum conditions of the US Corn Belt and for the specific hybrids under study. However, while these equations may provide fast and easier options for identifying the largest leaf, prior knowledge of the total leaf number is still required.

To improve accuracy of identification of the largest leaf, measuring four leaves around the ear was considered a more robust option, though time consuming, compared to using the established equation or those found in literature. As with findings from this study, Dwyer et al. (1992) showed that the largest leaf ranged from one immediately above the ear to two below the ear. Under time limiting situations, the established equation could still be used with some degree of confidence but care should be taken where total plant leaf number is <16 or >20, i.e., outside the range of leaf numbers observed in the current study. While ear position is hybrid dependent, the observed average in this study was usually higher than 11, which is consistent with other values reported in literature (Subedi and Ma, 2005). Ear position will also vary with hybrid or environmental conditions. For example, late plantings were observed to usually have higher ear positions, which would predispose plants to lodging. While higher ear placement tends to expose plants to stalk lodging due to the higher centre of gravity, no such issues were observed in the current study.

The observed differences in LAI among ENVs were largely due to temperature variations. Despite drought significantly affecting yields at some Waikato ENVs, water stress did not seem to have influenced leaf expansion greatly. It therefore appears that significant water stress effects were more apparent during grain filling rather than leaf expansion. For instance, RUK08 and NGA08, both averaging about 19^0C, had the greatest LAI, particularly for PD2 to PD4. Wilson et al. (1973) showed that temperatures $<18^0$C and $>25^0$C lowered LAI. Elsewhere, Tollenaar (1989a) observed maximum LAI at 19^0C. Lower temperature regimes of about 15 to 17^0C under early planting conditions in the current study thus reduced LAI. In NZ, Hardacre and Turnbull (1986) also reported reduced leaf size under mean temperatures of 20-23^0C. Even though daily mean temperatures of all treatments across the four ENVs rarely exceeded 23^0C during leaf expansion, maximum temperatures $>25^0$C were quite common especially under late planting treatments, thereby significantly reducing LAI. These and other temperature relationships observed in this study reflect the adaptation of this particular hybrid set. Because of their thermal adaptation, tropical hybrids will likely have a different relationship between LA and temperature.

While reduced LAI with early and late plantings was largely due to temperature, lower leaf numbers and increased moisture stress in some ENVs could also have contributed to lower LAI under very late planting conditions. Leaf size reductions have also been reported in water (Song et al., 2008) and N stress situations (Boomsma et al., 2009). Impact of leaf number on LAI was evidenced at RUK07 where PD4 had the highest LAI contrary to other ENVs where leaf number was significantly lower than for earlier PD treatments. In addition, temperature conditions were favourable for leaf expansion.

5.6 CONCLUSIONS

Silage yields were highest under moderate temperature and high radiation conditions, and resembled the response of GY to PD. Early planting resulted in low early season temperatures which reduced biomass and LA expansion but increased leaf number. Conversely, late planting resulted in higher spring temperatures which reduced LA, leaf numbers and actual time to reach silking, consequently lowering PTQs and thus, SY. Higher early (spring) temperatures also increased biomass and phyllochron. Phyllochron was also higher under low radiation and rainfall situations prior to TI. Late planted crops were usually taller, with higher ear placements that predisposed them to lodging risk.

In Waikato, the PD that maximised SY in a normal season was about 2 wk later than when mean spring temperatures were 1^0C higher (2 October vs. 9-15 October). Planting date recommendations based on field data can therefore be unreliable since optimum PDs usually vary from season to season. In Manawatu, the PD to achieve maximum biomass yields when temperatures were $1\text{-}2^0$C warmer than a normal season was 23 October. For Manawatu and Waikato, the variation in SY two or three weeks either side of the optimum PD, respectively, was quite small (<5%), but declined more rapidly with later plantings. Due to their smaller sink sizes, short season hybrids planted early at 11 plants m^{-2} did not significantly outyield late plantings at 10.5 plant m^{-2}, and in fact, later hybrids had about 20% greater LAI, suggesting that higher densities (>10%) in early hybrids are required to compensate for source and sink limitations.

Other than SY, late planting also significantly reduced silage quality by lowering HI, which consequently decreased starch and increased ADF and NDF contents. Crude protein levels were usually stable across PDs but since maize is an energy rather than CP source for livestock, its CP did not strongly influence silage quality. Predicted milk t^{-1} was generally maximised at a later PD than that required to maximise SY, an indication of the independence of factors determining quality and yield. Effects of late planting on hybrid maturity responses were larger for predicted milk yield ha^{-1} than SY.

Water stress caused plant height decreases with planting delay (-7 mm d^{-1}) compared to increases of 3-7 mm d^{-1} under optimum conditions. In drought situations, water stress effects were more profound in late plantings as soil water reservoirs were depleted by evapotranspiration, a caution on late planting in drought prone soils.

In general, late maturing hybrids were more susceptible to any form of stress that increased in intensity with time (e.g., drought, or declining temperature or radiation) compared to early hybrids. Water stress also reduced LA. Late planting resulted in a significant deterioration of environmental conditions (temperature, radiation and water) during grain filling. Since late maturing hybrids seemed less tolerant to stress than earlier hybrids, resulting in lower yields and/or poor quality silage, in late planting situations, long duration hybrids should not be planted.

The widely used linear regression for the estimation of phyllochron predicted emergence of the final leaf about 8 d earlier than the actual date, while a bilinear model significantly improved estimations, reducing RMSE by 50%. To standardise phyllochron values presented in literature, it is suggested that the number of leaves (relative to total leaf number) and temperatures used (soil or air) to estimate the value be mentioned. Even though leaf tip appearance is used to estimate phyllochron, fully expanded leaf counts are often collected for growth staging. In situations where the latter are available, a model based on the Gompertz function, developed to estimate leaf tip number from the data, improved the fit over the currently available linear regression models, especially for upper leaves (leaf tip >10). Total plant LA was also adequately estimated based on area of the largest leaf and total leaf number.

CHAPTER 6: USE OF THE CERES-MAIZE MODEL TO OPTIMISE PLANTING DATE AND MAIZE HYBRID SELECTION.

6.1 ABSTRACT

The CERES-Maize model was calibrated and verified using, respectively, nine and 11 data sets from four New Zealand (NZ) environments (ENVs). Using 31 yr of weather data from eight ENVs, the model was used to establish the best maize (*Zea mays* L.) hybrid maturity x planting date (PD) combinations required to minimise risk and maximise grain and silage yields (GYs; SYs).

The model predicted anthesis and physiological maturity (PM) to within 3 and 5 d. While kernel number and weight were simulated with reasonable accuracy under optimum soil water conditions, the model underestimated leaf area index (≥30%) and stem dry weight at anthesis (45%). Provided water was non-limiting, GY predictions agreed well with measured values (RMSE=1257, mean=13748 kg ha^{-1}). Silage yields were systematically underpredicted by an average of 16.5% and for the purposes of this study, simulated yields were adjusted upwards by this amount.

Simulated kernel number and weight responses to moisture stress were more sensitive than field observations, though anthesis and PM durations were accurately predicted. The model default light extinction coefficient value (k) (0.85) was considered optimum under well-watered conditions while k=0.5 improved model fit in drought situations. Predictions of the grain filling duration were improved by using 0^0C as the base temperature. Model performance was improved further by using the Penman-Monteith method rather than the default Priestley-Taylor method for predicting evapotranspiration, and by increasing the lower optimum temperature required to maximise photosynthetic and grain filling rates from 16 to 19^0C. Thermal time for emergence was changed from 6 to 2^0Cd cm^{-1}.

Simulated PDs to maximise yields across eight contrasting ENVs ranged from 1-18 October. When planted outside the optimum PD range, yields were reduced at rates depending on ENV, hybrid maturity or crop. Warmer ENVs, earlier hybrids and silage crops had wider planting windows than later hybrids grown for grain in cool locations.

Planting too early significantly reduced yields, particularly in cooler ENVs where low spring minimum temperatures ($<8^0$C) and frosts were common. Highest yields were obtained when high total irradiance during grain filling (1317 MJ m^{-2}) coincided with moderate temperatures (19-25^0C). However, low pre-flowering temperatures (13.4^0C) significantly negated any benefits from high radiation.

6.2 INTRODUCTION

In NZ different environmental and agronomic conditions exist between and within the main maize growing regions, requiring different management options for individual farmer situations. Main variations include diseases, soil type, moisture availability, season length and frost risk. While the first three factors can be managed by planting disease or drought tolerant hybrids, the latter require a clear understanding of the interaction between hybrid development and climatic variations, a nearly impossible task within any single cropping season. The challenge is therefore to develop a tool capable of, among other things, matching hybrid maturity and season length based on long term weather data.

Factors such as hybrid maturity and PD need to be appropriately balanced with other agronomic and environmental factors. Crop yields are usually maximised when growth coincides with optimum growing conditions. There is, therefore, a need to select an appropriate maize hybrid that fits within a specified location and planting window, particularly in situations where planting has been delayed, or in replant situations (Benson, 1990).

Relative to the size of land area devoted to maize growing, the number of commercial hybrids available on the NZ market is disproportionately high (see sections 1.1.1, Chapter 1 and 2.3, Chapter 2), complicating hybrid decision making. Ideally, growers should be able to easily select the right hybrid, capable of maturing within the available timeframe with a low risk of crop failure, while maximising yield and profitability.

Even though agronomic studies are usually used to establish PD effects on maize growth, phenology and yield (Nielsen et al., 2002; Capristo et al., 2007), significant variation in length of the growing season across years and locations makes their utility of limited value (Saseendran et al., 2005). The complexity of crop x ENV interactions on crop production requires that a simple, user-friendly decision support system be developed to more accurately predict their effects in real time using long term weather information to determine a realistic estimate of risk. Simulation models can be used as decision support tools if they can accurately mimic real field situations, and can indicate the frequency of crop failure because of unusually cool conditions or other factors.

Simulation modelling has been used in research and extension to facilitate decision making at the farm or government level (Hoogenboom, 2000). For example, using the CERES-Maize model (Jones and Kiniry, 1986), Liu et al. (1989) established how GY was influenced by variation in crop genetics, management practices and soil physical ENVs. Improved understanding of crop responses to environmental conditions such as temperature, radiation and photoperiod can also be studied, increasing the reliability of yield estimations as well as better selection of hybrids appropriate for a given ENV (Atkinson and Porter, 1996).

Accurate prediction of phenology can help growers establish how variable environmental conditions would affect maize growth and development (Bannayan et al., 2005). This would help them select the right hybrids, capable of matching the growth conditions and the season length (Doorenbos and Kassam, 1979). Additionally, production potential of areas where maize has not been grown previously can be quantified (Soler et al., 2005; Binder et al., 2008).

Unlike AmaizeN (Li et al., 2009a,b) which lacks the capacity to simulate individual hybrid differences in genetic x ENV responses, CERES-Maize uses hybrid specific genetic coefficients to characterise hybrids by differentiating crop development attributes and phenological processes among hybrids (Jones and Kiniry, 1986). The coefficients thus distinguish between different hybrids based on life cycle duration, daylength sensitivity, vegetative and reproductive traits (Hoogenboom et al., 2003; 2004). This allows the model to simulate performance of different genotypes under a range of soil, management and weather conditions (Hunt et al., 1993). The ability to simulate temperature and photoperiodic effects on development processes by hybrid makes the model ideal as a management tool for decision making by growers (Ritchie, 1998). Unlike AmaizeN, the CERES-Maize source code is freely available to users, which readily enables modifications with potential to improve model performance.

Even though CERES-Maize has been extensively used the world over, there is no published information of its use or evaluation in NZ. The objectives of this study were therefore to:

1. Calibrate genetic coefficients for seven maize hybrids representing three maturity groups using field experimental data from three ENVs in NZ.

2. Evaluate the calibrated CERES-Maize model in four NZ ENVs using an independent data set.
3. Using a 31 yr weather data set from selected locations, extrapolate model simulations to eight contrasting ENVs across NZ, and use model output to determine the best hybrid maturity x PD combination required to minimise risk and maximise GY and SY for different ENVs.

6.3 MATERIALS AND METHODS

6.3.1 Experiment details

Five or six hybrids of varying maturities were sown in three Waikato (NGA08, RUK07 and RUK08) and one Manawatu (MAS08) ENV over four or five PDs (PD1-PD5). In all, a total of 110 PD x hybrid combinations were tested over two seasons. Full details of the field experimental procedures are described in Chapters 3, 4 and 5. The CERES-Maize model v4.0.2.0 was used to predict maize phenology, GY and SY.

6.3.2 Model description

CERES-Maize is a crop process model that simulates rate of progress towards specific crop phenology milestones using TT on a daily time step (Hoogenboom et al., 2003). Below is a brief description of the model, which is fully documented elsewhere (Jones and Kiniry, 1986; Ritchie et al., 1998; Hoogenboom et al., 2003, 2004; Jones et al., 2003).

The model calculates CGR as the product of canopy IPAR and RUE (Lizaso et al., 2005). Grain yield is calculated as a function of a partitioning coefficient, planting rate, KN plant^{-1} and average KW. While N is the only nutrient directly simulated by CERES-Maize, the model uses a user defined soil fertility factor (SLPF) to account for the effects of other soil nutrients on daily plant growth (Hoogenboom et al., 2003). To simulate a reduction in growth due to fertility factors, an appropriate SLPF value between 0 (total nutrient deficiency) and 1 (non-limiting conditions) is used.

The CERES-Maize model requires as input daily weather data (T_{min} and T_{max}, rainfall and solar radiation), initial soil water and N status, crop management (PD, planting rates, fertiliser scheduling etc.) and specific genetic coefficients (see Table 6.1). To allow for use of the Penman-Monteith FAO56 (Allen et al., 1998) formula to compute daily potential evapotranspiration, daily average dew point and wind speed data are also required.

A TT system is used to simulate all phenological development processes except photoperiodic induction of flowering. Maximum growth and development are assumed to occur at 34^{0}C, after which development will decrease linearly to zero at 44^{0}C. A base temperature 8^0C is used for all development phases. Thermal time to anthesis is determined from total leaf number and phyllochron. Leaf number is estimated from leaf primordia initiated between seedling emergence and TI, and TI date is determined using TT and photoperiod. Depending on hybrid specific coefficients, photoperiod may or may not affect TT to TI and the total number of leaves formed.

Table 6.1 Genetic coefficients used by the CERES-Maize model.

Coefficient	Description
P1	Thermal time from emergence to end of juvenile phase (^{0}Cd)
P2	Development delay h^{-1} increase in photoperiod above 12.5 h (d)
P5	Thermal time from silking to physiological maturity (^{0}Cd)
G2	Potential kernel number $plant^{-1}$
G3	Potential kernel growth rate (mg $kernel^{-1}$ d^{-1})
PHINT	Thermal time between successive leaf tip appearances (phyllochron) (^{0}Cd $leaftip^{-1}$)

Source: Hoogenboom et al. (2003).

The CERES-Maize model assumes a constant RUE of 4.2 g MJ^{-1} (PAR) and an extinction coefficient for radiation (k) of 0.85. Radiation use efficiency is driven by the photosynthetic reduction factor (PRFT) which is set at 1 under non-limiting conditions, falling to 0 as stresses reduce photosynthesis. Thus, RUE varies between its maximum under non-limiting conditions, or 0 when crop biomass accumulation is 0. Photosynthetic rate is assumed to be optimum between 16.5 and 33^0C, reaching zero at 44^0C. Grain growth rate (RGFIL) is maximised between 16 and 39^0C, before reaching zero at 48.5^0C.

CERES-Maize is a model that predicts plant biomass and its components, but does not estimate plant or grain moisture content, a critical determinant for accurate timing of silage maturity and grain harvest. The model can, however, simulate SY as total aboveground biomass yield, using a daily time step. Provided the dates to reach silage maturity can be determined, SY can therefore be estimated using the CERES-Maize model. Using data from a low plant density study and MAS08 experiments described in section 4.3.5 (Chapter 4), a relationship for estimating total aboveground whole plant moisture content at any given point after anthesis was developed and is fully described in section 4.4.10 (Chapter 4). For simplicity, in the present study, SY is being considered as the total aboveground biomass yield at silage harvest maturity, taken as that date when the crop reaches 35% aboveground plant dry matter content. CERES-Maize assumes that grain harvest date will coincide with PM but for purposes of this study, 24% was considered the ideal grain moisture for harvesting. This subject is discussed further in section 6.3.4.

6.3.3 Model calibration and verification

Model calibration and verification/evaluation were used to test how well the model predicts the observed events. Calibration involves modification of model parameters to obtain the best fit between simulated and observed data. Evaluation involves testing model performance using a data set independent of the one used for calibration, to confirm that the model performs accurately (Tedeschi, 2006).

Maize growth and development data from the PD experiments described in Chapters 3, 4 and 5, in addition to weather and soil information were used to calibrate and evaluate the CERES-Maize model. Independent data sets were used for calibration and evaluation purposes. Eight data sets from the 19 field experiments (see section 3.3.2, Chapter 3) and the low density experiment (section 4.3.5, Chapter 4) were considered as treatments showing the least abiotic stress and were thus used for model calibration. These were obtained from NGA08 (PD1, PD3 and PD4), MAS08 (PD3 and PD5) and RUK07 (PD1, PD2 and PD5). The remaining 11 data sets were used to evaluate the model.

Model calibration was conducted by minimising RMSE (Willmott, 1982; Potter and Williams, 1994) resulting from an iterative manipulation of the relevant genetic coefficients (see section 5.3.3, Chapter 5, for RMSE description and formula). Initially, the model was run using field estimated coefficients, refining the values in subsequent runs until there was a good model fit (Hunt et al., 1993). The photoperiod range experienced in the current study was too narrow (see sections 4.4.5 and 4.5.1, Chapter 4) to provide adequate estimates of photosensitivity among hybrids, so initial genetic coefficients for this trait were obtained from Pioneer® Hi-Bred International (Jun Wei, pers. comm., 2006).

Model output and field observed values were compared using RMSE. The RMSE tests the model accuracy by defining the extent to which simulated values approach a corresponding set of observed values (Loague and Green, 1991). Normalised RMSE, estimated as the ratio of RMSE to mean of the observed values, was also calculated. In addition, an index of agreement (d) (Willmott, 1982) was computed as follows:

$$d = 1-\left[\frac{\sum(Pi-Oi)^2}{\sum(|P'i|+|O'i|)^2}\right]$$

where, Oi and Pi are observed and predicted values for the *i*th data pair; $P'i = Pi$ - average of the observed; and $O'i = Oi$ - average of the observed.

The d-index is considered more appropriate than the coefficient of determination (r^2) because it is an aggregate indicator of performance (Willmott, 1982; López-Cedrón et al., 2005). Accurate model performance occurs when RMSE approaches zero and the d-index is close to one.

Using RMSE and d-index statistics, model adequacy was determined by comparing simulated and observed GY and total aboveground biomass yields, KW, KN, HI, anthesis and maturity dates, leaf number and LAI for each hybrid. This was conducted systematically as proposed by Boote (1999), starting with developmental parameters P1, P2, P5 and PHINT using T_b8 to estimate TT, and 12.5 h as the critical value for photoperiod. Both P1 and P2 are used by the CERES-Maize model to predict anthesis date. Kernel growth rate under optimum conditions (mg d^{-1}) (G3) and maximum KN plant^{-1} (G2) were calibrated last, and are required for GY estimations.

Using TT duration from emergence to TI (section 4.4.5, Chapter 4) as a starting point, P1 was adjusted iteratively until model and field anthesis differences were minimised. Further refinement of anthesis prediction was achieved by slightly adjusting the field measured phyllochron values (PHINT). Mean TT to PM obtained during field experimentation (section 4.4.8, Chapter 4) was used as a starting point to estimate P5. CERES-Maize uses T_b8 to predict growth and development during grain filling.

Initial soil water contents and bulk densities in each ENV were obtained prior to planting as described in section 3.3.1 (Chapter 3) while other soil profile attributes such as saturated hydraulic conductivity, drained upper and lower limits, soil depth and albedo were obtained from the NZ soils database records (Landcare Research, 2009). Coefficient values that minimised RMSE and gave d-index values close to 1 were used for simulating maize growth and phenology of the remaining 11 experiments. Since CERES-Maize uses 0% grain moisture content for reporting GY, model output reports were modified to present yields at 14% water content, which is the standard in NZ.

6.3.4 Long term simulation studies

After evaluation, the model was extended to simulate interaction between PD and maize hybrid maturity on GY and SY in eight NZ ENVs using 31 yr of historical weather data (1978-2009). The ENVs, located in Northland, Waikato, Taranaki, Manawatu, Poverty Bay, Bay of Plenty (BOP) (North Island), Canterbury and Southland (South Island) were selected either because they were considered to represent the main maize growing areas of NZ or because they had a complete weather data set. In each ENV, weather data were obtained from the NIWA automated weather station closest to the largest concentration of maize production. In the absence of weather data or where gaps existed, values from the next closest weather station were used. The resultant stations and their locations are shown in Table 6.2.

Table 6.2 Location, latitude, longitude and elevation of the eight environments used for long term maize yield simulations using the modified CERES-Maize model.

Region	Station	Latitude	Longitude	Elevation
		^{0} S	^{0} E	m
Southland	Winton	46.16	168.33	44
Canterbury	Ashburton	43.91	171.74	97
Manawatu	Palmerston North	40.38	175.58	18
Taranaki	Stratford	39.34	174.30	300
Bay of Plenty	Whakatane	37.93	176.92	6
Poverty Bay	Gisborne	38.66	177.98	5
Waikato	Hamilton	37.87	175.34	50
Northland	Whangarei	35.77	174.36	37

For simplicity, the stations will be referred to by the name of the region where they are located. While the most dominant soil type for the selected ENV was generally used for model runs, in situations where soil information did not exist in the NZ soils database records, the next most dominant soil in the region was used (Table 6.3).

Even though most of the sites selected were located within the main maize growing areas of NZ, this was not the case with Taranaki where long term weather data prior to 2004 were not available for the main maize areas such as Hawera (39.61^0 S; 174.29^0 E; 98 m above sea level). A cooler ENV (Stratford) with a more complete set of weather data was thus selected. Similarly, the soil type selected in the Waikato ENV can be considered marginal compared to other Waikato soils, resulting in a possibility of lower yield potential.

Table 6.3 Soil types used in each environment/region during model simulations.

Environment	Common soil name	New Zealand soil classification
Southland	Gore silt loam	Acidic orthic brown soil
Canterbury	Lismore shallow silt loam	Pallic firm brown soil
Manawatu	Manawatu fine silt loam	Weathered fluvial recent soil
Taranaki	Stratford silt loam	Vitric orthic allophanic soil
Bay of Plenty	Whakatane loamy sand	Allophanic orthic pumice soil
Poverty Bay	Makorori silt loam	Weathered orthic recent soil
Waikato	Horotiu sandy loam	Vitric orthic allophanic soil
Northland	Papakauri clay loam	Typic orthic allophanic soil

Long term model simulations were conducted for three to six maize hybrids, representing two or three maturity classes, and nine PDs ranging from 1 September to 31 December. These were 1 and 15 September, 1 and 15 October, 1 and 15 November, 1, 15 and 31 December. In Northland, Waikato, BOP and Poverty Bay, six hybrids (34P88, 34D71 (late), 36M28, 36B08 (mid), 38P05 and 38H20 (early)) were simulated compared to five hybrids (36M28, 36B08 (late), 38P05, 38H20 (mid) and 39G12 (early)) in Taranaki and Manawatu. Only 38P05, 38H20 (late) and 39G12 (mid) were used in Canterbury and Southland. Since the later maturity hybrids sown in Manawatu (36M28 and 36B08) were considered too late and not adapted for Southland and Canterbury, 38P05 and 38H20 were classified as late hybrids while 39G12 was considered a mid season hybrid for the ENVs. Additionally, a virtual hybrid, identical to 39G12 genetically but differing in TT durations for hybrid maturity (P1 and P5) by 10%, was also simulated in Southland, and this was classified as an early maturing hybrid for the ENV.

A total of 11439 hybrid*PD*year grain or silage combinations were run as simulations over the 31 yr period. In each ENV, the PD and hybrid maturity treatments in the simulation experiment were arranged as a factorial design. The simulated GY and SY scenarios from the PD and hybrid maturity treatments were compared by ANOVA using the Mixed Procedure as discussed in section 3.3.5 (Chapter 3). The 31 yr were treated as replications (Saseendran et al., 2008).

To determine yield response to PD, simulations were conducted across the nine PD treatments, holding all other variables constant. Nitrogen was assumed to be non-limiting in all simulations since fertiliser applications for cropping are usually based on soil test results. Unlike other ENVs where maize is usually rainfed, rainfall amounts are not sufficient to sustain maize crop growth in Canterbury, requiring some form of supplementary irrigation. The water balance component of the model was therefore switched off in Canterbury simulations, giving results equivalent to a fully irrigated condition.

Planting rates for “34” and “36” series hybrids (e.g., 34D71 or 36B08) were 10.7 plants m^{-2} while “38” and “39” series hybrids were simulated at 11.4 plants m^{-2}. The Penman-Monteith option was used to calculate evapotranspiration in all simulations (see section 6.4.1.1).

Quadratic regression analysis was applied to the average yield data across the nine PD treatments to estimate the optimum PD for each ENV using the relationship:

$$\mathrm{DOYopt} = \frac{-b}{2c},$$

where *DOYopt* is the optimum day of year required to maximize yield, *b* and *c* are respectively, linear and quadratic components of the regression function. The best PD was considered as one resulting in the highest yields with the least risk of crop failure. Risk was regarded as crop failure due to either frost damage or inability to reach harvest maturity within a specified time-frame. Crops that failed to emerge prior to emergence of a later PD treatment were also regarded as having failed and this was particularly common with September PDs in cool years. It was assumed that delayed emergence due to low temperatures would significantly increase seed vulnerability to insect pests, diseases and water logging. While CERES-Maize is capable of stopping growth and development when the crop experiences sub-zero T_{min} values for four consecutive days, other decisions such as potential risks were determined empirically. These also included the opportunity cost of early harvest of the potential winter crop to make way for earlier maize planting.

Even though the 80% quantile is commonly used in agriculture as the acceptable risk level (Marton et al., 2007), 90% (i.e., a nine in ten chance of succeeding) was used in this study. This was considered appropriate to increase reliability of model predictions.

For practical purposes and to allow for planting flexibility, the range of optimum PDs, hereafter referred to as "planting window" were determined. To establish the optimum planting window, yield change from the optimum PD was estimated using the following relationship:

$$\mathrm{Yc} = \frac{Y - Yopt}{Yopt} \text{ x } 100\%,$$

where *Yc* is the yield change (%), *Y* is yield for a particular PD treatment and *Yopt* is yield for the optimum PD treatment (i.e., the maximum yield). Hereafter, any reference to % yield reduction is relative to maximum yields. Planting dates with ≤5% yield reduction (*Yc*) were considered to be within the planting window required to maximise yields. Estimation of the optimum planting window also took into account the risk probability and the chance of attaining threshold yield levels required to break-even.

The probability of achieving break-even yields within each ENV was estimated as follows: For grain, 10 t ha^{-1} was considered the break-even yield required to cover costs, and this was based on a grain price of \$325 t^{-1}, a total input and interest cost of \$2529 ha^{-1} and a grain drying cost of \$43 t^{-1} (Genetic Technologies, 2009a). For silage, 17.5 t ha^{-1} was considered the minimum yield required to meet a total production cost of \$3454 ha^{-1} (Genetic Technologies, 2009b) based on a silage field standing price of 20c kg^{-1} DM. In Southland, where such high SYs are improbable and where silage is likely to be grown on-farm as a full season crop (i.e., regrassing not practical, and therefore not part of the cost of silage production), break-even yields were set at 15 t ha^{-1}.

A lower probability ($P \geq 0.7$) of attaining break-even yields was considered acceptable (vs. $P \geq 0.9$ for crop failure risk) since the latter is driven more by TT. Crop yields, on the other hand, are dependent more on soil fertility and some of the sites selected in the study (e.g., Waikato) were low yielding sites which could barely achieve the $P \geq 0.9$ threshold. In addition, falling below the break-even yield would not eliminate yield entirely as might be the case under the crop failure scenario.

To allow for regrassing of the harvested paddocks with winter pasture, 30 April was considered as the “cut-off” date for silage harvesting (30th June or when crop was killed by frost in Southland). Crops that could not achieve 35% DM by this date were considered to have failed. Although failed crops can still be used for silage, quality is compromised because of high moisture content and incomplete grain fill, so for simplicity these were assigned a zero yield equivalent.

Grain was considered ready for harvest when its moisture content reached 24% (Genetic Technologies, 2009a). To estimate the ideal harvest date, the field established relationship described in section 4.4.11 (Chapter 4) was used. Any crop that could not reach 24% grain moisture by 30 June was considered to have failed and like silage, awarded a zero yield. This date was selected in order to reduce grain mycotoxin contamination due to late harvest (Lauren et al., 2007) and poor soil trafficability caused by the wet winter conditions.

Using the 31 yr of weather data, probability tables were constructed describing the risk of crop failure and the attainment of break-even crop yields by ENV, PD and hybrid maturity. The PD at which yield from a later maturing hybrid was less than a shorter season hybrid was considered the “switch” date. Switch date is defined here as the time when it was beneficial to change from planting one hybrid in favour of the other. Yield variability from year-to-year was estimated as the CV for the average annual yields over the 31 yr period.

6.4 RESULTS

6.4.1 Model calibration

6.4.1.1 Genetic coefficients, grain yield and yield components

For most of the hybrids, PHINT values ranged from 39.5-41.5^{0}Cd (Table 6.4) with the exception of 36M28 (44^{0}Cd). 36M28 had fewer leaves for its maturity (17.3), compared to, for example, 38P05, an earlier flowering hybrid, which averaged 18.7 leaves. Across hybrids, P1 values ranged from 173-235^{0}Cd for the shortest to longest duration hybrids.

Table 6.4 Genetic coefficients used to run CERES-Maize model after calibration.

	Parameter					
Hybrid	P1	P2	P5*	G2	G3	PHINT
	^{0}Cd	d h^{-1}	^{0}Cd	Kernels plant^{-1}	mg kernel^{-1} d^{-1}	^{0}Cd
34D71	233.0	0.15	1250	1220	5.70	39.50
34P88	235.0	0.00	1280	1200	6.25	40.00
36B08	205.0	0.19	1190	1180	7.20	41.50
36M28	192.5	0.15	1170	1285	6.55	44.00
38H20	182.0	0.20	1100	1515	6.40	40.75
38P05	182.0	0.25	1130	1170	7.10	40.50
39G12	173.0	0.20	1098	1200	7.30	40.00

* In degree days above 0^{0}C (T_b0)

A procedure for minimising variation in TT to anthesis among the tested hybrids resulted in low P2 values, ranging from 0-0.25 d. To further improve estimation of developmental durations, the default TT requirement for emergence was adjusted from 6 to 2^{0}Cd cm^{-1} of seed depth. This significantly improved the agreement between simulated and field observed emergence dates from ≥5 d to within 2 d. The modified model predicted anthesis quite accurately (RMSE=3.8 d; d=0.99; mean=92), resulting in the prediction falling within 4% of the mean measured value.

While the optimum P5 value (least RMSE) obtained using T_b8 resulted in the model accurately predicting most PM dates, there were significant simulated timing delays for late planted experiments, particularly those that experienced T_{min} values <8^{0}C during grain filling (RUK07, PD4 and PD5). Results described in section 4.4.1 (Chapter 4) revealed that during grain filling, T_b was closer to 0 than 8^0C. The CERES-Maize source code was thus modified so the model could simulate grain filling using T_b0. When grain filling was simulated using T_b0, timing of PM was significantly improved, decreasing average RMSE by 73.5% to 5.6 d.

Field observed maximum plant KN (G2) and kernel growth rates (G3), needed to estimate GY, required only slight modification as field data were obtained under optimum conditions. Grain yield simulations were also refined by adjusting the default lag phase duration from 170 to 208^0Cd as proposed by Wilson et al. (1995). Kernel weight accumulation during the linear grain filling phase (section 4.4.3, Chapter 4) was more adequately predicted with a lag phase of 208^0Cd, reducing RMSE by 20% to 26.9 mg kernel^{-1}.

To further improve the GY model predictions, particularly for late planted treatments which experienced low temperatures during grain filling, the default lower optimum temperatures for PRFT and RGFIL were increased from 16.5 and 16^0C to 19^0C (Wilson et al., 1995). When 16 or 16.5^0C were used, even though GY was adequately predicted for early planted treatments, yield variations of up to 30% were observed in late plantings, particularly in cooler seasons such as RUK07, where mean temperatures around flowering averaged $<19^0$C and T_{min} values during the latter stages of grain filling were usually $<8^0$C (section 3.4.1, Chapter 3).

Across all treatments, replacing the default Priestley-Taylor with the Penman-Monteith FAO-56 evapotranspiration option also improved model simulations for GY and the associated yield components. A k value of 0.5 vs. 0.85 (default) significantly improved model performance under drought conditions, reducing RMSE for grain and total above ground biomass yields from, respectively, 2474 to 1652 kg ha^{-1} and 3177 to 1816 kg ha^{-1}. However, the default k value (0.85) resulted in a better model fit for non-water stressed conditions (data not shown). Across ENVs, SLPF values of between 0.7 and 0.8, required to quantify soil fertility status, also significantly improved the GY fit between simulated and observed data.

Grain yield simulations of the modified model resulted in a lower RMSE value, which was about 9% of the measured mean GY. Even though the main focus of the simulations was on yields, the model also estimated yield components and other factors such as LAI. While aboveground biomass weight at anthesis, maximum LAI and HI were poorly estimated, with respective normalised RMSE equivalent to 35, 34 and 23% of the mean observed values, leaf number and GY components (KW and KN plant^{-1}) were predicted with adequate accuracy (normalised RMSE ≤10%; d ≥0.74). On average, the model significantly underpredicted maximum LAI and total aboveground biomass at anthesis by ≥32%. Simulated HI values were about 22% higher than measured ones.

6.4.1.2 Silage yields

While model simulations for total aboveground biomass at grain harvest were considered reasonable (RMSE=2475 kg ha^{-1}; d=0.75; mean=22502 kg ha^{-1}), predicted SYs were less than measured yields by an average of 16.5% (Figure 6.1), resulting in a high RMSE (4412 kg ha^{-1}), equivalent to 19% of the mean field SY (d=0.38).

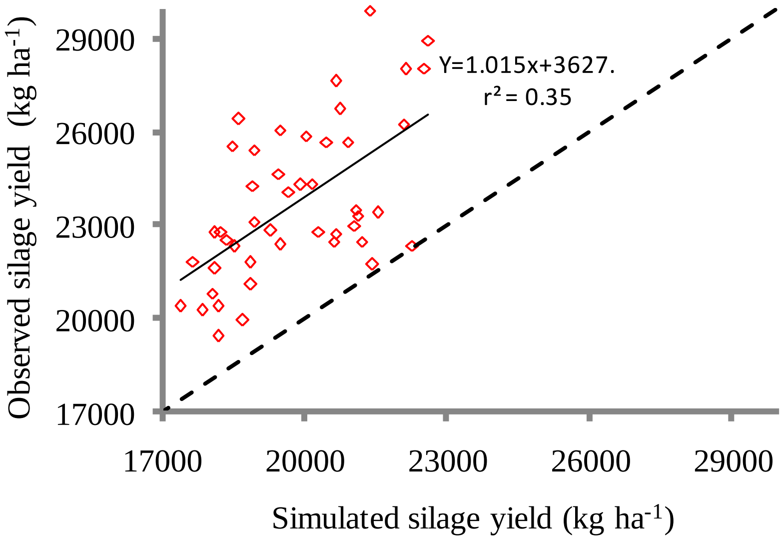


Figure 6.1 Comparison of observed and simulated silage yields for seven maize hybrids grown under three environments (MAS08, RUK07 and NGA08) over a range of planting dates. Dotted and solid lines represent, respectively, 1:1 and regression lines.

A time series analysis of simulated ear, leaf and stem weights at anthesis vs. observed values showed that while ear and leaf weights were predicted with reasonable accuracy (data not shown), the model significantly under-predicted stem weight at anthesis by an average of 45% (Figure 6.2). Simulated leaf weight at anthesis averaged 3674 kg ha^{-1}

(2299-5409 kg ha^{-1}) vs. observed values of 3659 kg ha^{-1} (2930-4795 kg ha^{-1}). Even though the RMSE (708 kg ha^{-1}) was relatively high, there was no consistent trend by the model to over- or underpredict leaf weights.

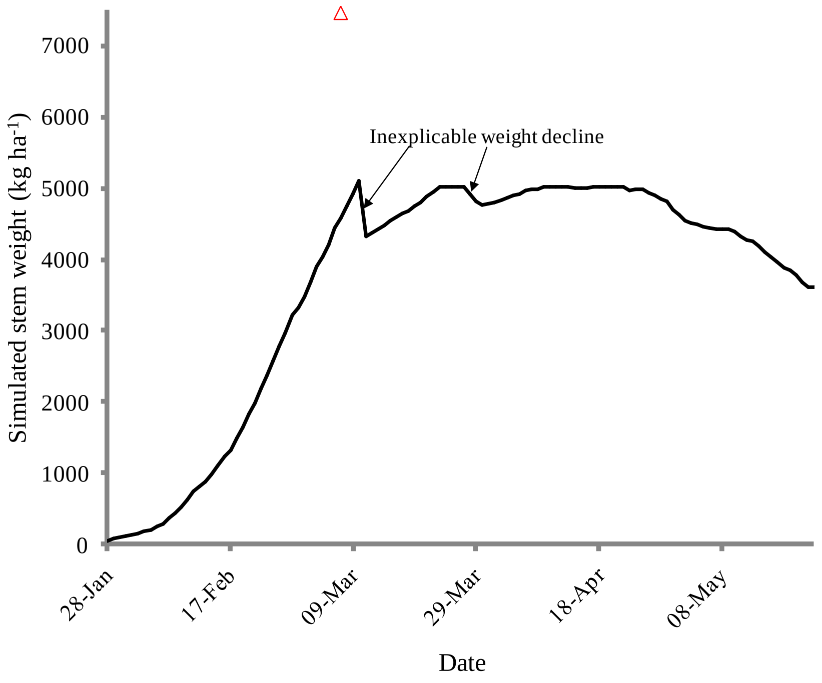


Figure 6.2 Observed stem weight at anthesis (△) and simulated stem weight using CERES-Maize from emergence to maturity (line) for 34D71 planted at RUK07 under PD5 conditions.

The simulated time series graph (Figure 6.2) revealed unexpected sharp declines in stem weight soon after anthesis and about 3 wk later, both followed by an immediate biomass increase thereafter. Even though the example shown represents one hybrid planted in one ENV, the time series response was consistent across hybrids and ENVs. This finding further confirmed the inadequacy in model coding of the stem growth function. When stem weight differences between simulated and observed field values were added to simulated SY, RMSE significantly improved, decreasing by >50% to 2086 kg ha^{-1}, which equated to 9% of the observed mean value.

6.4.2 Model verification/evaluation

Through fitting the model against nine experimental data sets from three ENVs (MAS08, RUK07 and NGA08) under a range of PD treatments, the modified model was considered adequate and genetic coefficients so generated (Table 6.4) were used to evaluate model performance using independent data from those used for model calibration.

Using 11 independent data sets, model runs were conducted to test ability of the modified model to simulate crop phenology, GY and SY. Even though SY was not accurately predicted using the model and a possible reason identified, no effort was made to correct model formulations due to lack of sufficient field-based data to describe leaf sheath and stem expansion. Instead, simulated SYs were adjusted upwards to account for the 16.5% model underestimation.

When all 11 data sets were used for model evaluation, anthesis and PM were simulated with an adequate level of accuracy (RMSE=3.3 and 6.33 d; d=0.98 and 0.94), both equivalent to a normalised RMSE of about 4%. Total final leaf number was also adequately simulated (RMSE=1.3 leaves; d=0.72; mean=18.6). Maximum LAI was significantly underestimated by 35% (RMSE=2.38; d=0.39), averaging 4.3 vs. 6.6 for measured values. However, field observed senescence values (see section 4.4.12, Chapter 4) showed measured values for LAI approaching the simulated LAI around PM (Figure 6.3).

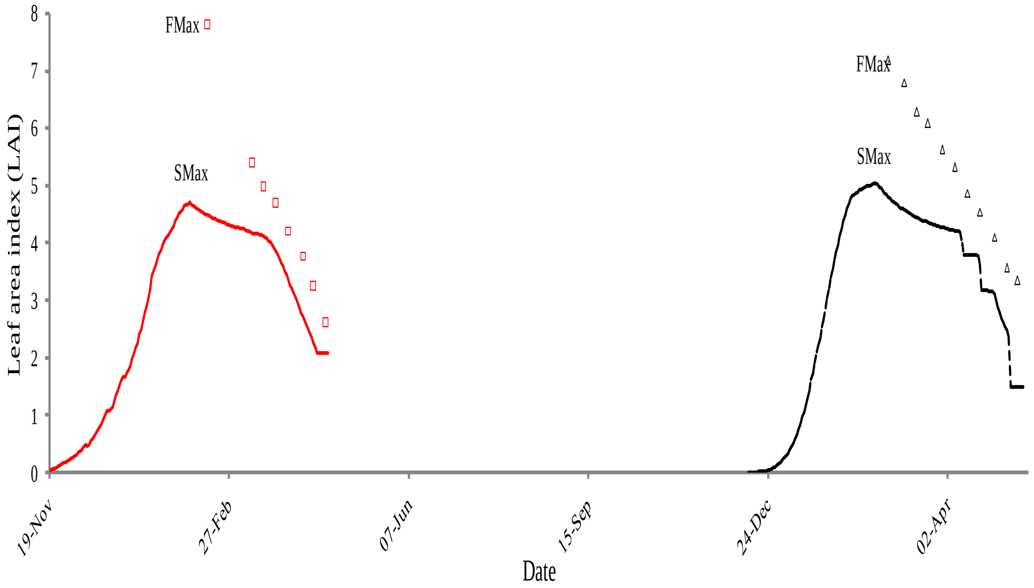


Figure 6.3 Comparison of observed (points) leaf area index (LAI) and simulated values (lines) for 34P88 planted at RUK07 (□) and NGA08 (△) under PD3 and PD5 conditions. FMax and SMax denote, respectively, the maximum field or simulated LAI values.

Over all ENVs (11 data sets), observed GY (corrected to 14% moisture content) averaged 10246 kg ha^{-1} (3336-18839 kg ha^{-1}) compared to 9273 kg ha^{-1} for model simulations (RMSE=1926 kg ha^{-1}), a 9% underestimation. Components of GY (KN $plant^{-1}$ and KW) were inaccurately simulated, with normalised RMSE magnitudes ranging between 16 and 20%. Despite the model significantly underpredicting both KN $plant^{-1}$ and KW and consequently lowering GY, HI was overestimated, implying a significant underestimation of vegetative biomass.

Further data analysis showed that the large variances in GY, SY, KN and KW were largely due to data from RUK08. In this severely water stressed ENV, the model significantly underpredicted KN $plant^{-1}$ (RMSE=63.1 kernels; d=0.7) and KW (RMSE=0.06 g; d=0.37), resulting in normalised RMSE $\geq$27% of the mean field observed values. The simulated GYs for RUK08 were consequently 35% lower than field recorded data (RMSE=2474 kg ha^{-1}; d=0.45; mean=6276 kg ha^{-1}). The regression slope (0.586) and intercept (3894) for the simulated vs. observed data were respectively, significantly different from 1 and 0, signifying poor model performance under severe water stress (Figure 6.4).

By eliminating data from RUK08, GY was adequately estimated (RMSE=1257 kg ha^{-1}; d=0.9) (Figure 6.4). The slope (1.14) and intercept (2070) values of the regression between simulated and observed data were respectively, not significantly different from 1 and 0, indicating model adequacy for the tested ENVs.

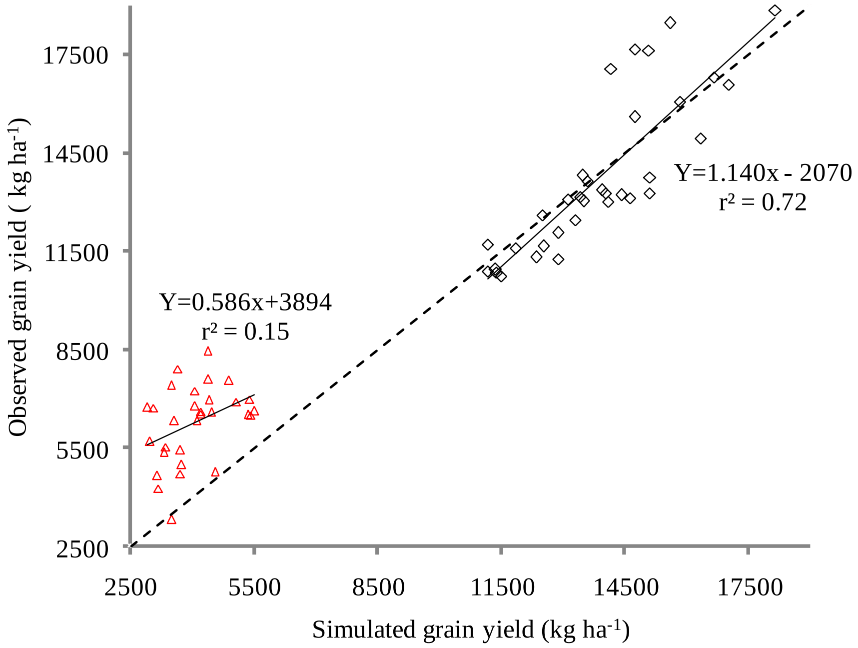


Figure 6.4 Comparison of observed and simulated grain yields (adjusted to 14% moisture content) for seven maize hybrids grown at RUK08 (△), MAS08, NGA08 and RUK07 (◇) over a range of planting dates.

6.4.2.1 Silage yields

When simulated biomass data from CERES-Maize were adjusted to account for stem weight underprediction (i.e., +16.5% of simulated results), SY was simulated with a reasonable degree of accuracy (RMSE=2237 kg ha^{-1}; d=0.96) (Figure 6.5). Like GY simulations, the model significantly underpredicted SY at RUK08. The slope of the regression line for RUK08 (0.752) was significantly less than 1, indicating a tendency to underpredict SY in excessively water stressed conditions. Impact of water stress on model performance for SY was however less dramatic than for GY, which had a regression slope of 0.586 for observed vs. simulated. Exclusion of these data resulted in a significant improvement in the model fit, reducing the RMSE value to 1826 kg ha^{-1}. Due to poor model simulations of GY, and the components of SY and GY under water stress conditions, RUK08 data were only used to evaluate predictions of crop phenology (Table 6.5).

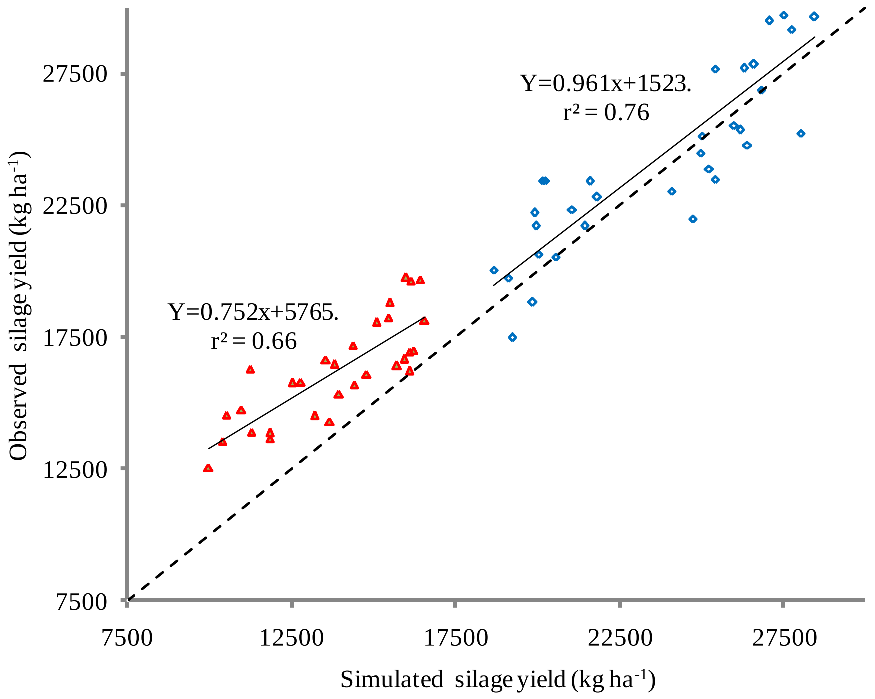


Figure 6.5 Comparison of observed and simulated silage yields (adjusted for model underprediction of stem weight at anthesis) for seven maize hybrids grown at RUK08 (Δ), MAS08, NGA08 and RUK07 (◇) over a range of planting date treatments not originally used for model calibration.

Table 6.5 Measured and simulated developmental and growth parameters in seven maize hybrids using independent data from the relatively well-watered sites of RUK07, MAS08 and NGA08, and the test statistics to evaluate model accuracy.

Variable Name	Mean observed	Mean simulated	RMSE	Normalised RMSE %	d-index	n
Anthesis day*	85	85	3.30	3.88	0.98	64
Maturity day*	149	151	6.33	4.25	0.94	64
Final leaf number*	18.6	18.0	1.30	6.99	0.72	64
Maximum LAI*	6.6	4.3	2.38	35.87	0.39	64
Kernels m^{-2}	4323	4213	435	10.05	0.83	34
Kernels plant^{-1}	400	386	42.09	10.54	0.81	34
Harvest index	0.51	0.65	0.14	28.16	0.24	34
Kernel weight g	0.28	0.29	0.03	12.22	0.76	34
Silage yield kg ha^{-1**}	24451	23850	1826	7.47	0.96	34
Grain yield kg ha^{-1}	13748	13871	1257	9.15	0.90	34

*Includes five data sets from RUK08 **Adjusted for poor model predictions

6.4.3 Simulation studies

Over eight ENVs and nine PDs, long term simulated yields (31 yr) ranged from 0-24 t ha^{-1} (grain) or 0-36 t ha^{-1} (silage). When planted early, later maturing hybrids tended to outyield earlier ones, particularly for silage. In Manawatu and Taranaki however, late hybrids were considered too late for the ENV, and there were no advantages in planting these hybrids, particularly for grain rather than silage. For purposes of this study, where the objective was to establish the interaction between PD and hybrid maturity, comparative yield performance by maturity will not be discussed in much detail.

There were significant yield variations from year-to-year, with the largest variations recorded in either cooler regions (CV>25%) or for a 1 September PD or mid to late December PDs (CV>50%). Yield variability was also attributed to intermittent droughts. The lowest yields were obtained under water stress, very early or late PD conditions, whereas highest yields came from simulations of early to mid October plantings (Table 6.6). Depending on ENV, hybrid maturity or crop use (i.e. grain or silage), the planting window, where yields were within 95% of the maximum, ranged from 0-4 wk from the optimum PD, resulting in a planting window of 1-7 wk. Except for Poverty Bay and Northland, both of which experience warm spring weather (Table 6.7), optimum planting windows were usually longer for silage than grain crops. Table 6.8 shows the total rainfall and average global radiation amounts for the eight ENVs.

Risks of crop failure varied across ENVs and hybrid maturity classes. Risks due to early planting were higher in cooler ENVs such as Taranaki, and least in Northland. There were no differences in hybrid maturity response for risk due to very early PDs. However, crop failures caused by late planting (due to inability to mature within the set timeframe as a result of frost damage or insufficient TT requirement for the crop to mature) were greatest for late season hybrids and cooler ENVs.

Table 6.6 Estimated planting windows required to achieve ≥95% of the highest possible grain and silage yields and maintain crop failure risks to $P<0.1$ for two or three hybrid maturity classes across eight environments of New Zealand. Date in parenthesis refers to the planting date resulting in the maximum grain and silage yields.

		GRAIN	SILAGE
Environment	Hybrid maturity	Optimum PD	Optimum PD
BOP	Early	29 Sep - 2 Nov (16 Oct)	1 Oct - 5 Nov (18 Oct)
BOP	Mid	23 Sep - 27 Oct (9 Oct)	27 Sep - 31 Oct (13 Oct)
BOP	Late	19 Sep - 20 Oct (2 Oct)	26 Sep - 27 Oct (10 Oct)
Northland	Early	15 Sep - 6 Nov (3 Oct)	16 Sep - 2 Nov (9 Oct)
Northland	Mid	17 Sep - 3 Nov (10 Oct)	21 Sep - 1 Nov (11 Oct)
Northland	Late	24 Sep - 1 Nov (13 Oct)	22 Sep - 30 Oct (11 Oct)
Poverty Bay	Early	1 Oct - 5 Nov (18 Oct)	30 Sep - 6 Nov (18 Oct)
Poverty Bay	Mid	30 Sep - 3 Nov (17 Oct)	30 Sep - 4 Nov (17 Oct)
Poverty Bay	Late	25 Sep - 28 Oct (11 Oct)	26 Sep - 29 Oct (12 Oct)
Waikato	Early	23 Sep - 27 Oct (9 Oct)	23 Sep - 2 Nov (15 Oct)
Waikato	Mid	20 Sep - 24 Oct (6 Oct)	27 Sep - 29 Oct (12 Oct)
Waikato	Late	17 Sep - 15 Oct (26 Sep)	27 Sep - 28 Oct (12 Oct)
Manawatu	Early	24 Sep - 22 Oct (4 Oct)	30 Sep - 4 Nov (17 Oct)
Manawatu	Mid	24 Sep - 24 Oct (6 Oct)	26 Sep - 30 Oct (13 Oct)
Manawatu	Late	19 Sep - 19 Oct (1 Oct)	26 Sep - 28 Oct (12 Oct)
Taranaki	Early	24 Sep - 29 Sep (25 Sep)	29 Sep - 29 Oct (14 Oct)
Taranaki	Mid	N/A	29 Sep - 14 Oct (6 Oct)
Taranaki	Late	N/A	N/A
Canterbury	Mid	28 Sep - 7 Oct (3 Oct)	1 Oct - 1 Nov (17 Oct)
Canterbury	Late	29 Sep - 4 Oct (2 Oct)	30 Sep - 30 Oct (14 Oct)
Southland	Early	N/A	3 Oct - 25 Oct (17 Oct)
Southland	Mid	N/A	1 Oct - 7 Oct (7 Oct)
Southland	Late	N/A	N/A

N/A - Hybrids either failed to reach harvest maturity or risk of crop failure exceeded 10%

Table 6.7 Mean monthly minimum (T_{min}) and maximum (T_{max}) temperatures across eight New Zealand environments over a 31 yr period (1978-2009).

	Southland		**Canterbury**		**Manawatu**		**Taranaki**		**Waikato**		**BOP**		**Poverty Bay**		**Northland**	
Month	Tmax	Tmin	Tmax	Tmin	Tmax	Tmin	Tmax	Tmin	Tmax	Tmin	Tmax	Tmin	Tmax	Tmin	Tmax	Tmin
									^{0}C							
September	13.7	3.7	15.5	4.1	15.1	6.8	13.6	5.5	16.3	6.3	16.5	6.4	17.0	7.1	17.2	9.3
October	15.1	5.1	17.5	6.1	16.6	8.2	15.0	6.6	17.8	8.0	18.2	8.4	19.0	8.8	18.7	10.6
November	16.7	6.5	19.4	7.9	18.4	9.6	16.8	8.1	19.8	9.5	20.2	10.3	21.0	10.7	20.5	12.2
December	18.6	8.3	21.4	9.9	20.8	11.7	18.8	9.9	22.0	11.5	22.1	12.6	23.2	13.0	22.7	14.0
January	19.9	9.3	23.4	11.2	22.8	12.7	20.8	11.1	24.1	12.4	23.9	13.8	24.7	13.9	24.2	15.5
February	19.9	8.7	22.7	10.9	23.2	13.0	21.1	11.3	24.6	12.7	24.2	14.1	24.2	14.0	24.3	16.0
March	18.1	7.3	20.8	9.0	21.5	11.3	19.5	10.0	22.8	11.0	22.7	12.0	22.6	12.4	22.9	14.6
April	15.7	5.4	17.7	6.2	18.6	8.8	17.0	8.0	19.9	8.5	20.0	8.9	19.9	9.8	20.5	12.6
May	12.6	3.4	14.3	3.5	15.6	6.8	14.4	6.5	16.8	6.2	17.3	6.3	17.4	7.5	18.1	10.6
Mean	16.7	6.4	19.2	7.6	19.2	9.9	17.4	8.6	20.5	9.6	20.6	10.3	21.0	10.8	21.0	12.8

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Table 6.8 Mean monthly total rainfall (Rain) and average daily global solar radiation receipt (SRad) for eight New Zealand environments over a 31 yr period (1978-2009).

	Southland		**Canterbury**		**Manawatu**		**Taranaki**		**Waikato**		**BOP**		**Poverty Bay**		**Northland**	
Month	Rain mm	SRad. MJ m^{-2} d^{-1}	Rain mm	SRad. MJ m^{-2} d^{-1}	Rain mm	SRad. MJ m^{-2} d^{-1}	Rain mm	SRad. MJ m^{-2} d^{-1}	Rain mm	SRad. MJ m^{-2} d^{-1}	Rain mm	SRad. MJ m^{-2} d^{-1}	Rain mm	SRad. MJ m^{-2} d^{-1}	Rain mm	SRad. MJ m^{-2} d^{-1}
September	66.5	11.1	50.8	12.1	76.1	12.5	172.2	13.1	97.0	11.8	117.6	14.3	72.8	14.2	118.2	13.9
October	76.7	15.5	62.1	16.8	90.5	16.1	221.6	16.7	107.7	15.3	126.1	18.5	65.7	18.6	92.7	17.7
November	75.5	19.6	60.3	20.5	76.3	20.3	154.0	20.8	94.7	18.5	111.3	21.4	61.7	21.8	83.3	20.9
December	94.6	20.9	61.0	21.5	93.9	21.8	161.2	22.7	116.8	20.2	132.0	22.8	66.6	23.2	104.3	22.6
January	100.0	19.9	55.0	21.7	59.9	23.0	119.0	23.5	80.4	21.0	97.4	23.7	54.2	23.3	92.3	22.4
February	79.1	17.0	53.9	18.2	67.4	20.0	122.3	20.7	77.6	18.0	102.5	20.2	72.9	19.4	99.7	19.5
March	83.4	12.6	62.7	13.8	61.6	15.4	141.7	16.0	84.1	14.5	123.6	16.4	97.0	15.3	133.5	15.9
April	73.6	8.1	55.0	9.3	68.3	10.8	157.6	11.3	90.9	10.6	127.7	12.1	97.1	10.9	97.8	11.5
May	97.1	4.6	60.8	5.9	74.5	7.0	176.5	7.7	99.4	7.4	127.8	8.5	88.9	7.7	103.6	8.4
Total	746	3917	522	4240	668	4449	1426	4623	849	4157	1066	4788	677	4680	926	4628

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6.4.3.1 Southland

In Southland, where mean monthly T_{min} values for the 31 yr were between 3.4 and 9.3^{0}C during the maize growing period (Table 6.7), temperature was considered the most limiting factor for maize production. As a result, the shortest maturing hybrid tested in the current experiment (39G12) was of too great a duration for this ENV, with a potential crop failure rate of P=0.06 to P=0.13 when planted between 1 and 15 October, increasing to about P=0.4 two weeks either side of this range (Table 6.9).

Crop failure was due to frost or cold temperatures affecting crop establishment and/or timely maturity. Compared with silage yields obtained from a 1 October planting in Southland, a 15 September planting yielded 75%, while 15 October and 1 November plantings yielded 87 and 62%.

Table 6.9 Probability of silage crop failure due to variable planting dates for three maize hybrid maturities simulated over 31 yr in eight New Zealand environments.

Planting date		01-Sep	15-Sep	01-Oct	15-Oct	01-Nov	15-Nov	01-Dec	15-Dec	31-Dec
Site	Maturity	**Probability**								
BOP	Late	0.24	**0.08**	**0.00**	**0.00**	**0.00**	**0.00**	0.24	0.90	1.00
	Mid	0.24	**0.08**	**0.00**	**0.00**	**0.00**	**0.00**	**0.06**	0.63	1.00
	Early	0.24	**0.08**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	0.19	0.97
Waikato	Late	0.34	0.11	**0.00**	**0.00**	**0.03**	**0.08**	0.42	0.92	1.00
	Mid	0.34	0.11	**0.00**	**0.00**	**0.00**	**0.03**	0.21	0.85	1.00
	Early	0.34	0.11	**0.00**	**0.00**	**0.00**	**0.00**	**0.10**	0.42	1.00
Poverty Bay	Late	0.20	**0.09**	**0.00**	**0.00**	**0.00**	**0.00**	**0.10**	0.85	1.00
	Mid	0.20	**0.09**	**0.00**	**0.00**	**0.00**	**0.00**	**0.03**	0.40	0.97
	Early	0.20	**0.09**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.06**	0.90
Northland	Late	**0.04**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	0.27	0.98
	Mid	**0.04**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.03**	0.94
	Early	**0.04**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	0.61
Manawatu	Late	0.32	**0.08**	**0.00**	**0.00**	**0.02**	**0.10**	0.29	0.87	1.00
	Mid	0.32	**0.08**	**0.00**	**0.00**	**0.00**	**0.03**	0.13	0.65	1.00
	Early	0.32	**0.08**	**0.00**	**0.00**	**0.00**	**0.00**	**0.06**	0.29	0.94
Taranaki	Late	0.60	0.35	0.11	0.18	0.58	0.79	1.00	1.00	1.00
	Mid	0.58	0.27	**0.06**	**0.10**	0.16	0.58	0.94	1.00	1.00
	Early	0.58	0.29	**0.00**	**0.00**	**0.10**	0.23	0.71	1.00	1.00
Canterbury	Late	0.53	0.35	**0.00**	**0.02**	**0.03**	0.26	0.61	0.97	1.00
	Mid	0.48	0.35	**0.00**	**0.00**	**0.03**	**0.10**	0.32	0.90	1.00
Southland	Late	0.64	0.45	**0.10**	0.15	0.35	0.68	0.89	0.97	1.00
	Mid	0.64	0.35	**0.06**	0.13	0.35	0.61	0.90	0.97	1.00
	Early	0.64	0.35	**0.03**	**0.03**	**0.10**	0.26	0.55	0.87	0.97

When a virtual hybrid with a total growth duration equivalent to 90% of 39G12, was considered in the simulations for Southland, risk of crop failure decreased to P=0.03 when planted between 1 and 15 October, and to P=0.1 for 1 November plantings.

Planting on 1 November consequently yielded 81% of the 1 October planted silage crop, though mean yields from 1 October plantings were still comparatively low (14 t ha^{-1}). A further two week delay (15 November) meant that only 61% of the SY was achieved with the virtual hybrid, compared to 33% for 39G12. Simulated yield variability over 31 yr was high (CV for 39G12 >32%).

Due to the narrower risk-free window, considered here as P<0.1 of crop failure, late maturing hybrids were deemed too risky for Southland. Even though planting 39G12 (mid) on 1 or 15 October did not result in any significant yield differences, the probability of attaining ≥15 t ha^{-1} was higher for 1 October plantings than for 15 October plantings (P=0.45 vs. 0.29) (Figure 6.6).

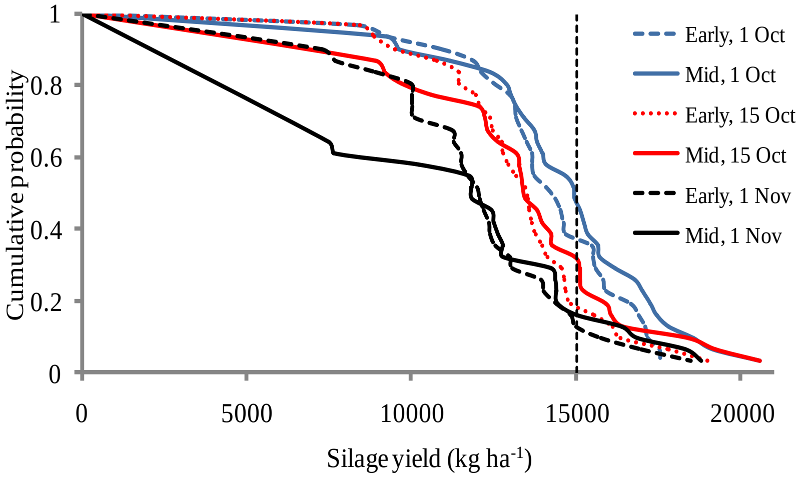

Figure 6.6 Comparison of silage yield probability curves for early and mid-maturity maize hybrids in Southland across three planting dates (1 and 15 October and 1 November). The vertical dotted line denotes the break-even yield level.

6.4.3.2 Canterbury

In Canterbury, where simulations were run under non-limiting N and water conditions, yields over all PDs averaged 16.2 t ha^{-1} (SY) or 6.5 t ha^{-1} (GY), though occasional yields as high as 28.0 t ha^{-1} and 15.6 t ha^{-1} were obtained by planting on 1 October.

Grain yields

Even though grain production was much riskier than silage, planting around 1 October guaranteed ≥95% success for the mid and late hybrids (Table 6.10). The highest possible yields were also obtained by planting around this period (Table 6.6). One month either side of this PD resulted in up to P=0.6 risk of potential crop failure while the probability of crop failure was P>0.75 if planting was conducted around 15 November or later.

Table 6.10 Probability of grain crop failure/risk for nine planting dates and two or three maize hybrid maturities simulated over 31 yr in seven New Zealand environments.

Planting date		01-Sep	15-Sep	01-Oct	15-Oct	01-Nov	15-Nov	01-Dec	15-Dec	31-Dec
Site	Maturity	**Probability**								
BOP	Late	0.24	**0.08**	**0.00**	**0.00**	**0.03**	0.19	0.61	0.97	1.00
	Mid	0.24	**0.08**	**0.00**	**0.00**	**0.00**	**0.02**	0.32	0.90	1.00
	Early	0.24	**0.08**	**0.00**	**0.00**	**0.00**	**0.00**	**0.06**	0.52	0.98
Waikato	Late	0.34	0.11	**0.03**	**0.03**	0.19	0.42	0.87	1.00	1.00
	Mid	0.34	0.11	**0.00**	**0.00**	**0.05**	0.15	0.48	0.94	1.00
	Early	0.34	0.11	**0.00**	**0.00**	**0.02**	**0.06**	0.29	0.73	0.98
Poverty Bay	Late	0.20	**0.09**	**0.00**	**0.00**	**0.00**	**0.00**	0.27	0.87	1.00
	Mid	0.20	**0.09**	**0.00**	**0.00**	**0.00**	**0.00**	**0.03**	0.47	0.97
	Early	0.20	**0.09**	**0.00**	**0.00**	**0.00**	**0.00**	**0.02**	0.13	0.90
Northland	Late	**0.04**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	0.19	0.97
	Mid	**0.04**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	0.58
	Early	**0.04**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	0.15
Manawatu	Late	0.32	**0.08**	**0.00**	**0.03**	**0.10**	0.24	0.73	0.97	1.00
	Mid	0.32	**0.08**	**0.00**	**0.00**	**0.03**	**0.10**	0.29	0.84	1.00
	Early	0.32	**0.08**	**0.00**	**0.00**	**0.03**	**0.06**	0.19	0.81	1.00
Taranaki	Late	0.73	0.53	0.50	0.73	0.95	1.00	1.00	1.00	1.00
	Mid	0.61	0.39	0.29	0.37	0.66	0.95	1.00	1.00	1.00
	Early	0.58	0.39	**0.10**	0.32	0.55	0.81	1.00	1.00	1.00
Canterbury	Late	0.53	0.35	**0.05**	0.23	0.60	0.90	1.00	1.00	1.00
	Mid	0.48	0.35	**0.03**	0.16	0.39	0.77	1.00	1.00	1.00

Planting a grain crop on 1 November resulted in 57 and 38% less GY for late and mid hybrids, with the respective yield losses for 15 November PD being 90 and 78%. When grain crops were planted outside the 15 September - 15 October timeframe, year-on-year yield variability was very high (CV>50%).

Silage yields

Silage crops had a larger risk free planting window (Table 6.9). Even though optimum PDs for mid and late hybrids were 17 and 14 October (see Table 6.6), SY for 1 November planting was >90% of these yields. By delaying PD to 15 November, mid and late hybrids yielded, respectively, 81 and 68% of the highest yields, while for 1 December PD, yields were 41 and 65% less. By planting between 1 and 30 October, there was ≥98% chance of obtaining SYs ≥17.5 t ha^{-1} with mid and late hybrids (Figure 6.7).

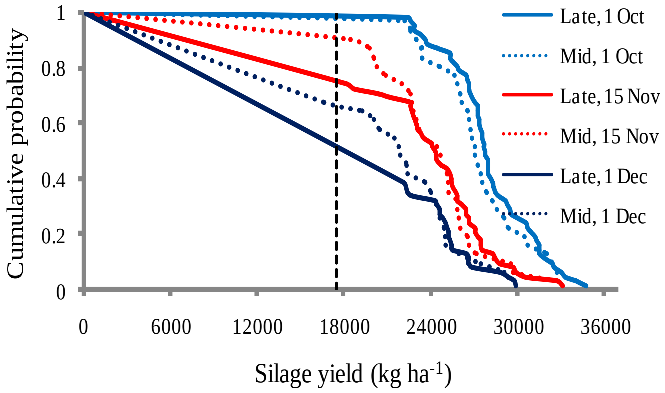

Figure 6.7 Comparison of silage yield probability curves for mid and late maize hybrid classes planted in Canterbury over three planting dates (1 October, 15 November and 1 December). The vertical dotted line denotes the break-even yield level.

Planting after 15 October resulted in high yield variability over the 31 yr period (CV >20%). A 15 November PD resulted in higher crop failure risk (P=0.3) for late compared to mid hybrids (P=0.1), with probabilities of failure increasing sharply beyond this PD.

6.4.3.3 Taranaki

Silage yields

While average simulated SYs across all PDs in Taranaki were quite low (10.5 t ha^{-1}), the highest yields (21 t ha^{-1}) were obtained with a 14 October PD. Planting on 15 December or later resulted in a P=1 chance of crop failure. When late hybrids were planted two weeks later than the optimum PD, SY reductions of 49% ensued, vs. 11 and 12% for early and mid hybrids.

Planting on 1 or 15 September yielded at least 50 or 20% less SY than for optimum PD. Probability of crop failure for late hybrids planted on 15 September was P=0.35. Three quarters of this risk was associated with cooler spring temperatures and early frost damage while the remainder was due to failure to reach silage maturity by the cut-off date. When planted around 1 or 15 October, early hybrids were the only maturity class with a 100% guarantee of reaching maturity by the cut-off date or before a killing frost. Mid hybrids had respective crop failure probabilities of P=0.06 and P=0.1 vs. P=0.11 and P=0.18 for late hybrids.

When planted late, short duration hybrids were higher yielding than later maturing hybrids (Figure 6.8). For instance, planting on 15 November caused 76, 56 and 28% reduction in SY for late, mid and early hybrids, respectively.

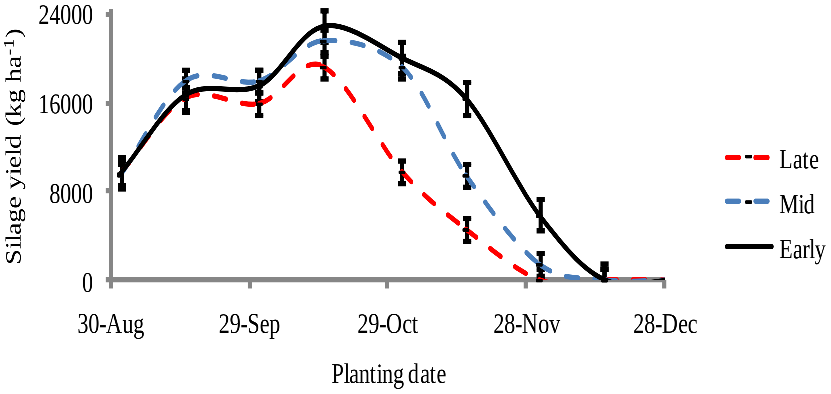

Figure 6.8 Comparison of simulated silage dry matter yields in Taranaki over 31 yr (1978-2009) for three hybrid maturity classes and nine planting dates (PDs) ranging from 1 September to 31 December. The vertical line bars denote the standard error (±se) of the mean for each PD treatment.

Across hybrid maturities, the highest probability of obtaining SYs ≥17.5 t ha^{-1} was observed with 15 October planting, where early, mid and late hybrids averaged P=0.97, P=0.90 and P=0.81, respectively (Table 6.11). Delaying planting to 15 November reduced these probabilities to 0.74, 0.42 and 0.21.

Grain yields

Average GYs across all hybrids and PDs in Taranaki ranged from 0-8.2 t ha^{-1} and the highest yields were obtained with the early hybrid planted around 1 October (9.4 t ha^{-1}).

However, grain production was considered even riskier than in Canterbury. Depending on PD, probability of crop failure ranged from P=0.29 to P=1 (mid) and P=0.5 to P=1 (late hybrids). For the early hybrid class, when planting was conducted before 15 September or after 15 October, risk of crop failure was P≥0.32 and potential GYs were ≤62% of their maximum. Irrespective of PD, the maximum probability of obtaining GYs ≥10 t ha^{-1} was P<0.5, P<0.6 or P<0.7 for late, mid and early hybrids, respectively.

Table 6.11 Probability of obtaining silage yields ≥17.5 t ha^{-1} for two or three hybrid maturity classes and nine planting dates in eight New Zealand environments over 31 yr.

Planting date		01-Sep	15-Sep	01-Oct	15-Oct	01-Nov	15-Nov	01-Dec	15-Dec	31-Dec
Site	**Maturity**	**Probability**								
BOP	Early	0.6	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.8**	0.0
	Mid	0.7	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.8**	0.4	0.0
	Late	0.7	**0.8**	**0.9**	**0.9**	**0.9**	**0.9**	0.7	0.1	0.0
Canterbury**	Mid	0.5	0.6	**1.0**	**1.0**	**1.0**	**0.9**	0.6	0.1	0.0
	Late	0.5	0.6	**1.0**	**1.0**	**1.0**	**0.7**	0.4	0.0	0.0
Poverty Bay	Early	**0.8**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**0.9**	0.1
	Mid	**0.8**	**0.9**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	0.6	0.0
	Late	**0.8**	**0.9**	**1.0**	**1.0**	**1.0**	**1.0**	**0.9**	0.1	0.0
Manawatu	Early	0.7	**0.8**	**0.8**	**0.9**	**0.8**	**0.7**	0.7	0.5	0.0
	Mid	0.7	**0.9**	**0.9**	**0.9**	**0.9**	**0.8**	0.6	0.3	0.0
	Late	0.6	**0.7**	**0.8**	**0.9**	**0.8**	**0.7**	0.5	0.0	0.0
Taranaki	Early	0.4	**0.7**	**0.7**	**1.0**	**0.9**	**0.7**	0.3	0.0	0.0
	Mid	0.4	**0.7**	**0.7**	**0.9**	**0.8**	0.4	0.1	0.0	0.0
	Late	0.4	0.6	0.6	**0.8**	0.4	0.2	0.0	0.0	0.0
Waikato	Early	0.7	**0.8**	**0.8**	**0.8**	**0.8**	**0.7**	**0.8**	0.5	0.5
	Mid	0.6	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	0.6	0.1	0.0
	Late	0.5	**0.7**	**0.8**	**0.8**	**0.8**	**0.7**	0.5	0.0	0.0
Northland	Early	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**0.9**	0.2
	Mid	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**0.9**	0.0
	Late	**0.9**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**0.7**	0.0
Southland*	Early	0.1	0.2	0.4	0.2	0.1	0.1	0.0	0.0	0.0
	Mid	0.2	0.4	0.5	0.3	0.2	0.1	0.0	0.0	0.0
	Late	0.2	0.3	0.4	0.3	0.1	0.1	0.0	0.0	0.0

* Threshold yield is 15 t ha^{-1} ** Irrigated crop

6.4.3.4 Manawatu

<u>Silage yields</u>

Across PDs, Manawatu SYs averaged 15.8 t ha^{-1} and the highest average yields were obtained by planting around mid October (21.3-21.4 t ha^{-1}) (Table 6.6). The planting window required to maximise SY for short and mid duration hybrids was about a week wider than for the late group. By planting late hybrids between 1 October and 1 November, and early and mid hybrids up to 15 November, the simulated SYs were >90% of the highest attainable yields. The probability of crop loss for these windows was $P \leq 0.03$.

Conversely, a PD of 1 September had a crop failure probability of P=0.28 whereas a PD on 15 September averaged a SY of 19.8 t ha^{-1} and had a P=0.08 chance of failing due to frost or cold temperatures during the seedling stage while yielding ≥86% of maximum yields.

A significant difference in risk among hybrids was observed with late planting. By planting on 1 December, early, mid and late hybrids yielded 86, 80 and 65% of their yield maxima. Delaying planting to 15 December resulted in late hybrids only yielding 11% compared to 31 and 62% of yield maxima for mid and early maturity classes.

While the chance of attaining the threshold SY (≥17.5 t ha^{-1}) was $P \geq 0.7$ for PDs between 15 September and 15 November for all hybrids, the potential for early, mid and late classes decreased to 68, 65 and 52% for a PD on 1 December (Figure 6.9). A further planting delay (15 December) resulted in a P=0.03 chance for late hybrids to attain the threshold SY (>17.5 t ha^{-1}), while mid and early hybrids had a P=0.26 and P=0.5 chance (Table 6.11).

Year-to-year yield variability was lowest (CV≤20%) for PDs between 1 October and either 15 November (early), 1 November (mid) or 15 October (late). Variation was highest under PDs of 1 September and 1 December or later, and was greatest in later hybrids.

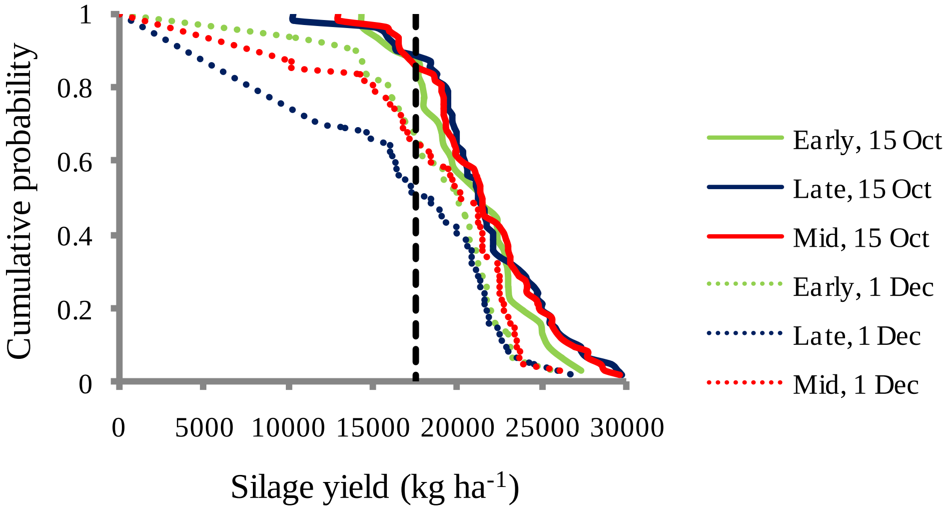

Figure 6.9 Comparison of silage yield probability curves for early, mid and late maize hybrid classes planted in Manawatu on 15 October and 1 December. The vertical dotted line denotes the break-even yield level.

Grain yields

Over the nine PDs, Manawatu GYs averaged 7.5 t ha^{-1}, and the highest average yields (11-11.4 t ha^{-1}) were obtained when maize was planted between early and mid October. Late hybrids maximised GY with PDs between 19 September and 19 October compared to 24 September to 24 October for early and mid hybrids (Table 6.6). The PDs required to maximise GYs for the three maturity classes were 1-2 wk earlier than for silage crops.

Whereas planting mid hybrids between 24 September and 24 October was required to maximise yields (similar to early hybrids), planting on 1 November resulted in GYs that were ≥90% of the maximum yields. Conversely, a 1 November PD resulted in a yield reduction of 13% for late hybrids. When early, mid and late hybrids were planted on 15 November, yield reductions were respectively, 15, 17 and 30%. Simulated GYs for 1 December planting were respectively, 69, 60 and 23% of the yield maxima.

When planted on or after 1 November, long season hybrids were 8-65% lower yielding than early and mid hybrids. By planting a grain crop on 15 November, the chance of crop failure using long season hybrids was P=0.24 compared to between P=0.06 (early) and P=0.1 (mid hybrids). Across the three hybrid classes, the risk free planting period was two weeks shorter than for silage production (Table 6.10).

The greatest opportunity to achieve the threshold GY (≥10 t ha^{-1}) was with PDs between 19 September and 16 October (Table 6.12). The probability of obtaining ≥10 t ha^{-1} with 1 November PD was P≤0.6 for all hybrids. A PD on 1 December resulted in a P=0.15 chance for late hybrids to attain such yields compared to P=0.4 and P=0.5 for mid and early hybrids.

Table 6.12 Probability of obtaining grain yields ≥10 t ha^{-1} for two or three hybrid maturity classes and nine planting dates in seven New Zealand environments over 31 yr.

Planting date		01-Sep	15-Sep	01-Oct	15-Oct	01-Nov	15-Nov	01-Dec	15-Dec	31-Dec
Site	**Maturity**	**Probability**								
BOP	Early	0.6	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	0.5	0.0
	Mid	**0.7**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	0.5	0.0	0.0
	Late	0.6	**0.7**	**0.7**	**0.8**	**0.7**	**0.7**	0.3	0.1	0.0
Canterbury	Mid	0.5	0.6	**1.0**	**0.8**	0.6	0.2	0.0	0.0	0.0
	Late	0.4	0.6	**1.0**	**0.8**	0.4	0.1	0.0	0.0	0.0
Poverty Bay	Early	**0.7**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.8**	0.1
	Mid	**0.7**	**0.8**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	0.5	0.0
	Late	**0.8**	**0.8**	**0.9**	**0.9**	**0.9**	**0.9**	**0.7**	0.1	0.0
Manawatu	Early	0.5	**0.7**	**0.7**	**0.7**	0.6	0.5	0.5	0.1	0.0
	Mid	0.5	**0.7**	**0.7**	**0.7**	0.6	0.5	0.4	0.1	0.0
	Late	0.5	0.6	**0.7**	**0.7**	0.5	0.5	0.1	0.0	0.0
Taranaki	Early	0.4	0.6	**0.7**	**0.7**	0.4	0.2	0.0	0.0	0.0
	Mid	0.3	0.6	0.6	0.6	0.3	0.0	0.0	0.0	0.0
	Late	0.2	0.5	0.4	0.3	0.0	0.0	0.0	0.0	0.0
Waikato	Early	0.6	0.6	**0.7**	**0.8**	0.6	0.6	0.5	0.1	0.0
	Mid	0.5	**0.7**	**0.7**	**0.7**	**0.7**	0.5	0.3	0.0	0.0
	Late	0.5	0.6	**0.7**	**0.7**	0.5	0.4	0.1	0.0	0.0
Northland	Early	**0.9**	**0.9**	**1.0**	**0.9**	**0.9**	**0.9**	**0.9**	**0.8**	0.2
	Mid	**0.9**	**1.0**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.8**	0.1
	Late	**0.8**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.7**	0.0

6.4.3.5 Waikato

<u>*Silage yields*</u>

In Waikato, average simulated SY across all PDs was 16 t ha^{-1} and the highest yields (22.2-22.4 t ha^{-1}) were obtained when crops were planted between 12 and 15 October. The optimum planting window ranged from about 1 October to 1 November for all hybrids. Planting early, mid and late hybrids on 15 November resulted in respective SY reductions of 6, 8 and 13%. A PD of 1 December resulted in respective SYs equivalent to 85, 74 and 54% of the yield maxima. Probability of crop failure with 1 or 15 September planting was P=0.34 or P=0.11, whereas on or after 1 December, it was P≥0.10, P≥0.21 and P≥0.42 for early, mid and late hybrids (Table 6.9).

When planted on 1 October, at 23.3 t ha^{-1}, late hybrids significantly outyielded both early (21.8 t ha^{-1}) and mid hybrids (22.0 t ha^{-1}) (Figure 6.10). This was also the case with 15 October plantings, where late hybrids yielded 23.2 vs. 21.8 t ha^{-1} for early and mid hybrids. All hybrids yielded similarly with a 1 and 15 November PD while a PD on 1 December resulted in early hybrids outyielding mid and late hybrids by 13 and 32%.

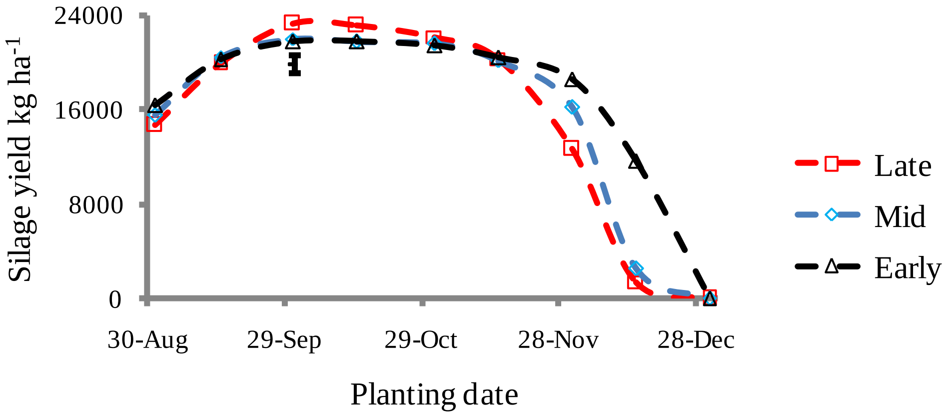

Figure 6.10 Comparison of simulated silage dry matter yields in Waikato over 31 yr (1978-2009) for early, mid and late hybrids planted on nine dates ranging from 1 September to 31 December. The vertical line bar denotes the standard error (±se) of the mean of planting date and maturity treatments.

Provided planting occurred between 15 September and 15 November, the probability of achieving the 17.5 t ha^{-1} threshold was ≥0.7 for all hybrids (Table 6.11). By 1 December, this decreased to P=0.6 and P=0.5 for mid and late hybrids, plummeting to

P=0.08 and P=0.03, respectively, when planting was delayed to 15 December. On this date, there was, however, a P=0.52 chance of obtaining ≥17.5t ha^{-1} with early hybrids.

Variability in SY across years was usually highest under very early or late plantings (CV≥40%). As in Manawatu, variation in SY under late PD situations was most apparent in late maturing hybrids. For example, when planted on 1 December, the CVs for early, mid and late hybrids were, respectively, 39, 57 and 88%. The lowest year-on-year variability in SY (CV=21%) was observed for PDs around 1-15 October.

Grain yields

Average simulated Waikato GYs over all PDs were about 7.6 t ha^{-1}, and highest average yields (≥11.8 t ha^{-1}) were obtained when late hybrids were planted on 26 September. Early and mid hybrids maximised GY when planted on 9 or 6 October. Planting on 1 or 15 November resulted in early and mid hybrids outyielding the longer duration hybrids by 16 and 35%, respectively. When planting occurred later than 15 November, early hybrids had a large advantage over both mid and late season hybrids. This was largely because by planting on 15 November, yield reductions for late, mid and early hybrids were 44, 19 and 13%. The respective yields for 1 November planting were 82, 94 and 95% of the maximum GYs. With 1 December PD, yields were much lower for later hybrids, where average GYs for late, mid and early hybrids were equivalent to 9, 46 and 67% of their maxima.

While a 1 November planting resulted in chance of crop failure of P≤0.05 for early and mid hybrids, the probability for late hybrids was P=0.19, increasing to P=0.42 for 15 November planting, vs. P=0.06 and P=0.15 for early and mid season hybrids. Consequently, planting late hybrids after 1 November resulted in a P<0.5 chance that GYs were ≥10 t ha^{-1} (Figure 6.11). Overall, the chance of obtaining ≥10 t ha^{-1} with late hybrids in Waikato was lower than for early and mid hybrids, especially when planted after 15 October (Table 6.12).

The year-to-year GY variability was much higher than for SY, particularly for late hybrids (CV≥36%). Similarly, very early and late planting resulted in higher CVs. On average, GY was more consistent for 1 and 15 October plantings and this was largely attributed to the sandy nature of the soil used for model simulations.

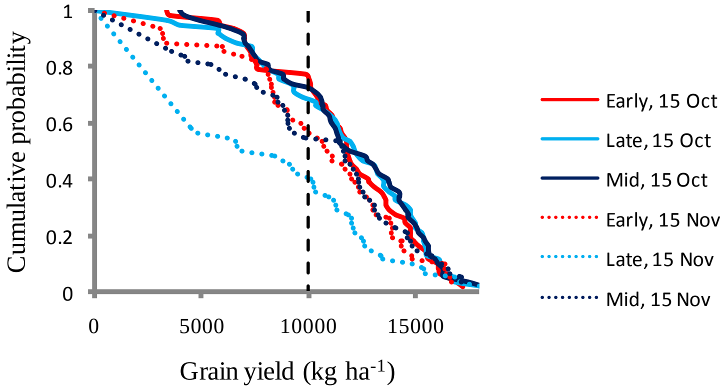

Figure 6.11 Comparison of grain yield probability curves for early, mid and late maize hybrid classes planted in Waikato on 15 October and 15 November. The vertical dotted line denotes the break-even yield level.

6.4.3.6 Bay of Plenty (BOP)

Silage yields

Average SY across all PDs and hybrids in BOP was reasonably high (18.5 t ha^{-1}) and maximum yields (23.8-24.2 t ha^{-1}) were recorded for 10-18 October PDs. However, SY varied little (<10%) between 1 October and 15 November for mid and late hybrids, and between 1 October and 1 December for the early group. Planting too early (1 September) resulted in all hybrids yielding <80% of the maximum yield potential, though a 15 September planting resulted in <10% yield reduction for all hybrids.

Hybrid maturity response to PD followed the same trend as other ENVs (e.g., Waikato). Between 15 September and 15 October, late hybrids significantly outyielded early and mid hybrids by 5-10%, after which, early and mid hybrids yielded similarly to late season hybrids. Planting on 1 December caused a 29% reduction in the SY of late hybrids, vs. 12 and 6% for mid and early hybrids. A 15 December PD resulted in earlier hybrids outyielding later ones largely due to the failure of late and mid hybrids that yielded only 9 and 35% of their maxima, while early hybrids still yielded 75% of their highest potential SY.

Risk of total crop failure was P<0.1 when planting was conducted between 15 September and 15 November for late hybrids and up to 1 December for mid and early maturing hybrids (Table 6.9). These PD ranges also resulted in P≥0.7 of achieving

≥17.5 t ha^{-1} for the respective hybrids, with the window for early hybrids extending to 15 December, followed by a significant reduction thereafter (Table 6.11).

Across years, SYs from plantings between 1 October and 15 November were more stable (CV=16-20%). In general, mid and late hybrids had much higher SY variability than early hybrids, especially under late PD situations. September planted crops also resulted in high SY variation over the 31 yr period (CV≥30%).

Grain yields

Simulated BOP GYs over all PDs averaged 9.3 t ha^{-1} for the 31 yr. The highest average yields (≥13.0 t ha^{-1}) were obtained when maize was planted between 2 and 16 October. Planting on 1 September resulted in ≥20% GY reduction. Depending on maturity, the optimum planting window in BOP ranged between 19 September and 2 November (Table 6.6). Provided planting was conducted between 15 September and 1 November, all hybrids achieved ≥90% of the maximum yields. Even though a PD on 15 November decreased the GY of late hybrids by 22%, early and mid hybrids yielded ≥90% of the October yields. When planted on 1 December, early hybrids yielded about 90% of the highest yields vs. 33 and 63% for late and mid hybrids. As a result, early and mid hybrids outyielded late hybrids by >50% for plantings of 1 December or later.

When planted on or later than 15 November, risk of crop failure increased to P≥0.19 for late season hybrids. However, it remained at P<0.1 for mid and early hybrids planted up to 15 November and 1 December, respectively. Grain yields ≥10 t ha^{-1} were achieved around a similar window.

Over all years, there was considerable variability for GY, whereby the lowest CV values (about 30% or less) were obtained by planting between 1 and 15 October (late) or 1 October and 15 November (early and mid hybrids). The largest variability in GY was observed by planting late hybrids on 1 September.

6.4.3.7 Northland

Over 31 yr, of all ENVs chosen, Northland averaged the highest T_{min} (13.1^0C) during the growing season (Table 6.7). As a result, the lowest production risks were obtained in this ENV, where probability of grain or silage crop failure was P<0.05 even if late hybrids were planted between 1 September and 1 December. Planting early and mid hybrids by 15 December resulted in a crop failure risk of $P<0.1$ for grain and silage crops. Similarly, GYs and SYs within this timeframe were >90% of maximum yields.

Compared to other simulated ENVs, Northland had the widest planting window for maximising yields, coupled with the least risks of crop failure, and these encompassed 15 September to 6 November (Table 6.6). The systematic structure evident in other ENVs, where grain crops and late season hybrids had earlier PD requirements than silage crops and early hybrids, did not exist at this northernmost site. However, the risk free period was two weeks longer for early and mid hybrids, compared to late season hybrids.

Silage yields

Simulated SYs over 31 yr and nine PDs in Northland averaged 20.1 t ha^{-1}. Maximum SY for the three maturity groups occurred between 9 and 11 October. However, provided planting was conducted between 15 September and 30 October, simulated SYs were within 95% of the highest achieved yields for all hybrids. Planting silage crops on 15 December resulted in a 38% SY reduction in late hybrids compared to 17 and 14% for mid and early hybrids.

Relative to other ENVs, Northland had the least year-to-year SY variation, and this was particularly apparent for PDs between 15 September and 1 December ($CV \leq 12\%$). When planted within this timeframe, the probability of attaining SYs ≥17.5 t ha^{-1} was ≥0.98.

Grain yields

Average simulated Northland GYs between 1 September and 31 December PDs were 11.4 t ha^{-1} but when planting was conducted between 15 September and 6 November, simulated yields ranged from 12.5-13.0 t ha^{-1}. If PD was delayed to 1 December, GY fell by <10%, but a 15 December PD significantly reduced GY of late hybrids by 31%, vs. 17 and 16% for mid and early hybrids, respectively. Between 1 September and 15 December, the probability of achieving GYs ≥10 t ha^{-1} was $P>0.8$ for early and mid hybrids while this held for late hybrids only until 1 December plantings.

6.4.3.8 Poverty Bay

Poverty Bay had the second highest average T_{min} (11.2^{0}C) after Northland. Consequently, there was some similarity with Northland in that all hybrids, grain or silage, had a quite similar optimum planting window (25 September - 6 November). Rainfall amounts for the September - April growing season were among the lowest of the eight ENVs (588 mm) (Table 6.8).

Silage yields

Despite the low rainfall amounts, Poverty Bay simulated SYs averaged 21.9 t ha^{-1} over the nine PDs. The highest SY, averaging about 28 t ha^{-1} was obtained from 12-18 October PDs. While SYs of early and mid hybrids were >90% of maximum yields when planted up to 1 December, this only occurred up to 15 November for late hybrids. Late hybrids recorded a 15% yield loss for the 1 December PD. A 15 December PD resulted in significantly greater SY reductions in late hybrids (87%) vs. 47 and 16% for mid and early hybrids.

Chances of crop failure risk were $P \leq 0.1$ for 15 September to 1 December plantings. However, year-to-year SY variability was lowest between 1 October and 1 December PDs for early hybrids (CV=9-12%) and 1 October to 15 November for mid and late hybrids (CV=12-14%). The probability of obtaining a SY ≥17.5 t ha^{-1} was $P > 0.8$ if planting was between 15 September and 1 December.

Grain yields

Compared to all ENVs, Poverty Bay had the highest average simulated GYs over all PDs (11.8 t ha^{-1}). Highest yields (15.2-15.3 t ha^{-1}) were observed for the 11-18 October PDs. On average, planting on 1 or 15 September resulted in 25 and 11% yield reductions, respectively, for the tested hybrids (Table 6.10). By planting late hybrids on 1 December, a 33% yield loss was predicted while GYs for 15 December planting were 75% (early), 45% (mid) and 11% (late) of the yield maxima.

Provided planting was conducted between 15 September and 15 November, the probability that GY was ≥10 t ha^{-1} was $P \geq 0.8$ for all hybrids (Figure 6.12). However, year-to-year GY variability was about double that of SY for the 1 October - 1 December plantings. On a maturity basis, there was only a minor variation in GY for early and mid hybrids (CV<10%) between 1 October and 1 December compared to a 1 October to 15 November window for the late maturity group.

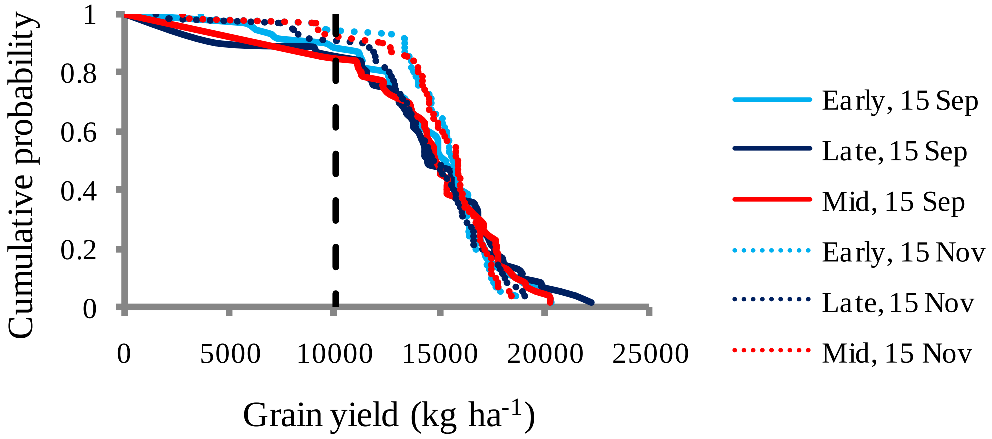

Figure 6.12 Comparison of grain yield probability curves for early, mid and late maize hybrid classes planted in Poverty Bay on 15 September and 15 November. The vertical dotted line denotes the break-even yield level.

6.4.3.9 Hybrid maturity switch date

The planting windows required to achieve break-even yields by either 30 April (silage) or 30 June (grain), with a risk level (crop failure) of P<0.1, varied across ENVs, crop or hybrid maturity. In Northland, the latest date to plant late hybrids for both grain and silage was around 30 November vs. 22 October for grain in Manawatu (Table 6.13). Yield reductions for a 1 December PD in Manawatu ranged from 31-77% (grain) or 14-35% (silage). In Southland and Taranaki, late hybrids were not viable for either grain or silage.

Even though the silage harvest cut-off date was two months earlier than for grain, silage planting windows were generally wider than for grain. This was particularly true in cooler ENVs where late season temperatures were insufficient to sustain grain filling and enable grain drydown. In general, the latest PD for early hybrids to attain threshold yields and reduce crop failure risk to P<0.1 was generally two weeks later than that of late season hybrids. In Manawatu, when planted for grain, late hybrids were too long in duration for the ENV and consequently, there was no advantage in planting late over mid hybrids after 22 October. Under Waikato ENV test conditions (relatively poor soil quality), late hybrids could only be planted up to 21 October for grain, after which the potential to maximise yields was greatly reduced. Earlier hybrids were thus a less risky choice for grain production.

For silage crops in Southland and Taranaki or grain crops in Canterbury, despite reasonably wide PD windows to achieve 95% of the maximum yields, planting a few days past the optimum window resulted in higher risks ($P>0.1$) of crop failure (see Table 6.6 and Table 6.13). In these regions, there was a significant decline in temperature and global radiation after summer (Table 6.7 and Table 6.8).

Table 6.13 The latest planting dates required to maintain crop failure risk at $P<0.1$ for two or three hybrid maturities in eight New Zealand environments.

Environment	Hybrid maturity	GRAIN Latest PD	SILAGE Latest PD
BOP	Early	27-Nov	03-Dec
BOP	Mid	19-Nov	27-Nov
BOP	Late	09-Nov	24-Nov
Northland	Early	16-Dec	06-Dec
Northland	Mid	05-Dec	02-Dec
Northland	Late	29-Nov	01-Dec
Poverty Bay	Early	09-Dec	12-Dec
Poverty Bay	Mid	06-Dec	03-Dec
Poverty Bay	Late	20-Nov	30-Nov
Waikato	Early	24-Nov	29-Nov
Waikato	Mid	06-Nov	22-Nov
Waikato	Late	21-Oct	16-Nov
Manawatu	Early	12-Nov	24-Nov
Manawatu	Mid	09-Nov	20-Nov
Manawatu	Late	22-Oct	14-Nov
Taranaki	Early	01-Oct	01-Nov
Taranaki	Mid	N/A	14-Oct
Taranaki	Late	N/A	N/A
Canterbury	Mid	07-Oct	15-Nov
Canterbury	Late	04-Oct	09-Nov
Southland	Early	N/A	25-Oct
Southland	Mid	N/A	07-Oct
Southland	Late	N/A	N/A

6.5 DISCUSSION

6.5.1 Model evaluation

The modified CERES-Maize model accurately predicted anthesis and PM to within three and five days, respectively. Despite failure to adequately predict GY and SY under drought conditions, the model accurately simulated anthesis and PM with almost the same accuracy under drought as in non-water stressed conditions. This is in agreement with findings of López-Cedrón et al. (2008) who also noted that CERES-Maize was able to accurately predict phenology even under water stress situations. Further support is documented by Yang et al. (2009) who found that anthesis and PM simulations were independent of G2, G3 or soil parameter variations. However, N deficiency has been found to delay predicted anthesis and maturity in CERES-Maize (Gungula et al., 2003).

The model's relatively poor prediction of phenology observed under cool temperature conditions using T_b8 has also been reported in the literature by Liu et al. (1989). Even though Liu and co-workers also observed a simulated delay in silking, in the present study, only grain filling duration was affected by cool temperatures. The anomaly in grain filling was thought to have been largely influenced by choice of T_b. Despite T_b8 being widely used for estimating maize grain filling duration (e.g., Major et al., 1983; Andrade et al., 1999; Sarlangue et al., 2007), its use may present problems (as observed in this study), especially at temperatures close to or below 8^0C during grain filling. In the current study, significant improvements in simulation of grain filling duration were observed by using T_b0. Use of T_b0 during grain filling duration is not new, particularly in temperate conditions, such as NZ (Gambín et al., 2007, 2008; Borrás et al., 2009). Muchow (1990) has also reported similar findings in the tropical climate of Queensland. Justification for its use over T_b8 is detailed in section 4.4.1 (Chapter 4).

Lower P2 values obtained in this study (0-0.25 d) are consistent with other research showing little or no photoperiod response in modern temperate germplasm (Ellis et al., 1992a; Bonhomme et al., 1994; Birch et al., 1998c). Long photoperiods generally result in increased leaf numbers in photoperiod sensitive germplasm (Warrington and Kanemasu, 1983c), delaying silking as a result. However, differences in leaf numbers recorded in this study were considered to have been largely caused by temperature variation (see section 5.4.8, Chapter 5). Provided N levels are optimum, the modified CERES-Maize model can therefore be considered adequate for predicting phenology.

Despite relatively high rainfalls in most NZ maize growing ENVs, the Penman-Monteith method of estimating evapotranspiration option resulted in more realistic yield simulations across all treatments, irrespective of soil moisture status. Inadequacy of the Priestley-Taylor method (default for CERES-Maize) has also been observed by Jamieson et al. (1998) under NZ conditions and this was attributed to its tendency to overpredict actual crop evapotranspiration and hence crop water use. Additionally, López-Cedrón et al. (2008) also observed an improvement in model predictions when the Penman-Monteith method was used under water stress and cool conditions of Spain. They also found that reducing the light extinction coefficient, k, from 0.85 to 0.5 significantly improved biomass, GY and HI predictions under water limiting conditions.

Though maize is largely rainfed in NZ, severe drought is quite rare (Harman, 1999) and rainfall amounts are usually sufficient to sustain growth. For instance, using the Waikato long term weather data (1978-2009), it is rare to experience rainfall totals of <300 mm for the 15 October to 15 April period (experienced in the 2007-08 season). The majority of seasons receive >500 mm, which is sufficient to sustain crop growth (Brouwer and Heibloem, 1986). As a result, the default k value (0.85) was used in the present study since it resulted in a better fit in non-water stressed conditions, considered more typical of NZ growing seasons. In severely water stressed situations, it is recommended that k=0.5 be used to compensate for the loss of lower leaves. The difference in the k values could be that under drought situations, lower leaves senesce, resulting in most of the radiation interception occurring in the upper leaves. However, in well-water conditions, both lower and upper leaves intercept light, resulting in larger k values. Leaf rolling, which typically occurs under drought situations also reduces k.

Changing the T_{min} required to maximise photosynthetic and grain filling rates from about 16 to 19^0C improved model performance, especially under cool conditions. Wilson et al. (1995) thus showed that mean temperatures $<19^0$C during grain filling negatively affected KW. The wider range of temperatures currently used in CERES-Maize to maximise photosynthesis and grain filling mean that the model's RUE and grain growth functions are relatively insensitive to temperature. This was evident under cool conditions where simulated yields were up to 30% higher than measured yields.

Under non-limiting water conditions, simulated GYs closely matched measured values. This finding further supports conclusions by several researchers that CERES-Maize was versatile and offered realistic predictions over a reasonably wide range of ENVs when temperate maize germplasm was being compared (Hodges et al., 1987; Carberry et al., 1989; Jagtap et al., 1993; López-Cedrón et al., 2005; Soler et al., 2007; López-Cedrón et al., 2008; Yang et al., 2009). Although there is a range of literature showing that the model, particularly the earlier versions, struggled to simulate GY components such as KN (e.g., Jagtap et al., 1993; Ritchie and Algarswarmy, 2003; Soler et al., 2007), in this study, KN and KW were both simulated with reasonable accuracy under optimum soil water conditions. However, maximum LAI was significantly underpredicted in all ENVs, and this deficiency has been reported elsewhere (e.g., Ben Nouna et al., 2000; Ben Nouna et al., 2003; López-Cedrón et al., 2005).

Even though the model significantly underestimated SY, in almost all cases model estimates were usually lower by about 16.5%, a difference of about equal magnitude to that between observed and simulated absolute stem weight at anthesis. Failure of the CERES-Maize model to simulate SY was thus most likely due to inability to accurately predict stem weight. CERES-Maize uses leaf number and leaf growth rate to calculate stem growth rate. Since leaf number predictions were within ±0.7 leaves, failure to accurately simulate stem weight was thus most likely due to errors caused by inadequate formulation of the leaf sheath and internode growth functions, and in particular, how partitioning to the stem was handled. The higher HI values simulated by CERES-Model are therefore largely a result of the underprediction of vegetative biomass at flowering.

On the other hand, LA estimates by CERES-Maize are based on leaf weight and leaf growth rates. Like leaf number, leaf weight simulations had a reasonably good model fit, reiterating the inadequacy of the leaf sheath growth rate formulation or specific leaf weight simulations, leading to a systematic underestimation of LAI. Since leaf sheath growth rates and specific leaf weights were not measured in this study, no attempts were made to correct the disparity. Efforts to improve LAI formulation in CERES-Maize have been attempted by Lizaso et al. (2003) who established an improved function but noted that more work was required to improve LA calculations. Research on correcting LAI predictions, particularly for water stress conditions, have also been attempted (Ben Nouna et al., 2003; Lizaso et al., 2005), but a generic solution is yet to be found.

While variation between measured and simulated green LAI was high at anthesis (≥30%), the margin narrowed by PM, suggesting that simulation of leaf senescence may be too conservative for NZ conditions (see section 4.4.12, Chapter 4). Other researchers have however reported that leaf senescence rates from CERES-Maize are usually much higher than field observed values (Ben Nouna et al., 2003; López-Cedrón et al., 2008). While some of the accelerated senescence levels observed in the current study could be attributed to drought stress, even ENVs with little or no evidence of water stress exhibited the same trend. There is therefore no logical explanation for this disparity other than the fact that CERES-Maize may underestimate leaf senescence in cool temperature ENVs. Ben Nouna et al. (2000) thus suggested that leaf growth and senescence functions for CERES-Maize require modification to improve LAI simulations for some specific ENVs.

Since LAI measurements were only conducted between anthesis and PM, it was not possible to establish how simulated LA deviated from measured values between emergence and anthesis. Pinpointing stages at which significant deviations between observed and simulated values occur will be important for any modifications to the LAI formulation. It is however worth noting that among all parameters measured, maximum LAI and biomass yield at anthesis showed the poorest model fit, with simulations of each being 34 and 33% less than field values. The reduced biomass was largely due to poor stem weight simulations, which is in part determined by LAI through its influence on light interception and assimilate flux. This is supported by the observed positive correlation (r=0.67***) between LAI and biomass yield at anthesis (see section 5.4.6, Chapter 5). In addition, genetics may also play a role, for instance, under the cool spring conditions typical in NZ, CERES-Maize leaf growth functions developed from hybrid responses in the 1980s may have failed to simulate the rapid leaf growth under cool spring conditions which is characteristic of newer hybrids.

Model failure to adequately simulate GY under drought was attributed to poor KN and KW estimations which appeared overly sensitive to moisture stress. Lizaso et al. (2007)

and López-Cedrón et al. (2008) have observed a similar response in KN and reported that KN prediction could be improved by substituting the current equation with an older curvilinear function proposed by Edmeades and Daynard (1979b). When the proposed modification was effected in the present study (data not shown), there was no significant improvement in model performance for RUK08 (water stressed ENV), resulting in no reduction in RMSE for KN and 7% improvement in RMSE for GY. Use of this function for the remaining (unstressed) treatments also showed no improvement in the model fit. As a result, the default linear function was maintained. Despite these findings, there is further evidence in the literature that the curvilinear function is more versatile in predicting KN over a range of other conditions such as when IPAR per plant was limiting (Andrade et al., 2000; Lizaso et al., 2001).

Even though variation in KN accounts for most of the variation in GY under drought (Bolaños and Edmeades, 1996), in the current study, KW was also a significant factor contributing GY variation (r=0.76; section 3.4.5, Chapter 3) and hence, would have played a significant part in determining the accuracy of GY simulation. Consequently, LAI and KW have been reported as the major contributory factor for poor model performance under drought stress (Xie et al., 2001). Unsatisfactory CERES-Maize model performance under water stress situations has also been reported in other ENVs (e.g., Carberry et al., 1989; Liu et al., 1989; Wu et al., 1989).

Visual comparisons of time series graphs for KW accumulation between anthesis and PM against measured values (see section 4.4.3, Chapter 4) (graphs not shown) showed that when soil water was not limiting, KW during linear grain filling was accurately simulated. However, periodic sampling of kernel size was not conducted under drought stress (RUK08) and thus, it was not possible to establish the stage when simulated values started deviating from the field values. Any modifications to improve model performance under drought conditions should therefore, in addition to KN, also address genetic variation for sensitivity of KW to water stress.

Silage yield predictions were also significantly reduced by water stress, with more impact apparent at the lowest yield levels. Despite CERES-Maize performing well under the largely ideal growing conditions of NZ, more work is required to improve performance under drought conditions as well as prediction of SY in general. It is anticipated that once the LAI formulation has been corrected and partitioning to stem growth has been adjusted, SY calculations will also be improved. How this change will affect GY estimations remains to be seen.

6.5.2 Long term simulation study

With the exception of Taranaki and Waikato, the rest of the ENVs were considered to constitute soil and weather conditions typical of the greater proportion of the maize growing area for the region. Even though reported yields and probability levels to achieve break-even grain and silage yields for Waikato may be considered lower than for a typical Waikato soil, the general response of yields to PD was not expected to differ in this region. Conversely, due to the higher altitude (300 m) for the simulated Taranaki ENV, the reported findings may be more applicable to the cooler parts of Taranaki rather than the wider region.

Overall, across the eight ENVs, simulated yields were consistent with those reported in side by side NZ maize trials (Genetic Technologies, 2009c,d). For instance, between 1992 and 2008, average GY observed at Rukuhia Research Station (identical to the simulated Waikato ENV) for all Pioneer® commercial hybrids was 10.8 t ha^{-1} compared to 11.4 t ha^{-1} for simulated yields (Genetic Technologies, unpublished data). For the 17 yr period, the observed probability of attaining ≥10 t ha^{-1} was P=0.71 vs. P=0.65 for the simulated data. Considering that hybrid and PD treatments simulated were not necessarily the same as those physically tested, the capacity of the model to predict GY for this ENV can be considered reasonable.

Waikato yields were also similar to those reported in sections 3.4.2 (Chapter 3, grain) and 5.4.2 (Chapter 5, silage). The 20 t ha^{-1} SYs obtained by planting silage crops between 1 and 30 October in Taranaki are consistent with the 20-21 t ha^{-1} yields reported for the ENV for 5-24 October PDs (Densley et al., 2005). The findings further support reports in literature that when validated for an ENV and a known set of hybrids, the CERES-Maize model can adequately predict maize yields (Jagtap and Abamu, 2003; Soler et al., 2007). The model has also been successfully used to determine optimum PDs for different maize maturity classes elsewhere (Soler et al., 2007; Braga et al., 2008).

There were no published GY data in Taranaki to compare against simulated results. Similarly, historical SY data were not available for Poverty Bay. In Southland, where maize production is uncommon, simulated SYs were consistent with those observed from a handful of crops planted in recent years (Grant Matthews, pers. comm., 2010).

Simulated optimum PDs for the eight ENVs were around early and mid (1-18) October. The observed ranges are in general agreement with those from field studies in Waikato and Manawatu (see sections 3.6, Chapter 3 and 5.4.2, Chapter 5). Even though the observed PDs to maximise GY in Manawatu were at least two weeks later than simulated dates, the difference was considered seasonal. The season when field data were obtained was characterised by a very wet and cold spring (also see section 7.3.3, Chapter 7) which would have significantly negated any gains from early planting. Similarly, a 2 wk variation in optimum PD to maximise SY was also observed under field situations in Waikato when spring temperatures differed between two seasons (see section 5.5.2). Such an anomaly is one of the limitations of using traditional agronomic techniques when predicting hybrid x environmental interactions, as described in section 2.6 (Chapter 2). The simulated optimum PDs required to maximise yields are also in agreement with the general recommendation that planting should be considered when soil temperatures are $\geq 10^0$C (Shaw, 1988; White et al., 1999).

Within an ENV, optimum PDs required to achieve the highest yields were generally similar, irrespective of hybrid maturity or whether they were for grain or silage. Field studies conducted in Waikato and Manawatu (section 4.5.1, Chapter 4) revealed that the main difference between hybrids of dissimilar maturities was in the grain filling duration rather than emergence-anthesis duration. Consequently, onset of grain filling is generally similar for hybrids planted on the same PD irrespective of maturity. Maize crops planted around early to mid October plantings would thus normally flower in January. Therefore, grain filling occurs under high irradiance and moderate temperature conditions of between 19 and 25^0C, resulting in high yields (Muchow et al., 1990; Otegui et al., 1995b). Temperature and radiation effects on GY and SY are discussed in more detail in sections 3.5.1 (Chapter 3) and 5.5.2 (Chapter 5).

Planting outside the optimum PD range resulted in yield reductions, varying in magnitude in a way that depended on ENV, hybrid maturity or crop (i.e., grain or silage). For example, while all hybrids in BOP maximised SY and GY with early to mid October planting, GY loss due to planting long duration hybrids on 1 November was 5% vs. 0% for mid hybrids, or 22 and 4% for the 15 November PD. At the same time, loss in SY was only 2 or 5% when late hybrids were planted on 1 and 15 November. Similarly, planting mid hybrids on 1 December in Waikato resulted in a 26% SY reduction vs. 54% for GY. When early hybrids were planted on 1 December, SY and GY decreases were, respectively 15 and 33% vs. 46 and 91% for late hybrids. These results are in agreement with other findings in literature reporting >50% GY reductions for a 10 wk planting delay (Soler et al., 2007).

Effect of late planting on yield was greatest in cooler ENVs where temperature decline after summer was most rapid such as in Southland, whose mean temperatures during grain filling for 1 November plantings were 10.8^0C vs. 19.8^0C for Northland. In Northland all hybrids could still be planted on 1 December and produce >90% of the maximum GY or SY. In Canterbury, for example, planting late and mid hybrids on 15 November only yielded, respectively, 68 and 81% (SY) or 10 and 22% (GY) of maximum yields. The same PD in BOP produced 95% (SY) and 78% (GY) for late hybrids. Mid and early hybrids yielded at least 96% when planted on this date. In Taranaki, Southland and Canterbury, temperature was considered the most limiting factor to maize production, resulting in the length of the grain planting windows being only about 1 wk at the most. Additionally, higher latitude (southern) ENVs (e.g., Manawatu and Canterbury) also resulted in significant reductions in global radiation levels after summer compared to northern ENVs (Table 6.8), greatly affecting late plantings (also see previous Chapters for discussion on radiation effects on yield performance).

Observations from the simulation study showed that in low potential situations (e.g., low water holding capacity soils) with a high potential of a mid season drought, such as the selected Waikato ENV, late hybrids have a lower probability of producing greater GYs compared to earlier hybrids. For instance, even though late hybrids are commonly grown for grain in Waikato, under test conditions earlier hybrids had a greater probability of achieving the break-even GY. Similarly, Soler et al. (2007) also reported that when compared to later hybrids, early season hybrids were more adapted for off-season growing. The difference is likely due to their shorter duration, smaller sink size, a better source-sink balance under suboptimal conditions, and a lower probability of encountering adverse growing conditions, as discussed in sections 3.5.1 (Chapter 3) and 5.5.2 (Chapter 5). Since earlier hybrids' performance was less variable (vs. late hybrids) under different environmental conditions, they should therefore be planted in stressful conditions or when planting is delayed. Likewise, due to their larger sink and source sizes, late hybrids should be planted under the best and most reliable growing conditions to take full advantage of the ENV capability (Capristo et al., 2007).

The longer growth durations of later hybrids subjected grain crops to a greater risk of failing to mature in a timely manner when planted late. Higher risks due to late planting of long season hybrids have also been reported widely in the literature (e.g., Braga et al., 2008; Fletcher et al., 2008) and the P=0.1 risk of crop failure observed by planting mid hybrids on 15 November in Canterbury agrees with findings by Fletcher et al. (2008). As a result of the higher risks associated with grain filling, year-to-year yield variability was much greater for grain than silage crops, particularly for late hybrids. Possible reasons for this response have been discussed in section 3.5.1 (Chapter 3). Higher yield variability observed for early PDs has also been reported by Otegui et al. (1996) who attributed this to frost damage.

Earlier hybrids, warmer ENVs and silage crops thus had wider planting windows. Even though silage crops can be planted much later than the optimum PD with little impact on total biomass yield, poor silage quality caused by low grain and high water contents is a major concern (Braga et al., 2008; also see section 5.5.3, Chapter 5).

While early planted crops usually experience and accumulate the highest total amount of radiation, cool temperatures, frosts and seedling losses during spring significantly reduce yields. For instance, between planting and anthesis, average T_{min} values for the 1 September PD were 7.5^{0}C (Southland), 7.8^{0}C (Canterbury), 8.1^{0}C (Taranaki), 8.9^{0}C (Waikato), 9.1^{0}C (Manawatu), 9.3^{0}C (BOP), 9.5^{0}C (Poverty Bay) and 11.3^{0}C (Northland). The average T_{min} values for Southland, Canterbury and Taranaki were just at or below T_b8 required for maize growth and development (Muchow, et al., 1990), significantly reducing canopy development and yields.

Planting on 1 September thus resulted in significant yield reductions ranging from <10% in Northland to 21% (Poverty Bay), 25% (BOP), 31% (Manawatu), 35% (Waikato), 50% (Canterbury) and 60% (Taranaki and Southland). The differences among ENVs can be ascribed to spring temperature variations. Despite higher early mean temperatures in Waikato vs. Manawatu (14^0C vs. 13.5^0C), Waikato is more prone to frosts and cold temperatures (T_{min}). The model reflected this and predicted lower yields and a higher probability of crop failure for very early planted maize in Waikato (see Plate 6.1 and section 3.5.1, Chapter 3).

Plate 6.1 Cold affected maize seedlings with characteristic pale green or bleached appearance when planted on 18 September 2006 in a Waikato environment (RUK07).

Simulated yields in Northland were higher than Poverty Bay for very early or late plantings. This was attributed to Poverty Bay's lower September and October T_{min} values (7.1 and 8.8^0C), vs. 9.3 and 10.6^0C for Northland. Even though radiation levels were comparable for late PD treatments during grain filling, mean temperatures were about 2^0C higher in Northland than Poverty Bay.

On average, GYs and SYs were, respectively 4 and 9% greater in Poverty Bay than Northland, with the differences larger for optimum PDs. For example, GY in Poverty Bay was ≥18% higher for October plantings than for Northland. This could in part, be attributed to higher total radiation levels in Poverty Bay (≥5%) as well as cooler night temperatures in Poverty Bay. Higher night temperatures experienced in Northland accelerate development rate and increase plant respiration which consumes carbohydrate at the expense of DM partitioning into developing grain. High night temperatures also reduce KN due to a shorter duration of the KN determination period (Andrade et al., 1999). Higher temperatures as experienced in Northland reduce crop growth duration, decreasing the total amount of accumulated radiation (Otegui et al., 1996). Dry matter accumulation and consequently yields, are largely determined by the amount of radiation absorbed by the canopy (Kiniry et al., 1989; Muchow, 1990; Sinclair and Muchow, 1999) and maize has an experimentally observed RUE of up to 3.7 g MJ^{-1} (IPAR) under optimum growing conditions (Lindquist et al., 2005). CERES-Maize however assumes a higher RUE value (4.2 g MJ^{-1}) for non-limiting conditions, which also seems to have worked well under study conditions. This value is then adjusted downwards to account for any stress factors experienced in field situations as described in section 6.3.2. For instance, Wilson et al. (1995) reported a linear decrease in RUE from maximum at 16^0C to zero at 8^0C.

Poor yields in Southland can be attributed to low temperature and radiation levels. For instance, 1 October planting received a total of 985 MJ m^{-2} during grain filling, compared to 1322 MJ m^{-2} for Taranaki. Mean temperatures $<18^0$C, commonly experienced in Southland, have been found to decrease yields (Wilson et al., 1995). Muchow (1990) also showed that yields were maximised when radiation levels were high and temperatures were about 19^0C.

In Taranaki, while the highest radiation receipts during grain filling were achieved by planting on 1 October, cool temperatures pre-flowering (13.4^0C) meant that yields were instead maximised with 15 October planting (1272 MJ m^{-2} and 13.9^0C). The high grain filling radiation receipts in Taranaki were largely due to the lower average temperatures which resulted in longer phenological durations and thus, more IPAR. Later plantings resulted in a decrease in both radiation and temperatures during grain filling, causing a significant yield reduction. Lower temperatures also prolong crop growth duration due to slower rate of TT accumulation (Cirilo and Andrade, 1996), intensifying frost damage risk in late planted crops. Further discussions on this subject are presented in section 3.5.1 (Chapter 3).

6.6 CONCLUSIONS

For the CERES-Maize model to be relevant to NZ maize growers, it must accurately simulate maize yields and phenology under typical management conditions. Model simulations showed that provided soil moisture was not limiting, CERES-Maize can be used in NZ to predict maize phenology and GY with an accuracy of >90%. Modifications to grain filling T_b (decreased from 8 to 0^0C) and lag phase duration (increased from 170 to 208^0Cd) significantly improved estimations of grain fill duration and GY, especially under late planting or cool conditions. Adjustment of the TT required for maize seedlings to emerge from the default 6 to $2^0Cd\ cm^{-1}$ of seed depth also improved model predictions of emergence dates.

The model systematically underpredicted SY by about 16.5%, and this failure was attributed to its inadequate simulation of stem weight, which may also be linked to its consistent underestimation of LAI. To improve LAI simulations, the formulation estimating leaf growth rate was identified as the priority factor requiring modification. Such an adjustment may also correct stem weight and total biomass or SY underprediction by the model because of the increased partitioning that should result.

Under the cool temperature conditions of NZ, the Penman-Monteith option more accurately predicted evapotranspiration than the Priestley-Taylor method, which tends to overestimate plant water use and exhaust soil water reserves too rapidly under rainfed conditions. Even though k=0.85 was adopted as the light extinction coefficient in this study, k=0.5 proved more ideal under conditions of severe water stress.

Using long term weather data in eight contrasting ENVs in NZ, CERES-Maize model simulated yields were generally comparable to those reported in independent field trials as well as those reported in Chapters 3 and 5. Potential yields in areas where maize is not widely grown (e.g., Southland), Gisborne where silage is not common, or Taranaki, where grain crops are not planted, were also simulated.

Across the eight simulated ENVs, planting between 1 and 18 October maximised GY and SY. Early hybrids, silage crops and warmer ENVs had wider PD windows and a lower probability of crop failure when planted late. While late hybrids tended to outyield earlier ones when planted early, the reverse occurred when planting was delayed. Late (vs. early) hybrids resulted in much higher yield loss when planted late, and the effect was more pronounced in cooler ENVs and for grain crops. Late hybrids were also considered too long in duration for reliable grain production when grown on lighter soils in Waikato or in the shorter Manawatu season. Yield variability from year-to-year was higher under very early and late PDs, especially for late hybrids.

In cool ENVs such as central Taranaki, despite quite high grain filling radiation levels for early October plantings, cool pre-flowering temperatures (13.4^0C) reduced the probability of achieving break-even yields. Conversely, the greater risk of late planting was attributed to low temperature and radiation levels during grain filling. To maximise yields, a balance between high radiation and moderate temperature levels must therefore exist. Additionally, low autumn temperatures also prolonged the grain filling duration, increasing the risk of crop failure through frost damage.

Using CERES-Maize, it was possible to analyse how PD affected choice of hybrid maturity in terms of yield performance. The model can thus be used to determine the “switch” date when an earlier hybrid should replace a later one based on long term weather data, a choice not possible without use of a decision support system. The date for switching hybrids in order to minimise risk and maintain reasonable yields was dependent on the ENV. The switch date was later in warmer ENVs and for silage crops than for cooler ENVs or for grain crops. In general there was a two week difference in planting window length between one hybrid maturity and the succeeding one.

CHAPTER 7: GENERAL DISCUSSION AND CONCLUSIONS

7.1 INTRODUCTION

In NZ there is a continuing need to increase maize yields and yield stability through appropriate combinations of hybrid choice, PD and the growing ENV. Maximum returns from the crop over time depend on striking the right balance between PD and maize hybrid maturity for a given location.

Most agronomic recommendations are based on field experimentation, but because of year-to-year variation in weather, field trials in any single year may prove an unreliable guide (Swanson and Wilhelm, 1996; Saseendran et al., 2005). For this reason, a decision support system in the form of a crop simulation model linked to long-term weather databases can be considered a very useful option.

This study therefore aimed to calibrate, modify as needed, and evaluate an existing model, CERES-Maize, for its ability to predict how hybrid maturity x PD interactions influenced grain and silage yields, as well as establish risks associated with different management strategies across key maize growing locations in NZ.

To modify and evaluate the CERES-Maize model for NZ conditions, field experiments were conducted involving hybrids of contrasting maturity and sown on a range of PDs. These are fully described in Chapters 3-5. Chapters 3 and 5 document the collection of data required to calibrate and evaluate model adequacy for predicting GY, SY, yield components, phenology, and the suitability of some of CERES-Maize's growth sub-models. Alternate methods to simplify routine phenological field measurements required in crop models are also highlighted. Chapter 4 complements Chapters 3 and 5 and discusses effects of TT on maize phenological processes that lie at the heart of the prediction of development milestones in the model.

Finally, Chapter 6 reports on the modifications and evaluation of CERES-Maize using data obtained from field studies described in Chapters 3-5. It also describes how well the modified model agreed with an independent set of field data. The modified model was then used to predict grain and silage production as affected by PD and year-to-year weather variation in other regions within NZ. This section ties together Chapters 3-6 and extrapolates the findings to a much wider array of NZ maize-growing ENVs. Constraints experienced during the course of the study and future research needs are also discussed.

7.2 DEVELOPMENT OF A DECISION SUPPORT SYSTEM

7.2.1 Crop management decisions based on research outcomes

Results from the field studies (Chapters 3 and 5) highlighted the random nature of weather that affects outcomes of agronomic experiments and the risks involved in extrapolating results to other locations or seasons. For example, even though RUK07 and RUK08 experiments were conducted on the same site, due to contrasting weather they behaved like very different ENVs. It is therefore critical that experimental details or conditions be studied closely prior to developing recommendations from a small number of field based experiments.

Maize SY, GY and the associated yield components generally respond to PD in a convex-upward curvilinear fashion adequately described by a quadratic equation with an optimum. Where responses to PD were linear in the present study, this usually meant that the earliest tested PD was not early enough for the ENV, or that PD effects were confounded by other factors such as water stress. Use of such data could lead to inappropriate or inconclusive recommendations. CERES-Maize simulations using 31 yr weather data revealed a general quadratic response of these variables to PD (Chapter 6). The main criticism of models is that they use historical weather data and thus, averaged model results may be quite different to observations for specific seasons. As such, model results in Chapter 6 are discussed more in terms of probabilities of specific outcomes rather than as absolute certainties.

In some cases it may not be easy to explain trends in yield of field trials, as yield is a complex trait and several factors may be involved in crop growth and development. With simulation models, it is possible to check whether variation was due to radiation, temperature, photoperiod, rainfall or fertility, something not easily achievable with field trials. Even if the problem lies in the coding of the model itself, as was the case with the LAI sub-model (section 6.4.1.2, Chapter 6), this can be identified by careful examination of the model assumptions, and tested in the model by varying inputs singly and then in groups.

While early maturing hybrids tended to yield less than later hybrids, due to their smaller stature and shorter growth duration, it is possible to increase planting densities to a level where LAI (source) and kernel size and number (sink) match those of later maturing hybrids. This is however not an exact science, as was observed in the field experiments of this study. The upward adjustment of plant density in early hybrids was insufficient, and LAI for early hybrids was about 20% lower than for late hybrids (Chapter 5). This suggests that even higher densities may be required to compensate for source limitation in early maturing hybrids. It is difficult to establish with certainty the optimum density required for early hybrids to match the level of radiation interception of later maturing hybrids, as this varies depending on growing conditions, but matching them for LAI is a useful start. For instance, LA per plant could be used to estimate the appropriate ratio of plant densities required to give the same LAI for all hybrids. However, this may result in more kernels m^{-2} for early hybrids, resulting in a greater sink size (vs. late hybrids).

In the field studies (Chapters 3-5), there were relatively few occasions where performance among hybrid maturities differed significantly. Among elite commercial hybrids that have been extensively tested, differences in performance can be expected to be small. Lack of significant hybrid effects was also attributed to the statistical model used, which considered hybrids within a maturity group as a random variable, rather than a fixed effect. Such a model makes the analysis conservative when assessing hybrid maturity groups as main effects. This was not considered a limitation since the objective of this work was not to test differences among hybrid maturities *per se* but rather, the interaction between hybrid maturity and PD.

7.2.2 Improvements in methods used to collect phenological and some growth data required for crop simulation models

Phyllochron data (Chapter 5) is widely used in crop simulation models (see Chapter 6) to predict flowering. Most researchers use the linear model of leaf tip regressed on TT to estimate phyllochron (e.g., Ritchie and NeSmith, 1991; Birch et al., 1998e; Padilla and Otegui, 2005). It was observed in this study that the bilinear response was a superior method (section 5.4.11, Chapter 5), resulting in about 50% improvement in accuracy over the linear fit. The difference in the two methods was caused by the last 10-15% of leaves emerging more slowly than the rest. Use of phyllochron values estimated from the rate of appearance of all leaves, as is sometimes found in the literature may therefore result in errors in predicting TT requirement to flower.

Additionally, phyllochron values found in literature are usually difficult to interpret as there is no standard methodology for measuring them. For instance, some researchers ignore the first 2-3 leaves and/or the last 10-15%, while others use air temperature to estimate phyllochron throughout the whole leaf emergence phase (e.g., Vinocur and Ritchie, 2001). The ideal would be to use soil temperature prior to emergence of the growing point above the soil surface (Swan et al., 1987; Padilla and Otegui, 2005), but in most cases, this information is not highlighted in literature. Finally the method used to calculate TT often varies (McMaster and Wilhelm, 1997), and this will have an immediate effect on published phyllochron values. A wrong choice of base temperature, for example, can also result in phyllochron values that differ with mean temperature. Thus it has been reported that phyllochron is larger in warmer and low light situations (Birch et al., 1998d,e; Padilla and Otegui, 2005). Delayed leaf emergence was also recorded under water stress conditions and this trend has been reported in other crops (Leong and Ong, 1983; Krenzer et al., 1991). To standardise phyllochron values in literature, it is therefore suggested that conditions and methods used for generating the data be clearly defined. It is also clear from the current study that phyllochron has an important genetic component, as shown with hybrid 36M28 whose phyllochron differed significantly from the other entries (see sections 5.4.11, Chapter 5 and 6.4.1.1, Chapter 6).

Fully expanded leaf data are more routinely collected for purposes such as growth staging (Ritchie et al., 1986b). However, they cannot be directly used to estimate phyllochron. It is therefore critical that the relationship between rates of fully expanded leaf appearance and leaf tip appearance (rarely measured) be assessed. A model based on the Gompertz function estimated leaf tip numbers more accurately than the currently available linear regression models (Chapter 4) (Hardacre and Turnbull, 1986). It is envisaged that this construct will play a significant part in estimating phyllochron where only fully expanded leaf data are available.

Tassel initiation, a critical developmental milestone required in maize models to predict leaf number and consequently flowering, is usually determined through destructive dissection methods using a dissecting microscope. An indirect non-destructive procedure for estimating TI, which was more accurate for NZ conditions than others reported in literature (Hunter et al., 1974; Bonhomme et al., 1991), was established as an alternative. For this method to be accurate it is important that plant leaf numbers be correctly counted, starting from the seedling stages before any lower leaves are lost.

Leaf area per plant and LAI are important parameters in determining the ability to intercept light, and the prediction of LA per plant provides a critical ingredient in crop simulation models such as CERES-Maize. Leaf area meters such as the Delta-T SunScan (Delta-T Devices®, Cambridge, UK) are commonly used but in this study measurements were conducted manually. Manual non-destructive LA estimations in the field are time consuming, so a simpler method, based on area of the largest leaf and total leaf number was evaluated. To further simplify the process, a way to quickly identify the largest leaf on the plant was assessed. Since the largest leaf is usually near the ear (Dwyer et al., 1992), the process involved measuring four leaves around the ear, including the EL, since the largest leaf was almost always (P=0.98) between EL+1 and EL-2 positions. The main disadvantage of this method is that knowledge of the total plant leaf number (not routinely measured) is required. Historical leaf number data for maize hybrids is not always available. However, as evidenced in Chapter 5, even if leaf number was available, it varies with temperature and photoperiod, requiring that leaf counts be established in-field every season that LA measurements are required. Leaf number is easy to count provided the lower leaves have been counted and marked when the plant is knee high (i.e., before the bottom leaves senesce).

7.2.3 Prediction of crop cycle duration

Despite T_b8 being widely used to predict development processes, in this study, T_b0 was more appropriate post-flowering. This finding is not new (Muchow, 1990) but use of T_b8 continues to be popular among researchers (Andrade et al., 1999; Sarlangue et al., 2007). As observed in this study, the inadequacy of T_b8 was only apparent if grain filling occurred at very low temperatures ($<8^0$C), usually coinciding with crops planted after 20 November. This date lies outside the normal planting timeframe for the majority of NZ growers. Continued use of T_b8 is therefore common because most research studies are conducted within the confines of the normal maize growing period where the accumulated error from using this base temperature is not very large. Despite this, it is recommended that T_b0 should be used for all grain filling duration estimates.

Another common practice involves use of real time (d) to quantify KGR (e.g., Cirilo and Andrade, 1996; Borrás et al., 2009). Due to effects of temperature variation on crop development, use of TT resulted in greater stability and provided a uniform platform for comparing values across locations. The reduction in the growth cycle duration results in an overestimation of KGRs in real time for crops grown under high temperature regimes.

When TT is used, it is usually assumed that crop cycle durations (e.g., the emergence-anthesis phase) are stable or consistent. This was not necessarily the case, as TT requirement to reach flowering varied with PD, in line with leaf number and phyllochron variations (Chapter 4). Any factors that influence the two (e.g., temperature and photoperiod) will therefore also directly affect the growth cycle duration.

Drought delays silk emergence, extending the planting to flowering duration where silking is used as a development indicator. The time from planting to anthesis is little affected by drought and is considered a more stable indicator for maize flowering than the widely used trait, silking. For this reason, CERES-Maize uses anthesis rather than silking, but at the same time does not simulate the effects of drought on increasing the anthesis-silking interval (Bolaños and Edmeades, 1993b).

Grain filling thermal duration, also considered a stable parameter specific to each hybrid, can also be influenced by factors other than TT. Low source:sink ratios, exacerbated by declining moisture, IPAR and temperature, significantly reduce filling duration (Stewart et al., 1998a,b). These findings highlight the need to consider the whole plant-ENV system when estimating thermal durations, most easily done through use of dynamic simulation models.

Black layer was considered as an indicator of PM since it signals cessation of kernel DM accumulation, marking the beginning of grain drydown (Daynard and Duncan, 1969). Use of the black layer method is not without its problems (Brooking, 1990). For example, assimilate deprivation for kernel growth (Tollenaar and Daynard, 1978b; Sala et al., 2007a) and cool or frost conditions (Daynard, 1972) can hasten black layer formation prior to maturity. Despite these shortcomings, the method continues to be widely used as it is easy to observe and more practical than alternatives (Abrecht and Carberry, 1993; Earl and Davis, 2003). In situations where grain filling conditions are not optimal, caution should be exercised in use of the method. CERES-Maize for instance, in the summary report of the model output, highlights when grain filling was prematurely halted, for example, by incidence of frost or water stress.

7.2.4 Use of the CERES-Maize model in NZ

The main objective of this study was to develop a support tool for growers to make hybrid x management x ENV decisions. The model is not intended to be used by growers directly. Instead, staff from Genetic Technologies Limited will collect and assemble all relevant information required to answer the growers' needs and make necessary recommendations based on model outputs. The main reason for this is that CERES-Maize requires a considerable amount of input data, most of which are not readily available to growers. The modified CERES-Maize model will be used for, among other things:

7.2.4.1 Prediction of maize phenological stages for planning purposes

Ability to estimate timing of growth stages is particularly important in key aspects of crop management, such as herbicide or fertiliser applications, and harvest timing. The model can accurately predict flowering and PM, but is not capable of estimating either grain or whole plant moisture content.

A stand alone multiple regression model established in field studies (Chapter 4) is therefore used to estimate grain harvest time, defined here as the stage when grain moisture reaches 24%. Using this model, in conjunction with CERES-Maize, growers can plan ahead by estimating harvest timing and deciding when artificial grain drying will be required. Importantly, results can also be utilised by growers to determine the fit of different hybrid maturity classes for a particular planting window, or determine whether maize is a viable cropping alternative in areas where it has not been previously grown (e.g., grain production in Taranaki). The model can also be used as a template by plant breeders to target a specific breeding strategy such as predicting yields of a particular hybrid maturity or reliability of the hybrid for a given location or conditions.

Even though CERES-Maize is not a silage model, SYs can be extracted from the total aboveground biomass output. Another stand alone model based on the Gompertz function (Chapter 4), when used in combination with the CERES-Maize model, can estimate the date at which total whole plant DM content of 35% was achieved. CERES-Maize can be forced to output the biomass yields for that particular date, which will then be considered as the SY.

7.2.4.2 Decision on the best hybrid for different growing scenarios (e.g., planting dates)

CERES-Maize, in combination with long term weather data, can be used to estimate potential yields and risks arising from combinations of hybrids and PD scenarios in most NZ ENVs. For instance, using generated tables described in Chapter 6, three scenarios where CERES-Maize could be useful are as follows:

Scenario 1

What would be the best grain or silage hybrid maturity to plant in a sandy soil in Waikato for a 15 November target PD?

Using 31 yr historical weather data, late hybrids can be planted and harvested for silage by April 30, with a potential risk of failing to reach maturity equivalent to $P<0.1$. Late and mid hybrids have a 73 and 77% chance of achieving a break-even SY of ≥ 17.5 t ha^{-1}. Alternatively, by using Table 6.13 (Chapter 6) it can be ascertained that late hybrids can be planted up to 16 November. A late maturity hybrid would therefore be recommended for silage for the proposed PD.

For grain, only early hybrids will achieve $P>0.9$ chance of reaching 24% grain moisture content by 30 June, rendering mid and late hybrids too risky to plant. Even though early hybrids had a 56% probability of exceeding the 10 t ha^{-1} GY threshold when planted on this date, 24 November can be considered the final PD where early hybrids can be planted with an acceptable risk of crop failure ($P<0.1$). Depending on the grower situation or cost structure, different recommendations will be considered.

Threshold yield levels used in this study assume specific cost and income levels (see Chapter 6) which can be modified to suit individual situations. For example, the cost structure for freehold farmers will be lower than for growers leasing land or servicing debt. Consequently, growers with a high cost structure will be advised not to grow grain as chances of exceeding the 10 t ha^{-1} threshold yield will be marginal. Freehold farmers, on the other hand, could plant early season hybrids and at least break-even.

<u>Scenario 2</u>

A BOP grain grower plans to plant a late maturing hybrid around 20 October. Due to wet weather conditions and the resulting planting backlog, it is highly improbable that he will achieve the target PD and thus, the grower wants to know the latest date he can plant the same hybrid without facing an unacceptable chance of losing money.

If planting was conducted on 1 November, there would be a 97% chance that the grain will reach 24% moisture by 30 June. Probability of achieving threshold yields by this PD will be P=0.71. If planting was delayed to 15 November, the probability that the crop would not mature within the required time frame equals P=0.19, while the chances of achieving the threshold yield level drop to P=0.66. Even though the probability of achieving the break-even yield is not much less than that for 1 November planting, the risk of crop failure is too high and thus, planting should not be later than 9 November, or the grower should switch to a mid maturing hybrid.

<u>Scenario 3</u>

Use of CERES-Maize to predict maize yields and risks in areas where the crop has not been grown before.

Traditional livestock farmers or wine growers may decide they want to exit the industry due to poor product prices or increased production costs. One of the available options could be to go into maize farming, but in situations where there has not been maize grown in the region previously, it would be difficult for them to estimate the potential yields and risk levels using traditional agronomic information. With CERES-Maize, in combination with long term weather data and soil information for the ENV, simulations could be run based on different scenarios to develop an understanding of the crop x environmental interactions, allowing the ability to predict crop growth, development and project potential yields and risks. Probability of attaining particular yield levels can be estimated. For example, the model will be used to ascertain the optimum PD required to achieve a certain yield level using a range of maize hybrids for the particular ENV.

7.2.5 Planting date recommendations

Across NZ, the PDs where yields were highest and risks of crop failure were lowest, were generally similar (1-18 October). Even though this defies the generally held view that optimum PD varies significantly across regions, the main difference among ENVs was the length of the planting "window", where growers could grow their crop and still realise ≥95% of the yield maxima.

Depending on ENV, hybrid maturity or crop, planting windows are much wider than is currently perceived in NZ. For instance, mid hybrids had a five week planting window when planted for grain in the Waikato while a one week window existed for both mid and late grain hybrids in Canterbury. In Manawatu, mid hybrids had a four or five week planting window when planted for either grain or silage, respectively. In situations where planting contractors are under immense time pressure, it is therefore apparent that in cooler ENVs, grain crops or late season hybrids should be planted first.

Despite silage crops having much wider planting windows than grain, poor silage quality due to late planting needs to be considered (Braga et al., 2008). Delayed PD reduces silage quality largely due to reduction in HI, which also lowers starch and increases ADF and NDF contents (see section 5.4.3, Chapter 5). Harvest index decreases could be attributed to higher early season temperatures which enhance vegetative growth, while less grain content ensued because of lower temperature and radiation conditions during grain filling. The response was greater for late season hybrids, emphasizing the need to switch to earlier hybrids when planting is delayed. Even though the CERES-Maize model does not take silage quality into account, this can be estimated indirectly by considering HI values that are routinely outputted as part of the GY summary report. Harvest index values of about 0.50 are considered normal under NZ conditions (see section 3.4.4, Chapter 3) and therefore, if model values decrease to around 0.45, concerns about silage quality should be raised.

7.3 CONSTRAINTS EXPERIENCED DURING THE STUDY

7.3.1 Drought

Due to lack of irrigation facilities, drought experienced in 2007/08 season severely affected production at one Waikato site (RUK08) where sandy soils resulted in low water holding capacity and exacerbated drought symptoms. Even though all relevant data were collected, water stress confounded PD effects, favouring either early planted crops or early maturing hybrids. Irrigation is rarely used for maize production in Waikato, so results are directly applicable to a rare but realistic situation faced by farmers.

7.3.2 Distance

Long distance between experiments meant that the Manawatu site was limited to collection of basic agronomic data.

7.3.3 Delayed planting in Manawatu

Due to persistent wet weather and complications in trying to fit with the Waikato programme, it was not possible to plant the Manawatu site before 16 October. This meant that field data was not obtained in the Manawatu on response to planting earlier than is the current practice.

7.3.4 Photoperiod

Photoperiod effects on maize development could not be tested because of the narrow range of daylengths obtained during experimentation, the general lack of photoperiod sensitivity in the hybrids, and the confounding effects of temperature on leaf number. To get accurate data on hybrids' photosensitivity, controlled environment experiments would be required.

7.3.5 Model coding

CERES-Maize is written in Fortran, which has been superseded by more modern languages such as C++. Modifying the base code of the model to improve its accuracy was challenging, and the only option was to locate someone with Fortran expertise locally, which resulted in a significant delay.

7.4 FUTURE RESEARCH

7.4.1 Test appropriate planting rates for different PD treatments

As observed in this study, early and late PDs are respectively associated with higher or lower radiation regimes during grain filling. Planting densities should therefore be varied to reflect the environmental conditions and to maintain an optimal source:sink balance. For instance, high plant densities under late planting conditions may exacerbate the declining radiation conditions through increased leaf shading. There is therefore need to establish the optimum planting densities for different PD conditions.

7.4.2 Test appropriate planting densities for the different hybrid maturities

It was observed in this study that the planting densities currently recommended by maize seed companies, particularly for early maturing hybrids are too low to compensate for their smaller source size, especially under good growing conditions.

7.4.3 Improving CERES-Maize performance

More work is required to adjust the formulation of the leaf growth function in order to improve LAI and SY simulations. To improve overall performance of the CERES-Maize model for NZ conditions, research is also required to correct performance under drought conditions, and in particular, the sensitivity of GY components to stress.

7.4.4 Create a silage subroutine

Currently, SYs are obtained from the CERES-Maize model indirectly through the total aboveground biomass subroutine. There is need to create an independent silage subroutine so that SY output can be directly obtained from the model.

7.4.5 Compare CERES-Maize with AmaizeN model

AmaizeN (Li et al., 2009a,b) is the most widely used maize model in NZ. It is worthwhile comparing performance under similar conditions and if possible, combine the two to come up with a more robust maize model. For instance, the AmaizeN model silage subroutine could be used to improve that of CERES-Maize.

7.5 CONCLUSIONS

- The main objective of this study was to develop a decision support tool for NZ maize growers, and this was successfully achieved. Optimum planting windows and planting "switch dates" for different maize hybrid maturities were established. Probability tables for predicting effects of PD x hybrid maturity x ENV interactions on crop yields and production risks were also developed.

- Under optimum moisture conditions, CERES-Maize predicted maize phenology and GY for NZ conditions with a degree of error <10%. A slight modification of lag phase duration from 170 to 208^0Cd and a change of grain filling T_b from 8 to 0^0C significantly improved estimations of grain fill duration and GY, especially under late planting or cool conditions. Use of the Penman-Monteith option for evapotranspiration and alteration of the minimum threshold temperatures for maximising photosynthesis and grain filling from 16 to 19^0C also further improved CERES-Maize performance. However, the model systematically underpredicted SY by an average of 16.5% and this failure was attributed to underestimations of LAI and stem growth rates.

- To estimate field grain drydown for CERES-Maize harvest timing prediction and provide some estimate of grain drying needs, a multiple-linear regression equation based on temperature and atmospheric relative humidity was successfully established.

- Using field data, optimum PD to maximise GY and SY generally varied from season to season. Model simulations using 31 yr weather data in eight contrasting NZ ENVs estimated 1-18 October as the optimum PD to maximise GY and SY. Planting "windows" where yields were ≥95% of the maximum, were much wider than previously believed, ranging from 1-7 wk. Early hybrids, silage crops and warmer ENVs had wider windows and less risk ($P<0.1$) of potential crop failure when planted late.

- Although TT was more consistent than real time when estimating phenology, TT to flowering and grain filling were somewhat inconsistent across PDs. Conditions that increased leaf number or phyllochron increased TT to flower. Grain filling duration was more sensitive to stress than the emergence-flowering phase, and unfavourable conditions during grain filling reduced this period. Even though the emergence-silking TT was usually longer than the grain filling duration, differences in maturity among hybrids were largely due to variations in the grain filling duration.

- Late planted crops were usually taller, with higher ear placements, making them more prone to lodging. Late planting also reduced silage quality by lowering HI, thereby decreasing starch and increasing ADF and NDF contents. Effects of late planting on hybrid maturity responses were larger for predicted milk yield ha^{-1} than for SY. Variation in CP levels in maize silage was small, and did not strongly influence silage feed quality for milk production.

- Provided water was not limiting, yields were highest under moderate temperature and high radiation conditions. For example, lowest KN m^{-2}, the main determinant of GY, was obtained when either rainfall or solar radiation were limiting 1-2 wk either side of flowering. Highest KN m^{-2} were observed under conditions where >20 mm rainfall and >24 MJ m^{-2} d^{-1} radiation were received during this flowering period. Even though higher spring temperatures, common under late planting, increased biomass and phyllochron, they also reduced LA, leaf numbers and duration to reach flowering, which consequently lowered the PTQ (i.e., radiation receipt to TT ratio), thereby decreasing yields. Low spring temperatures reduced leaf expansion, minimising IPAR and reducing source capacity. At mean temperatures $\geq 19^0$C, average radiation levels as low as 11 MJ m^{-2} d^{-1}, also common under late planting, did not affect KGRs as short term assimilate supply during low photosynthetic activity was likely met through stalk remobilisation.

- Late maturing hybrids were usually more susceptible than early season hybrids to any form of stress (e.g., drought or declining temperature and radiation). This was attributed to their greater sink size and dependence on current photosynthesis compared to remobilisation. Early hybrids, because of their smaller sink size and shorter cycle duration, have smaller assimilate demands and will also have shorter exposure to stress that increases in intensity with time. The smaller source and sink sizes and reduced duration of exposure to radiation also meant that early hybrids could not fully exploit the potential growing ENV when grown under ideal conditions (e.g., early planting). Sink and source limitation in early hybrids can however be mitigated by modest increases in planting densities.

- While grain moisture at PM ranged from 30-36%, late planting and stress conditions during grain filling resulted in higher grain moistures at the cessation of grain filling, potentially delaying harvesting and increasing artificial grain drying costs.

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