TESTING THE PERFORMANCE OF TWO MAIZE SIMULATION MODELS WITH A RANGE OF CULTIVARS OF MAIZE *(Zea mays)* IN DIVERSE ENVIRONMENTS

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Short Title: Testing the performance of maize models

ABSTRACT

Maize production is increasing in importance in Australia, and has 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, AUSIM-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. AUSIM-Maize predicts phenological and canopy development, total dry matter and grain yield. The Muchow - Sinclair model concentrates on total dry matter and grain yield. Sensitivity analysis indicated that the output of the models was most affected by the values used for the duration of the basic vegetative period, photoperiod sensitivity and leaf initiation rate (in AUSIM - Maize), radiation use efficiency, leaf appearance rate (in both models) and one coefficient that affects leaf area senescence (in the Muchow - Sinclair model). AUSIM - Maize consistently overpredicted the time from emergence to tassel initiation (especially with short season cultivars, and when environmental conditions favoured rapid plant development to TI), silking and physiological maturity. Leaf number was consistently overpredicted by AUSIM - Maize. Neither model predicted total dry matter 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 a limited range 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. Several areas of the models where modification is needed to improve predictions and to make the models more generally applicable are identified.

KEY WORDS

Maize, *Zea mays*, AUSIM - Maize, model, modelling, sensitivity, phenology, growth

SOFTWARE AVAILABILITY

Name of software	AUSIM - Maize AUSIM - Maize was derived from CERES -Maize (Jones and Kiniry, 1986), the changes giving rise to the version used here are documented in Carberry et al. (1989) and Carberry and Arbrecht (1991)
System requirements:	IBM PC computer or compatible, maths co-processor Operating system: MS DOS, with ANSI.SYS or equivalent declared in the CONFIG.SYS file. Required memory: 300 Kb RAM and 300Kb of free hard disk space Language: FORTRAN 77 (Version used here Lahey F77L)
Name of Software	The Muchow - Sinclair model The name is the reference used herein for a model published in Muchow et al. (1990) with a temperature adjustment for radiation use efficiency at low temperatures based on Andrade et al. (1993)
System requirements:	IBM PC or compatible Operating system: MS DOS Language: MS QBASIC

The corresponding authors in the original publications should be contacted for additional information.

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 - AUSIM - Maize (Carberry et al., 1989, Carberry and Arbrecht, 1991), and the simpler Muchow - Sinclair model (Muchow, Sinclair and Bennett, 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). AUSIM - 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 (individual grain weight and grain number) from environmental data (e.g. weather, radiation) and descriptions of the genotype being used.

The Muchow - Sinclair model uses inputs of weather data, final leaf number and size of the largest leaf and contains limited phenology prediction (silking at 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, and uses a linear increase in harvest index to predict grain yield.

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 14^{o} 28'S, longitude 132o 18'E, altitude 108 m) and Gatton (latitude 27^{o} 34'S, longitude 152^{o} 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 dates from 1983 to 1987 (Muchow, 1989, Muchow, pers. comm., 1993) and at Gatton on 12 dates from 1988 to 1991) (Birch, 1991, Karanja, 1993, Muchow, 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 AUSIM - Maize were available in the auxiliary data file for Katumani Composite B, DeKalb XL82, QK694, Barker, Hycorn 90, Pioneer 6875 and Sargeant. The cultivars Hycorn 40, Hycorn 50, GH5010 and GH5019wx grown at Gatton by Karanja (1993) were not supported by genetic constants - they were calculated from selected data sets of Karanja 1993 as described below.

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

P1 (thermal duration from emergence to the end of the juvenile stage using base, optimum and maximum temperatures of 8, 34 and 44 ^{O}C) and P2 (photoperiod sensitivity) were calculated for three cultivars (Hycorn 40, GH5009 and GH5019wx) from five data points in which tassel initiation occurred under comparable temperatures in the work of Karanja (1993). Limited data were available for Hycorn 50 and until TI, it had similar phenology to Hycorn 40 (Karanja, 1993), 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 1991 data set of Karanja (1993) to avoid conditions of grain filling under either very high or cool conditions 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 AUSIM-Maize was set at 672 to 680 for De Kalb XL82, Katumani Composite B, Hycorn 9, Sargeant and 672 and 677 for 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}). The experimental values of grain number per plant and daily grain growth rate for Hycorn 40, GH5009 and GH5019wx were calculated from the September data set of Karanja (1993). Daily grain growth rate 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). These calculations do not provide potential values for the genetic constants, G2 and G3, as the plant population is sufficiently high for interplant competition to occur. Thus, since the values calculated from the experimental data were less than the existing values of G2 and G3 in the auxiliary data file used by AUSIM - Maize, the values of 680 grains $plant^{-1}$ (G2) and 9.00 mg $grain^{-1}$ d^{-1} (G3) were retained as an interim measure.

Sensitivity analysis

A sensitivity analysis of the effect on the model output of changes to the values of selected variables in the models was carried out using an approach similar to that in Littleboy et al. (1989) using one data set from Gatton and one from Katherine. Large changes in the model output caused by small changes to input data or a parameter value indicate that care is needed in selecting the values to be used, but small changes to the output mean the value used may be of little importance to the performance of the model. Variables affecting crop phenological development, leaf area production and senescence, dry matter production and dry matter partitioning (in AUSIM - Maize only) were used in the sensitivity analysis.

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 (AUSIM-Maize only), silking (SILK) and physiological maturity (PM) (AUSIM-Maize only), leaf number (AUSIM-Maize only), green leaf area index (LAI), total dry matter, 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 (*a* in Tables 1 a and 1b) and slope (*b* in Tables 1 a and 1 b)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 significantly greater than 1.0 indicates excessive responsiveness of 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

Sensitivity analysis

The sensitivity analysis produced different results for the two sites. Overall, the output of both models was affected more by the changes when used with the data from Gatton than Katherine. The effects on the output of changing the values of some variables were inconsistent e.g. changing potential grain number (G2) and potential grain growth rate (G3) in AUSIM - Maize. The variables with the greatest effect on model output were RUE, leaf initiation and leaf appearance rates, and in AUSIM - Maize, the variables that affect time to TI. The variables that affect leaf area senescence had little effect on the output AUSIM - Maize at either Gatton or Katherine. However, increasing the exponent in the equation for leaf senescence in the Muchow -Sinclair model (causing more rapid leaf area senescence) sharply reduced time to the end of grain filling, total dry matter production and grain yield.

Model predictions compared to observed data

Table 1 summarises the results of the linear regression and RMSD assessments for both models. More comparisons are included for AUSIM - Maize than for the Muchow Sinclair model, because of the greater range of predictions made by AUSIM - Maize. 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 for both models.

Phenology prediction

AUSIM - 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 there was increasing overprediction of the duration of E to PM. The duration of E to SILK interval was, with two exceptions, overpredicted (Figure 1a). The RMSD values, though higher for the longer duration intervals (E to SILK and E to PM), 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 AUSIM - Maize). Because of the differing criteria in the model (end of grain filling) and the experimental data (physiological maturity), it is 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 e.g. prediction of 18 leaves for observed data of 16 to 20, 19 for 17.5 to 20 and 21 to 18.5 to 21. Prediction of LAI at silking was poor. The Muchow - Sinclair model, to which leaf number is provided predicted LAI more accurately. Nevertheless, the responsiveness to increasing LAI was limited, resulting in underprediction especially when LAI at silking exceeded 4.5.

Total dry matter

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

Yield and Yield Components

AUSIM - Maize predictions of grain yield were satisfactory for a few data points, mostly for the cultivar XL82, the balance being generally underpredicted (Figure 2a). For Gatton crops planted in January to March and matured under declining temperature, the model predicted yields were 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 AUSIM-Maize (Figure 2b). There was about equal incidence of overprediction and underprediction. Predictions of the components of yield by AUSIM-Maize (grain number and individual grain weight) was unsatisfactory, with no regression possible for individual grain weight.

DISCUSSION

Sensitivity analysis

The greater sensitivity of the output of the models to changes in the values of RUE, leaf initiation and leaf appearance rates, the exponent in the equation for prediction of leaf area senescence, and the variables that affect crop prediction of crop phenology (as appropriate to each model) means that the values used for these variables must be accurate. Also, for general use of the model, those variables that are not specific to particular genotypes (as are P1, P2, G2 and G3) must be robust across genotypes as well as environments. The sensitivity analysis indicates that some, at least, are not, the exponent in the equation for prediction of leaf area senescence in the Muchow - Sinclair model being a good example. The limited effect of altering the coefficient in the equation for leaf area senescence (and then only for the post-silking period, when most senescence occurs) in AUSIM - Maize was surprising, because of the importance of current photosynthesis to grain yield. The possible explanation lies in the interaction of this term with LAI (which was generally underpredicted) and the use of reduced RUE during grain filling. It appears, then, that leaf area senescence becomes a relatively unimportant process. This cannot be accepted from a biological viewpoint, and points to the need for improved prediction of LAI (and antecedent processes that affect LAI) as a first step in improving the overall performance of this model.

Performance of the models over diverse genotypes and environments

The performance of the two models was variable. There were some acceptable predictions over a limited range of observed data (e.g. 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 AUSIM - Maize, E to TI is predicted on the basis of thermal time and photoperiod sensitivity (as described in Carberry et al., 1989), 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 r^2 (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 need revision.

The interval from TI to SILK is predicted from leaf number and a constant, the thermal time requirement for appearance of successive leaf tips. Leaf number is predicted from the thermal time from sowing to TI and a constant, thermal requirement for initiation of successive leaves until the apex of the plant changes from the vegetative to reproductive state (i.e. at TI). Thus errors of prediction of the 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 functional form of the relationship or the constants may be inappropriate for application to diverse cultivars and/or environments. The errors in prediction of leaf number are partially at least the consequence of errors in prediction of the E to TI 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 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 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 the SILK to PM interval were mostly in crops that were in the grain filling stage during the late summer and autumn (declining temperatures) at Gatton and in inherently slow maturing cultivars e.g. Barker. These had the worst predictions. The temperature dependence of the prediction of the SILK to PM interval 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 ^{o}C). Despite the input of final leaf number, the model overpredicted the majority of E to SILK durations. Like AUSIM - Maize, the predictions are ultimately dependent on temperature relationships and the basis of calculation of thermal time and/or the equations that rely on thermal time must be reassessed.

Leaf area index

Leaf area index is predicted in AUSIM - 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. The accuracy of prediction of leaf area ultimately depends on the accuracy of prediction of leaf number. Also, the prediction of leaf senescence by a series of thermal time dependent equations may result in inappropriate rates of senescence of leaf area, resulting in errors in green leaf area prediction. It may be argued that, the senescence equations may have reduced leaf area too rapidly. However, this does not appear to provide a satisfactory explanation as the sensitivity analysis showed little effect on output of changing the coefficients that affect leaf senescence. The relationships used to predict senescence should be reviewed and, at least, would have to be adjusted if the cardinal temperatures are changed. It is also possible that different functional forms from that used in AUSIM - Maize may be needed to enhance the generality of the model.

The Muchow - Sinclair model 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 time based function. This function correctly predicts little senescence before silking, but the sensitivity analysis showed substantial change in the model output when the exponent in the equation was changed. Thus, the particular equation may need modification or the introduction of modifications for plants with more than the 18 - 20 leaves on the plants used in the development of the Muchow - Sinclair model. Nevertheless, the better prediction of leaf area index at silking by the Muchow -Sinclair model indicates that the approach to leaf area prediction may be more robust and thus could be used more widely by inclusion in other models. Prediction of senescence after silking, though, should be reassessed, and a range of possible functional forms examined.

Total dry matter and grain yield

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

Grain yield prediction by both models was unsatisfactory (Figure 2). Because AUSIM - Maize uses components of yield (individual grain weight, grain number) to predict yield, errors in prediction of 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 of very low predicted yield (Figure 2a) that was in the grain filling stage when temperatures were declining, indicating that AUSIM - 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 ^{o}C d, calculated from daily mean temperature (i.e. base temperature = 0 ^{o}C). Thus, as would be expected, it has a generally similar pattern of prediction of grain yield and total dry matter yield.

Residue yield is calculated in AUSIM - 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 causes 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 total dry matter, grain yield and residue prediction. Thus, there is little justification to discuss prediction of these further because of 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 need to be modifications to the equations and constants used in yield prediction, but the present evaluation cannot identify the nature of them.

CONCLUSION

Neither AUSIM - Maize nor the Muchow - Sinclair model are sufficiently general for use over diverse genotypes and environments. The routines, as appropriate, in each model for the prediction of phenological events, leaf area of individual leaves, leaf senescence, 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 those that predict phenological development and leaf area production and senescence have been improved.

These aspects are addressed in continuing research, which will lead to an improved simulation model of maize that is more generally applicable.

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*Table 1 The performance of two maize simulation models under non - limiting conditions assessed by linear regression (y = a + b*x) of predicted values (y) on observed data (x) and RMSD.*

(a) AUSIM - MAIZE

Data	Unit	Obs. Range	n	*a*	se of *a*	*b*	se of *b*	r^2	P	RMSD
E to TI	d	10 - 28	33	4.6	1.74	0.83	0.11	0.66	<0.01	3.1
E to SILK	d	44 - 72	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
Total DM	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
Grains 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	*a*	se of *a*	*b*	se of *b*	r^2	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
Total DM	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

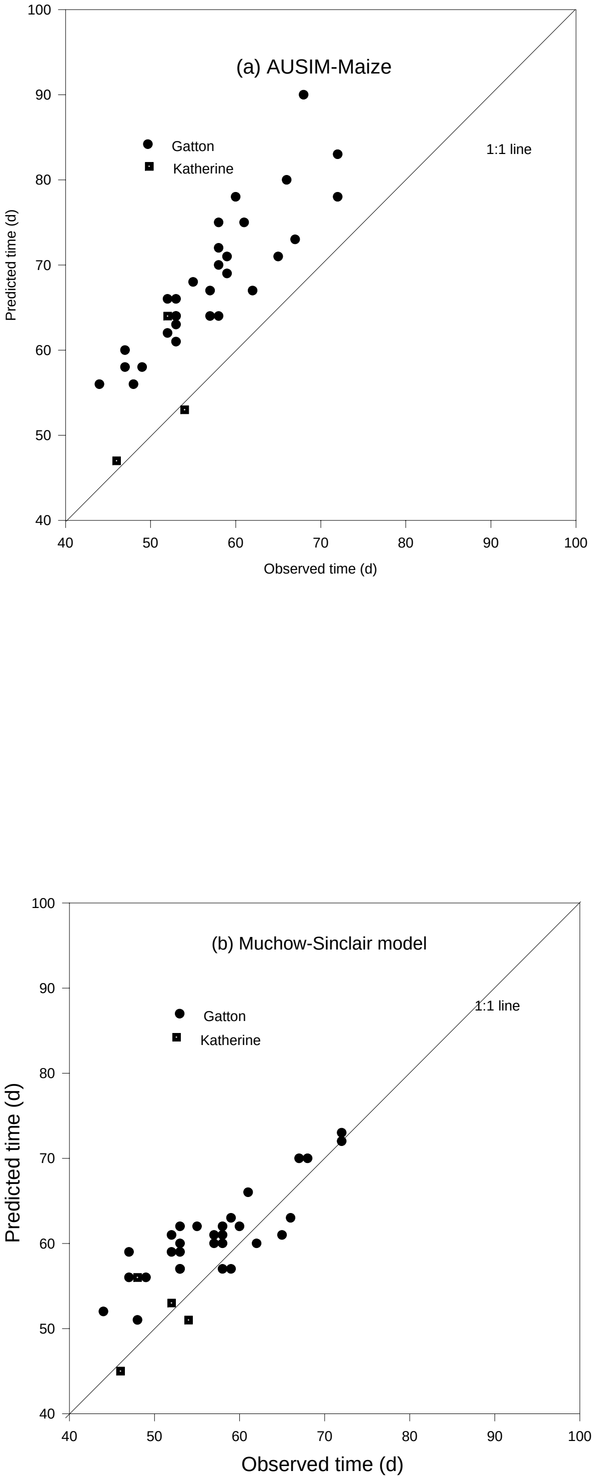

Figure 1. Comparison of predicted and observed time (d) from emergence to silking in Gatton and Katherine experiments by (a) AUSIM-Maize and (b) the Muchow-Sinclair model.

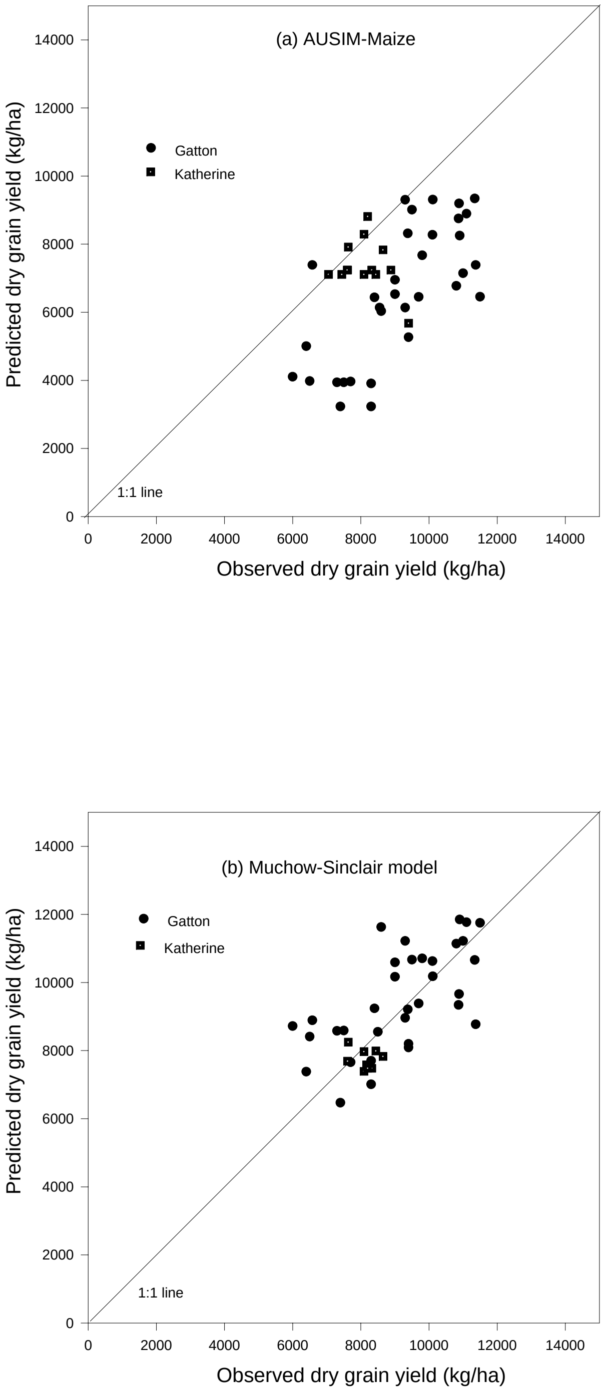

Figure 2 . Comparison of predicted and observed dry grain yield (kg ha^{-1}) in experiments at Gatton and Katherine: predictions by (a) AUSIM-Maize and (b) the Muchow-Sinclair model.