

Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

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

A thesis presented in partial fulfilment
of the requirements for the degree of

Doctor of Philosophy

in

Plant Science

At Massey University, Palmerston North,
New Zealand

ROWLAND TSIMBA

2011

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^oC mean temperature (spring) decrease advanced optimum PD by 1-2 wk. A base temperature of 8^oC (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^oC and >25^oC 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.

ACKNOWLEDGEMENTS

This PhD project would not have been possible without the financial, intellectual, technical and moral support provided by a range of people and organisations. I would like to extend my sincere gratitude to my supervisors. Special thanks go to my Chief Supervisor, Prof. Peter Kemp for your overall guidance of the project. You were always available to offer feedback on the manuscripts, and I am very grateful. To Dr James Millner, thanks so much for your advice on statistical analysis and feedback on the thesis manuscripts. Your assistance with field and laboratory work was also greatly appreciated. Dr Greg Edmeades, thank you so much for the advice from the inception to the end of this project, without which I would not have been where I am today. Your guidance and constructive criticism of the manuscripts was also quite invaluable.

Without the funding provided by the Tertiary Education Commission (Bright Future Scheme) and Genetic Technologies Ltd., this project would not have taken place. For that, I thank both organisations. To William and Philip Yates (respectively, Managing Director and Chairman, Genetic Technologies Ltd.), I would like to acknowledge your considerable generosity for allowing me to take on this project while I continued to work full time. To Barry McCarter, I am so grateful for your input and enthusiasm in this project, and most of all, for encouraging me to pursue PhD studies.

Special thanks also go to Mark Osborne for all the technical support needed to set up the Manawatu experiments. To Peter Jessop, Tiana, Angela and Ezra Rentoul, thank you so much for helping with the data collection. To Genetic Technologies staff that helped, I also offer my gratitude. I would also like to thank Dr Alasdair Noble for his advice with statistical analyses. Contributions by Sam Mudzanire on Fortran programming were also greatly appreciated. Thanks also to Prof. Gerrit Hoogenboom (University of Georgia, USA) and Dr Jun Wei (Pioneer® Hi-Bred International) for respectively, providing the CERES-Maize model source code and initial maize genetic coefficients.

Many thanks also go to my friends who always brought me joy and laughter when I felt low. To my parents, thank you so much for all the encouragement and help with some of the data collection. Finally, to my wife Fungisai, I can never thank you enough. You were always there for me, in good or bad times. Thanks also, for taking on most of the

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

TABLE OF CONTENTS

ABSTRACT.....	i
ACKNOWLEDGEMENTS	ii
TABLE OF CONTENTS.....	iv
LIST OF TABLES	ix
LIST OF FIGURES	xiii
LIST OF PLATES	xvi
LIST OF ABBREVIATIONS.....	xvii
CHAPTER 1: GENERAL INTRODUCTION, OBJECTIVES AND THESIS FORMAT	1
1.1 GENERAL INTRODUCTION.....	1
1.1.1 Climate.....	1
1.1.2 Hybrid x environment interactions	2
1.1.3 Simulation modelling.....	4
1.2 OBJECTIVES.....	6
1.2.1 Specific objectives	6
1.3 THESIS FORMAT	7
CHAPTER 2: LITERATURE REVIEW.....	8
2.1 INTRODUCTION	8
2.1.1 Phenological development.....	9
2.2 EFFECTS OF ENVIRONMENTAL FACTORS ON CROP GROWTH AND DEVELOPMENT	11
2.2.1 Temperature	11
2.2.2 Solar radiation.....	16
2.2.3 Water.....	18
2.2.3.1 Drought effects during vegetative growth	19
2.2.3.2 Drought effects during flowering.....	20
2.2.3.3 Drought effects during grain filling.....	21
2.2.4 Photoperiod.....	22
2.2.5 Interaction between temperature and solar radiation.....	23
2.2.6 Interaction between temperature and photoperiod.....	23
2.2.7 Interactions between water and other environmental factors	24
2.3 HYBRID SELECTION TO MAXIMISE YIELD.....	25
2.4 IMPACT OF EARLY PLANTING ON MAIZE GROWTH AND DEVELOPMENT	28
2.5 IMPACT OF LATE PLANTING ON MAIZE GROWTH AND DEVELOPMENT	30

2.6	CROP SIMULATION MODELS.....	31
2.7	SUMMARY OF LITERATURE REVIEW.....	36
CHAPTER 3: THE EFFECT OF PLANTING DATE ON MAIZE GRAIN YIELDS AND YIELD COMPONENTS.....		38
3.1	ABSTRACT.....	38
3.2	INTRODUCTION	39
3.3	MATERIALS AND METHODS.....	41
3.3.1	Site and planting details.....	41
3.3.2	Experimental design and treatments.....	43
3.3.3	Weather.....	44
3.3.4	Grain yield and grain yield components.....	46
3.3.5	Data analysis.....	47
3.4	RESULTS	48
3.4.1	Weather data.....	48
3.4.2	Grain yield.....	50
3.4.3	Biomass yield at grain harvest.....	53
3.4.4	Harvest Index.....	54
3.4.5	Kernel weight.....	56
3.4.6	Ears per plant and barrenness.....	58
3.4.7	Kernel number per ear.....	59
3.4.8	Kernel number per plant.....	60
3.4.9	Grain yield per plant.....	60
3.4.10	Kernel number m ⁻²	61
3.4.11	Test weight.....	62
3.5	DISCUSSION.....	64
3.5.1	Grain yield, yield components and grain traits.....	64
3.5.2	Total aboveground biomass and harvest index.....	69
3.6	CONCLUSIONS.....	71
CHAPTER 4: THE EFFECT OF PLANTING DATE ON MAIZE PHENOLOGY, THERMAL TIME DURATIONS AND GROWTH RATES		73
4.1	ABSTRACT.....	73
4.2	INTRODUCTION	75
4.3	MATERIALS AND METHODS.....	77
4.3.1	Site and planting details.....	77
4.3.2	Determination of a suitable base temperature for maize crop development.....	77
4.3.3	Seedling emergence and tassel initiation.....	77
4.3.4	Kernel growth rate during effective grain filling rate.....	78
4.3.5	Determination of genetic coefficients.....	79

4.3.6	Anthesis, silking and physiological maturity.....	81
4.3.7	Crop Growth Rates	81
4.3.8	Dry matter remobilisation.....	82
4.3.9	Leaf senescence	82
4.3.10	Rate of post-maturity grain drydown.....	83
4.3.11	Data analysis	83
4.4	RESULTS	85
4.4.1	Estimation of maize base temperature	85
4.4.2	Crop growth rate	85
4.4.3	Kernel growth rate during linear grain filling.....	88
4.4.4	Thermal time from planting to emergence	89
4.4.5	Predicting time of tassel initiation	89
4.4.6	Thermal time from emergence to silking.....	91
4.4.7	Anthesis-silking interval	92
4.4.8	Thermal time from silking to PM, and grain moisture at PM	92
4.4.9	Thermal time for total crop cycle duration	94
4.4.10	Whole plant moisture content post anthesis	95
4.4.11	Grain drydown post PM.....	97
4.4.12	Leaf senescence	98
4.4.13	Dry matter remobilisation.....	101
4.5	DISCUSSION.....	103
4.5.1	Thermal time durations and base temperature estimations.....	103
4.5.2	Crop growth rate	107
4.5.3	Estimation of post-anthesis whole plant DM content.....	108
4.5.4	Effective grain filling and field drydown	109
4.5.5	Leaf senescence and assimilate remobilisation	112
4.6	CONCLUSIONS	115
CHAPTER 5: THE EFFECT OF PLANTING DATE ON MAIZE SILAGE YIELD AND QUALITY, LEAF PRODUCTION AND LEAF AREA DISTRIBUTION.		117
5.1	ABSTRACT.....	117
5.2	INTRODUCTION	119
5.3	MATERIALS AND METHODS.....	122
5.3.1	Background.....	122
5.3.2	Photoperiod sensitivity	122
5.3.3	Leaf number, visible leaf tip appearance and fully expanded leaves	122
5.3.4	Plant and ear height	124
5.3.5	Leaf Area Index	125

5.3.6	Total biomass at 50% anthesis.....	125
5.3.7	Silage Yield.....	125
5.3.8	Data analysis	127
5.4	RESULTS	129
5.4.1	Weather summary	129
5.4.2	Silage yield	130
5.4.3	Silage quality traits	132
5.4.4	Milk t ⁻¹ index.....	135
5.4.5	Milk ha ⁻¹ index	136
5.4.6	Total biomass yield at anthesis	137
5.4.7	Plant height	138
5.4.8	Leaf number.....	139
5.4.9	Leaf area distribution	140
5.4.10	Leaf Area Index (LAI).....	142
5.4.11	Rate of leaf emergence/phyllonchro.....	144
5.4.12	Estimation of leaf tip counts from fully expanded leaves	146
5.5	DISCUSSION	148
5.5.1	Total DM yield at flowering	148
5.5.2	Silage DM yield	149
5.5.3	Silage quality and predicted milk production	151
5.5.4	Canopy development	153
5.6	CONCLUSIONS.....	161
CHAPTER 6: USE OF THE CERES-MAIZE MODEL TO OPTIMISE PLANTING DATE AND MAIZE HYBRID SELECTION.....		clxiii
6.1	ABSTRACT.....	clxiii
6.2	INTRODUCTION	clxv
6.3	MATERIALS AND METHODS.....	clxviii
6.3.1	Experiment details	clxviii
6.3.2	Model description	clxviii
6.3.3	Model calibration and verification.....	clxx
6.3.4	Long term simulation studies.....	clxxii
6.4	RESULTS	clxxvii
6.4.1	Model calibration.....	clxxvii
6.4.1.1	<i>Genetic coefficients, grain yield and yield components</i>	<i>clxxvii</i>
6.4.1.2	<i>Silage yields</i>	<i>clxxix</i>
6.4.2	Model verification/evaluation.....	clxxx
6.4.2.1	<i>Silage yields</i>	<i>clxxxiii</i>

6.4.3	Simulation studies.....	clxxxv
6.4.3.1	<i>Southland</i>	clxxxvii
6.4.3.2	<i>Canterbury</i>	clxxxix
6.4.3.3	<i>Taranaki</i>	cxc
6.4.3.4	<i>Manawatu</i>	cxciv
6.4.3.5	<i>Waikato</i>	cxcvii
6.4.3.6	<i>Bay of Plenty (BOP)</i>	cxcix
6.4.3.7	<i>Northland</i>	cc
6.4.3.8	<i>Poverty Bay</i>	ccii
6.4.3.9	<i>Hybrid maturity switch date</i>	cciii
6.5	DISCUSSION.....	ccv
6.5.1	Model evaluation.....	ccv
6.5.2	Long term simulation study.....	ccx
6.6	CONCLUSIONS.....	ccxvi
CHAPTER 7: GENERAL DISCUSSION AND CONCLUSIONS		ccxviii
7.1	INTRODUCTION.....	ccxviii
7.2	DEVELOPMENT OF A DECISION SUPPORT SYSTEM.....	ccxix
7.2.1	Crop management decisions based on research outcomes.....	ccxix
7.2.2	Improvements in methods used to collect phenological and some growth data required for crop simulation models.....	ccxx
7.2.3	Prediction of crop cycle duration.....	ccxxii
7.2.4	Use of the CERES-Maize model in NZ.....	ccxxiv
7.2.5	Planting date recommendations.....	ccxxvii
7.3	CONSTRAINTS EXPERIENCED DURING THE STUDY.....	ccxxviii
7.3.1	Drought.....	ccxxviii
7.3.2	Distance.....	ccxxviii
7.3.3	Delayed planting in Manawatu.....	ccxxviii
7.3.4	Photoperiod.....	ccxxviii
7.3.5	Model coding.....	ccxxviii
7.4	FUTURE RESEARCH.....	ccxxix
7.4.1	Test appropriate planting rates for different PD treatments.....	ccxxix
7.4.2	Test appropriate planting densities for the different hybrid maturities.....	ccxxix
7.4.3	Improving CERES-Maize performance.....	ccxxix
7.4.4	Create a silage subroutine.....	ccxxix
7.4.5	Compare CERES-Maize with AmaizeN model.....	ccxxix
7.5	CONCLUSIONS.....	ccxxx
REFERENCES		ccxxxii

LIST OF TABLES

Table 1.1 Comparison of average monthly minimum (min), maximum (max) and mean temperatures 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.....	2
Table 3.1 Average monthly minimum (Min) and maximum (Max) temperature data for RUK07, MAS08, NGA08 and RUK08 during the experimental periods of 2006-07 and 2007-08.	48
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.....	49
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.	50
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.	54
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.	57
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 estimates, expressed as kernels m ⁻² d ⁻¹ from PD1.	62
Table 4.1 Effect of base temperature (T _b) on the coefficient of variation of thermal time durations to different phenological stages of maize, using data obtained from RUK07. Optimum T _b is shown for each stage.	85
Table 4.2 Kernel growth rate based on either thermal (T _b 0) or real time, d, for RUK07 across 5 planting dates; se is standard error across PD treatments for all hybrids.....	89
Table 4.3 Thermal time requirement from emergence to tassel initiation for NGA08, RUK07, MAS08 and RUK08 across 4 or 5 planting dates (PDs); se is standard error across PD treatments for all hybrids.	90

Table 4.4 Thermal time (T_{b8}) requirement from emergence to silking for MAS08, NGA08, RUK07 and RUK08 across 4 or 5 planting dates (PDs); se is standard error across PD treatments for all hybrids.	91
Table 4.5 Thermal time requirement from 50% silking to physiological maturity for MAS08, NGA08, RUK07 and RUK08 across 4 or 5 planting dates (PDs); se is standard error across PD treatments for all hybrids.	93
Table 4.6 Grain moisture (%) at black layer for RUK07 across 5 planting dates (PDs); se is standard error across PD treatments for all hybrids.	94
Table 4.7 Thermal time requirement from emergence to physiological maturity for MAS08, NGA08, RUK07 and RUK08 across 4 or 5 planting dates (PDs); se is standard error across PD treatments for all hybrids.	95
Table 4.8 The Gompertz non-linear function equations and statistical parameters to estimate whole plant dry matter content (%) on thermal time (TT, (T_{b0}) in $^{\circ}\text{Cd}$) between anthesis and physiological maturity for three hybrid maturities, using data from NGA08, MAS08, RUK07 and RUK08.....	97
Table 4.9 Multiple regression equations and statistical parameters describing rates of grain moisture loss vs. thermal time (TT, (T_{b0}) in $^{\circ}\text{Cd}$) and relative humidity (RH%) using data from three planting date treatments at RUK07, expressed as % moisture loss d^{-1}	97
Table 4.10 Relative change in stover weight (%) between silking and maturity for RUK08, RUK07 and NGA08 across 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.	101
Table 5.1 Total solar radiation and mean temperature between emergence and flowering (maize) across planting date (PD) treatments for MAS08, RUK07, RUK08 and NGA08.....	129
Table 5.2 Average daylength and mean air temperature for 1-5 d prior to tassel initiation (TI) for four to five planting date (PD) treatment at MAS08, RUK07, RUK08 and NGA08 environments.....	129
Table 5.3 Silage dry matter yields for NGA08, RUK08, RUK07 and MAS08 across planting dates (PDs); se is standard error across PD treatments for all hybrid maturities.	130

Table 5.4 Predicted silage starch content averaged across planting dates (PDs) at NGA08, RUK07 and MAS08; se is standard error across PD treatments for all hybrid maturities.	132
Table 5.5 Correlation coefficients for silage quality traits vs. silage yield and harvest index (HI) across NGA08, RUK07 and MAS08. Only values with P<0.01 are presented. NS refers to not significant at P<0.01.	134
Table 5.6 Predicted milk t ⁻¹ from silage for RUK07, NGA08 and MAS08 averaged over 4 or 5 planting dates; se is standard error across PD treatments for all hybrid maturities.	135
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.	138
Table 5.8 Total leaf number for RUK07, NGA08, RUK08 and MAS08 across 4 or 5 planting dates (PDs); se is standard error across PD treatments for all hybrid maturities.	140
Table 5.9 Leaf area index (LAI) at NGA08, RUK08, RUK07 and MAS08, across 4 or 5 planting dates (PDs); se is standard error across all hybrids or maturities. Figures in parenthesis refer to mean temperatures (°C) during leaf expansion for the respective treatment.	143
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.	144
Table 5.11 Comparison of actual vs. predicted leaf tips from full leaf numbers across all hybrids and environments using linear and non-linear (Gompertz) regression models.	147
Table 5.12 Comparison of actual vs. predicted average timing of leaf development stage across all hybrids at RUK07, in thermal time (TT), using linear and bilinear regression models. Figures in parenthesis refer to differences, in days, between predicted and actual.	155
Table 6.1 Genetic coefficients used by the CERES-Maize model.	clxix
Table 6.2 Location, latitude, longitude and elevation of the eight environments used for long term maize grain and yield simulations using the modified CERES-Maize model.	clxxii
Table 6.3 Soil types used in each environment/region during model simulations.	clxxiii

Table 6.4 Genetic coefficients used to run CERES-Maize model after calibration.	clxxvii
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.	clxxxiv
Table 6.6 Estimated planting windows required to achieve $\geq 95\%$ 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.....	clxxxvi
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).....	clxxxvii
Table 6.8 Mean total rainfall (Rain) and average daily global solar radiation receipt (SRad) for eight New Zealand environments over a 31 yr period (1978-2009).	clxxxvii
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.	clxxxviii
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.	cxc
Table 6.11 Probability of obtaining silage yields $\geq 17.5 \text{ t ha}^{-1}$ for two or three hybrid maturity classes and nine planting dates in eight New Zealand environments over 31 yr.....	cxciii
Table 6.12 Probability of obtaining grain yields $\geq 10 \text{ t ha}^{-1}$ for two or three hybrid maturity classes and nine planting dates in seven New Zealand environments over 31 yr.....	cxcvi
Table 6.13 The latest planting dates to maintain crop failure risk at $P < 0.1$ for two or three hybrid maturities in eight New Zealand environments.	cciv

LIST OF FIGURES

Figure 2.1 Comparison of maize crop growth and development rate responses to temperature	15
Figure 2.2 Effect of planting time on silage yields of maize hybrids differing in maturity.....	27
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 (\pm 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.	51
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 (\pm se) across treatment means.	56
Figure 3.3 Kernel weight at (a) MAS08 and (b) RUK08 over 4 and 5 planting dates (PDs). The vertical bars show standard errors (\pm 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.	58
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 (\pm se) across treatment means.....	87
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 (\pm se) of the mean for each treatment.....	98
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 (\pm se) of the mean for each treatment.....	100
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 (\pm se) across treatment means.	131
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 (\pm se) across treatment means.	136

Figure 5.3 Comparison of actual and predicted total plant leaf area using independent data from RUK07 (PD2 and PD4).....	141
Figure 5.4 Leaf area distribution by hybrid maturity class and leaf position in the RUK07 ENV, averaged over 5 planting date treatments.....	142
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% 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.....	145
Figure 5.6 Observed leaf tip number (MAS08; NGA08; RUK08) vs. predictions based on RUK07 data using the Gompertz model.....	146
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.....	clxxix
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.....	clxxx
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.....	clxxxi
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.....	clxxxiii
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, MAS08, NGA08 and RUK07 over a range of planting date treatments not originally used for model calibration.	clxxxiv
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.	clxxxix

- 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. . cxci
- 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 ($\pm se$) of the mean for each PD treatment..... cxcii
- 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..... cxcv
- 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 ($\pm se$) of the mean of planting date and maturity treatments. cxcvii
- 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..... cxcix
- 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..... cciii

LIST OF PLATES

Plate 2.1 Illustration of maize seedlings at emergence (VE)	10
Plate 2.2 A maize seedling illustrating leaf tip and fully expanded or visible leaf collar	11
Plate 3.1 Positioning of a “Watch Dog” temperature logger suspended above the ground but within the crop canopy and apical meristem level.	45
Plate 3.2 Measuring grain moisture and test weight using a GAC 2100 meter	46
Plate 3.3 Comparison of RUK08 (top) vs. NGA08 (bottom) soils.	53
Plate 3.4 Crop status for PD5 at RUK08 (top) and NGA08 (bottom) on 25 March 2008.	67
Plate 4.1 Dissecting a maize plant under a stereoscopic microscope to determine timing to tassel initiation.....	78
Plate 4.2 Two dried cobs illustrating kernels removed from the central part of the cob.	79
Plate 4.3 A low density maize plot at NGA08.	80
Plate 4.4 A maize plot at physiological maturity (i.e., 50% kernel black layer).....	81
Plate 5.1 A maize plant showing a tagged leaf tip for use as a reference point.	123
Plate 5.2 A maize plant showing a leaf tip emerging from the whorl.....	123
Plate 5.3 A maize crop ready for silage harvesting	126
Plate 5.4 A modified chipper shredder used to mulch sample plants for dry matter subsampling.....	127
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).	ccxiv

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
r²	Coefficient of determination
R²	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