PERFORMANCE AND RELIABILITY OF TWO MAIZE SIMULATION MODELS IN A RANGE OF ENVIRONMENTS

C. J. Birch
The University of Queensland, Gatton College, Lawes, Queensland, Australia, 4343

Abstract Maize production is increasing in importance in Australia, and has the potential for substantial further expansion. Additional production areas and/or more intensive use of existing production areas will be needed. Simulation models offer the capacity to rapidly assess the suitability of a range of genotypes and phenotypes, and to predict yield and yield reliability over a range of environmental conditions. However, they must be validated and be sufficiently robust to provide reliable predictions. The performance of two maize simulation models, a complex mechanistic one, AUSIMM - Maize and a simpler one, the Muchow - Sinclair model was evaluated against experimental data from field trials at Gatton, South East Queensland and Katherine, Northern Territory. AUSIMM - Maize predicts phenological and canopy development, and biomass and grain yield. The latter concentrates on biomass and grain yield. AUSIMM - Maize consistently over - predicted the time from emergence to tassel initiation, silking and physiological maturity especially with short season cultivars and when environmental conditions favoured rapid plant development, but less so when longer duration of these intervals occurred. Leaf number was consistently over - predicted, but leaf area was under - predicted by AUSIMM - Maize. Neither model predicted biomass or grain yield satisfactorily over the range in the experimental data, though each tended to be more accurate than the other on one measure of model performance (regression or root mean square deviation). Both provided sound predictions within limited ranges of conditions and genotypes that resulted in relatively short crop durations, but were inaccurate when the data extended over a greater range of environmental conditions and genotypes.

INTRODUCTION

Simulation models have been proposed as a method of assessing resource suitability for production purposes and to assess the adaptation of crops to an area. To be used with confidence, the predictions need to be reliable over a wide range of environments. Thus the level of complexity needs to be such that the model can mimic the effects of variation in environment, yet be simple enough for ease of use and interpretation of the output of the model. Two recently published mechanistic models of maize were selected for this evaluation - AUSIMM-Maize (Carberry and Arbrecht 1991), and the simpler Muchow - Sinclair model (Muchow and Sinclair 1990), the version used having been subsequently modified by inclusion of routines to account for low temperature influences not originally part of the model. The former is derived from CERES - Maize (Jones and Kiniry 1986) by initially adapting routines in it from data for De Kalb XL82 grown at Katherine (NT) (Carberry et al. 1989) followed by additional changes to produce the version here (Carberry and Arbrecht 1991). AUSIMM - Maize predicts the detail of phenological development, individual and total leaf area development and senescence, dry matter accumulation and distribution, and final grain yield and yield components (grain weight and grain number) from environmental data and descriptions of the genotype being used.

The Muchow - Sinclair uses inputs of weather data, final leaf number and size of the largest leaf and contains limited phenology prediction (silking a set thermal duration after the end of leaf growth) and the end of grain filling. It uses the approach developed by Dwyer and Stewart (1986) to predict leaf area. It uses a linear increase in harvest index to predict grain yield, whereas AUSIMM - Maize uses a components of yield approach.

This study focuses on evaluating the performance of both of these models using data from Katherine, NT, and Gatton, South East Queensland, for a range of cultivars and planting times. The main objectives of this study are to assess the performance of the models over a diverse set of environmental conditions and to identify those areas of the models that are deficient.

MATERIALS AND METHODS

Data sets from experimental work at Katherine (latitude 14o 28'S, longitude 132o 18'E, altitude 108 m) and Gatton (latitude 27o 34'S, longitude 152o 20'E, altitude 90 m) were used as the basis of evaluation. The data set used for modifying CERES - Maize (Carberry et al. 1989) was excluded from this evaluation. The details of experimental procedures have been published elsewhere. In brief, maize was planted at Katherine on seven times from 1983 to 1987 (Muchow 1989, Muchow pers. comm. 1993) and at Gatton on 12 times from 1988 to

1993 (Birch 1991, Karanja 1994). Several cultivars were common to both sites but a wider range of crop durations to maturity occurred at Gatton than at Katherine. All experiments were conducted at a plant population of 6.7 to 7.0 plants m^{-2} under non-limiting conditions of water and nutrient supply.

Genetic descriptions (constants) required for AUSIMM - Maize were available in the auxiliary data file for Katumani Composite B, De Kalb XL82, QK694, Barker, Hycorn 90, Pioneer 6875 and Sargeant. These were not available for Hycorn 40, Hycorn 50, GH5010 and GH5019wx grown at Gatton by Karanja (1994) - they were calculated from selected data sets as described below.

Estimation of genetic constants for Hycorn 40, Hycorn 50, GH5009 and GH5019wx

P1 (thermal duration using base, optimum and maximum temperatures of 8, 34 and 44 °C from emergence to the end of the juvenile stage) and P2 (photoperiod sensitivity) were calculated for three cultivars (Hycorn 40, GH5009 and GH5019wx) from five data points (Karanja 1994) in which tassel initiation (TI) occurred under comparable temperatures (Karanja 1994).Limited data were available for Hycorn 50 and until TI it had similar phenology to Hycorn 40 (Karanja 1994), hence the values for Hycorn 40 were used for Hycorn 50. P1 and P2 values derived were 205 °C d and 22 °C d hr^{-1} (Hycorn 40), 232 °C d and 12 °C d h^{-1} (GH5009) and 280 °C d and 5 °C d h^{-1} (GH5019wx).

The thermal durations from silking to physiological maturity (P5) were derived from the September 1992 data set of Karanja to avoid conditions of grain filling under either very high or low temperatures in one or more of the cultivars. The derived values of P5 were 833 °C d (Hycorn 40, also used for Hycorn 50), 873 °C d (GH5009) and 864 °C d (GH5019wx).

The potential grain number per plant (G2) in the data file for AUSIMM-Maize was set at 672 to 680 for De Kalb XL82, Katumani Composite B, Hycorn 9, Sargeant, Barker and Pioneer 6875. The potential grain growth rate (G3) was set at 9 mg $grain^{-1}$ d^{-1} for all cultivars except Barker (7.7 mg $grain^{-1}d^{-1}$) and Pioneer 6875 (7.9 mg $grain^{-1}d^{-1}$). Values for G2 and G3 for Hycorn 40, GH5009 and GH5019wx were calculated from the September data set of Karanja (1993). G3 was calculated for 10 days after silking to two days before physiological maturity, this approach being similar to that described by Ritchie et al (1986). G2 and G3 values were within the range of data for the other cultivars and hence values of 680 (G2) and 9.00 (G3) were retained.

Evaluation of the performance of the models under non-limiting conditions

Both models were evaluated against experimental data for non-limiting conditions of water and nutrient supply. This paper reports on prediction of emergence (E) to TI (TI) (AUSIMM - Maize only), silking (SILK) and physiological maturity (PM) (AUSIMM - Maize only), leaf number (AUSIMM - Maize only), green leaf area index (LAI), biomass, grain and residue yield. The performance of the models was assessed by linear regressions of the predicted value (dependent variable) against observed data (independent variable) and root mean square deviation (RMSD) of predicted value from observed data. The regression takes into account both the accuracy of the predictions and the responsiveness of the model over the range in the experimental data while RMSD is a measure of accuracy only. The use of linear regression techniques allows comparison of the intercept and slope of the line relating predicted data to observed data. If the intercept is significantly different from zero, the model has one or more inherent errors A coefficient in the linear regression greater than 1.0 indicates excessive responsiveness in the model, but if less than 1.0 indicates inadequate rate of change in the prediction as the observed data increases from low to high values.

RESULTS

Table 1 summarises the results of the linear regression and RMSD assessments for both models, more comparisons being included for AUSIMM - Maize than for the Muchow - Sinclair model, because of the greater range of predictions made by the former model. As there were few data on emergence at Katherine, predictions involving emergence refer almost entirely to Gatton trials.

Both Regression and RMSD show variable and generally unsatisfactory performance of the models over the range in the data. For the purposes of illustration, Figures 1 and 2 show plots of predictions against observed data for E to SILK and dry grain yield..

Phenology prediction.

AUSIMM - Maize overpredicted the real time from E to TI and underpredicted that of E to PM when the observed duration of these intervals was short. However as the observed duration increased, the overprediction was less for E to TI but was greater for E to PM. (Figure 1a) The E to SILK interval was, with two exceptions, overpredicted. The RMSD values though higher for the longer duration intervals were of comparable relative magnitude. With the Muchow - Sinclair model, the phenological events that can be determined are silking and the end of grain filling (as distinct from PM, as in AUSIMM - Maize). Because of the differing criteria in the model (end of grain filling) and the experimental data (physiological maturity), it is

(a) AUSIMM- Maize

Data	Unit	Obs Range	n	Constant	se	Coefficient	se	r2	P	RMSD
E to TI	d	10 - 28d	33	4.6	1.74	0.83	0.11	0.66	<0.01	3.1
E to SILK	d	44 - 72d	33	6.1	6.43	1.08	0.11	0.74	<0.01	11.4
E to PM	d	90 - 165	33	-40.1	13.7	1.44	0.11	0.84	<0.01	19.7
LEAF NO		16.3 - 23	45	4.4	2.16	0.79	0.11	0.52	<0.01	1.2
LAI (silk)		2.7 - 5.4	36	3.2	0.39	0.14	0.09	0.04	ns	0.71
BIOMASS	kg ha^{-1}	11400 - 28180	46	6208	1342	0.55	0.07	0.57	<0.01	2968
GR YIELD	kg ha^{-1}	6100 - 11500	46	1089	1354	0.65	0.15	0.28	<0.01	2573
Grain m-2		2063 - 4100	46	707	575	0.61	0.18	0.19	<0.01	837
Gr wt	mg $grain^{-1}$	184 - 339	46	288	53.3	-0.09	0.19		ns	51.6
RESIDUE	kg ha^{-1}	5000 - 15500	46	8276	1417	0.16	0.14		ns	2648

(b) Muchow - Sinclair model

Data	Unit	Obs Range	n	Constant	se	Coefficient	se	r2	P	RMSD
E to SILK	d	44 - 72	34	18.4	4.90	0.73	0.09	0.68	<0.01	5.1
LAI (silk)		2.7 - 5.4	36	1.1	0.21	0.69	0.05	0.84	<0.01	0.1
BIOMASS	kg ha^{-1}	11400 - 28180	47	7005	1939	0.60	0.10	0.42	<0.01	2546
GR YIELD	kg ha^{-1}	6100 - 11500	47	2845	995	0.70	0.11	0.46	<0.01	1174
RESIDUE	kg ha^{-1}	5000 - 15500	47	5436	875	0.38	0.09	0.27	<0.01	1834

Table 1 The performance assessed by linear regression (se = standard error) and RMSD of two maize simulation models.

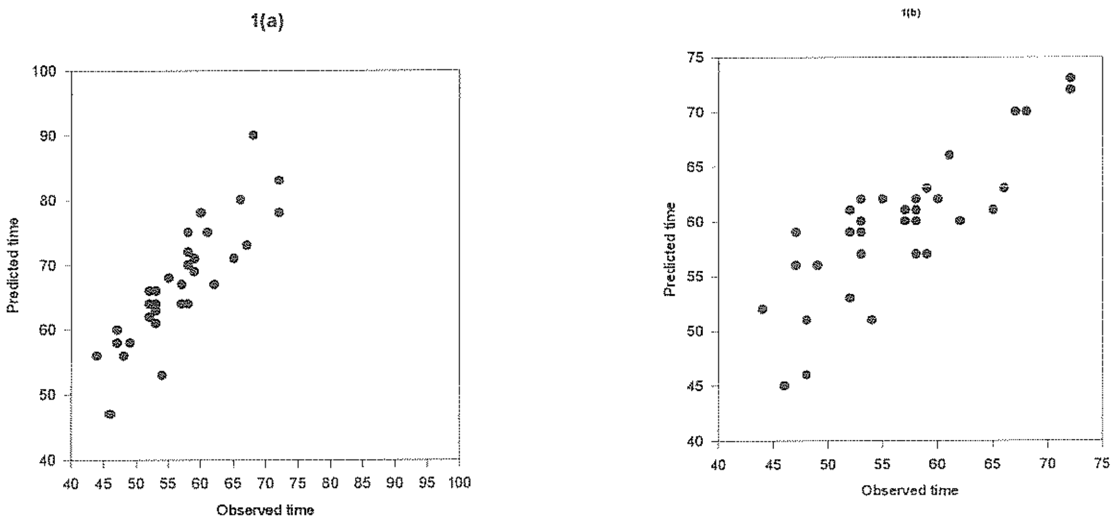

Figure 1 The predicted duration by (a) AUSIMM - Maize and (b) the Muchow - Sinclair model plotted against observed duration of emergence to silking.

not possible to make valid comparisons for E to maturity. For E to SILK, most points were overpredicted more so when the observed durations were short (Figure 1b).

Leaf number and leaf area

AUSIMM - Maize overpredicted leaf numbers in most comparisons. The model was not very responsive and some groups of predictions were easily detected eg prediction of 18 leaves for observed data of 16 to 20, 19 for 17.5 to 20 and 21 for 18.5 to 21. Prediction of LAI at silking was poor. The Muchow - Sinclair model, in which leaf number is provided as a model input predicted leaf area index more accurately. The responsiveness to increasing LAI was limited, resulting in underprediction especially when LAI at silking exceeded 4.5.

Biomass

Both models overpredicted biomass at low yields, but underpredicted at high yields and had similar responsiveness (coefficients were 0.55 and 0.60) over the range in the data. RMSD values were both high. Residue prediction (data not presented) followed similar patterns and was particularly poor in AUSIMM - Maize.

Yield and Yield Components

AUSIMM - Maize predictions of grain yield were satisfactory for a few data points, mostly for the cultivar De Kalb XL82, the balance being generally underpredicted (Figure 2a). For Gatton crops planted from January to March and matured under declining temperature, the model predicted yield well below the observed yields, and separated from other predictions. Also, it did not reflect the increasing yield well (coefficient = 0.65), the regression accounting for only 52% of the variation. The RMSD was high. With the Muchow - Sinclair model, there was a substantial scatter in the predictions which were generally higher than by AUSIMM - Maize (Figure, 2b). There was about equal incidence of overprediction and underprediction. Predictions of the components of yield by AUSIMM - Maize (grain number and grain weight), was unsatisfactory, with no regression possible for grain weight.

DISCUSSION

The performance of the two models was variable. There were some acceptable predictions over a limited range of observed data (eg Katherine for the cultivar De Kalb XL82, and for some data sets at Gatton) when the crop duration was relatively short. However, when a wider range of cultivars and crop durations were included, neither model adequately predicted the range of phenological, leaf number/leaf area index and yield variables accurately. Because of these limitations, neither model is capable of broad application for predictive or resource assessment purposes.

Phenology and leaf number prediction.

In AUSIMM - Maize, E to TI is predicted on the basis of thermal time (as described in Carberry et al. 1989) and photoperiod sensitivity, the latter extending the thermal duration of this interval when photoperiod exceeds 12.5 hours. Because of the overpredictions at short observed durations of this interval, the low r2 (0.65) and the coefficient (0.83) in the regression, the temperature regime used in the calculation of thermal time and/or the photoperiod responsiveness of maize needs revision.

The interval from TI to SILK is predicted from leaf number and a constant thermal time requirement for emergence of each leaf. This constant is also referred

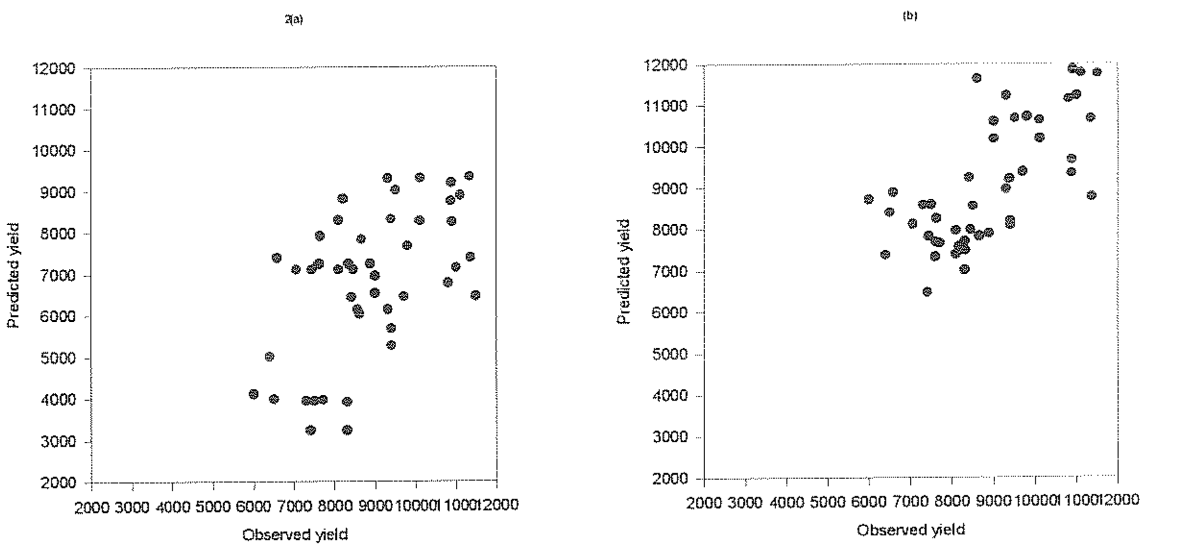

Figure 2. The predicted by (a) AUSIMM - Maize and (b) the Muchow - Sinclair model and observed dry grain yield (kg/ha)

to as leaf appearance rate (Carberry and Arbrecht 1991, Carberry et al. 1989). Leaf number is predicted from the thermal time from sowing to TI and another constant thermal requirement per leaf (also referred to as leaf initiation rate). Thus errors of prediction of leaf number and hence the duration from E to SILK must arise from one or more of the base, optimum and maximum temperatures used to calculate thermal time, or one or both of the constants, which rely on thermal time in any case. Alternatively, the constants may be inappropriate for application to diverse varieties and/or environments. The errors in prediction of leaf number are partially at least the consequence of errors in prediction of the E toTI interval. The tendency to overprediction especially in the shorter duration intervals from E to TI is followed by general and increasing (as the observed duration increases) overprediction of the E to SILK interval. Since the prediction of these intervals depends ultimately on thermal time calculation, the change in the nature of the errors of prediction are further evidence that the cardinal temperatures should be reassessed.

The predicted duration from SILK to PM relies on thermal time duration which is not expected to vary greatly with cultivar (Ritchie et al. 1986). The same cardinal temperatures are used for thermal time calculation in this interval as in others. The predictions were inaccurate in this interval (data not presented). When considering the whole crop cycle (E to PM) underprediction changed to substantial overprediction as the duration of the interval increased (coefficient 1.44).

The long observed durations of this interval were mostly in crops that were in the grain filling stage during the late summer and autumn (declining temperatures) at Gatton as well as in inherently slow maturing cultivars eg Barker. These had the worst predictions. The temperature dependence of the prediction of the SILK to PM as in earlier intervals again calls into question the appropriateness of the cardinal temperatures.

Alternatively, the model may not contain routines that are sufficiently sensitive to low temperature conditions that may induce physiological maturity.

The Muchow - Sinclair model predicts time to SILK from supplied final leaf number and an alternative calculation of daily thermal units (daily mean temperature minus 8 °C). Despite the input of final leaf number, the model overpredicted the majority of E to SILK durations. Like AUSIMM - Maize, the predictions are ultimately dependent on temperature relationships and the basis of calculation of thermal time and/or equations that rely on thermal time must be reassessed.

Leaf area index

Leaf area index is predicted in AUSIMM - Maize as the net effect of leaf number, leaf expansion and leaf senescence. The first of these has already been discussed and will not be considered further. Daily leaf area expansion depends on a series of equations involving the predicted leaf number and leaf appearance rate. Under certain conditions, leaf area is adjusted by use of specific leaf weight. The accuracy of prediction of leaf area ultimately depends on the accuracy of prediction of leaf number. Also, the prediction of leaf area senescence by a series of thermal time dependent equations may result in inappropriate rate of senescence of leaf area, resulting in errors in green leaf area prediction. In the present evaluation, the senescence equations may have reduced leaf area too rapidly. These relationships should be reviewed and would have to be adjusted if the cardinal temperatures are changed.

The Muchow - Sinclair is supplied with final leaf number and the area of the largest leaf and uses a function proposed by Dwyer and Stewart (1986) to predict individual leaf area. Leaf area prediction is thus not dependent on the prediction of one or more other variables. Senescence, though is dependent on the thermal unit function calculation mentioned earlier. Because of the better prediction of leaf area at silking by the Muchow - Sinclair model, the approach to leaf area prediction may be more robust and thus could be used more widely by inclusion in other models (provided that any use of leaf number prediction routine provides an accurate final leaf number estimate.

Biomass and grain yield

The mostly underprediction of biomass yield by AUSIMM - Maize is at least partly the consequence of the errors in prediction of phenology and leaf area. Since phenology was largely overpredicted, the underprediction of biomass yield must be attributed to the poor prediction of leaf area and leaf area index. Radiation use efficiency may also be too low. It may also be that the radiation use efficiency (g DM MJ^{-1} of photosynthetically active radiation) used in estimation of carbon fixation, the light extinction coefficient, or equations that depend on these variables, may be inappropriate. However, after allowing for the differences in expression of radiation use efficiency (photosynthetically active radiation in AUSIMM - Maize, total radiation in the Muchow - Sinclair model), a similar value is used in the Muchow - Sinclair model. Further, both use similar extinction coefficients. With the latter model, underprediction of biomass yield occurred in only about half of the comparisons, and overprediction of a similar magnitude in the other half. Thus, radiation use efficiency and the extinction coefficient may not be major contributors to the errors of prediction in AUSIMM - Maize. Hence, the routines that predict leaf number and leaf area emerge as the most likely cause of the poor prediction of biomass and thus grain yield in AUSIMM - Maize.

Grain yield prediction by both models was unsatisfactory (Figure 2). Because AUSIMM - Maize uses a components of yield approach, (grain number, grain weight) to predict yield, errors in prediction of one or one or both of these will result in errors in prediction of grain yield. The predictions of grain number and final individual grain weight were very poor. Also, in the yield predictions there was a sub group that was in the grain filling stage when temperature was declining, indicating that AUSIMM - Maize was not able to accurately predict yield under such circumstances.

The Muchow - Sinclair model uses a simple linear increase in harvest index from three days after silking to the end of grain filling (with a maximum harvest index of 0.5) to predict grain yield. It also has a maximum duration of 1150 thermal units, calculated from daily mean temperature (ie base temperature = 0 °C). Thus, as expected it has generally similar pattern of prediction of grain yield as biomass yield.

Residue yield is calculated in AUSIMM - Maize by difference, and in the Muchow - Sinclair model is equal to grain yield because of the use of harvest index of 0.5 (except in those instances where low temperature conditions cause the distribution of dry matter to be altered).

Both models ultimately rely on the accuracy of prediction of processes that affect phenology, leaf area and dry matter accumulation for accuracy in biomass, grain yield and residue prediction. Thus, there is little justification to discuss prediction of these further because of the errors in prediction of phenology and leaf area. Modifications elsewhere in the models are necessary if the prediction of yield is to be improved. There may also be need to modify the equations and constants used in yield prediction, but the present evaluation cannot identify where modifications are needed.

CONCLUSION

Neither AUSIMM - Maize or the Muchow - Sinclair model are sufficiently general for use over diverse genotypes and environments. The routines used in each model for the prediction of phenological intervals, leaf area of individual leaves, leaf senescence and dry matter accumulation and distribution need revision. The analysis provided here indicates that the first areas for critical review are the temperature relationships and thermal time calculation. Also, it appears that the method of calculation of leaf area in the Muchow - Sinclair model may be more reliable and could be used more widely. The routines that predict dry matter distribution should be examined only after the routines that predict phenological and leaf area development have been improved.

ACKNOWLEDGMENTS

Grateful acknowledgment is expressed to Drs P.S. Carberry and R. C. Muchow, of CSIRO for the supply of the Muchow - Sinclair and AUSIMM - Maize models, and data sets for use in the evaluation, and to the University of Queensland for provision of resources to enable this project to proceed.

REFERENCES

Birch, C.J. (1991) Development and yield of selected maize cultivars in the sub - tropics. pp 50 - 53 in 'Maize in Australia - Food, Forage and Grain. Proc. First Australian Maize Conference, 1991, Maize Assoc. of Australia.

Carberry, P.S., Muchow, R.C. and Mc Cown, R.L. (1989) Tailoring the CERES - Maize simulation model in a semi - arid tropical environment. *Field Crops Research, 20,* 297 - 315.

Carberry, P.S. and Arbrecht, D.G (1991) Tailoring crop models to the semi - arid tropics. In R.C. Muchow and J.A. Bellamy (Eds.) Climatic risk in crop production: Models and Management for the semi - arid tropics. Proceedings of International Symposium, July 2-6, 1990, Brisbane, CAB International.

Dwyer, L.M. and Stewart, D.W.(1986) Leaf area development in field grown maize. *Agron J. 78*, 334-343.

Jones, C.A. and Kiniry, J.R. (1986) 'CERES - Maize - A simulation model of maize growth and development'. Texas A and M University Press, College Station.

Karanja, D.R. (1994) The effect of planting date on the growth and development of short , medium and long season cultivars of maize *(Zea mays)* cultivars M. Agr. Sc. Thesis, The University of Queensland.

Muchow, R.C. (1989) Comparative productivity of maize, sorghum and pearl millet in a semi - arid tropical environment I Effect of sowing date on yield potential. *Field Crops Res. 20,* 191 - 205.

Muchow, R.C., Sinclair, T.R. and Bennett, J.M (1990) Temperature and solar radiation effects on potential maize yield across locations. *Agron. J. 82*, 338-343

Ritchie, J.T., Kiniry, J.R., Jones, C.A. and Dyke, P.T (1986) Model Inputs, Ch 3 in 'CERES - Maize - A simulation model of maize growth and development'. Texas A and M University Press, College Station.