# Analysis and Modelling of the Effects of Water Stress on Maize Growth and Yield in Dryland Conditions

Youhong Song[1], Colin Birch[1,4,*], Shanshan Qu[1], Al Doherty[2] and Jim Hanan[3]

([1]*The University of Queensland, School of Land, Crop and Food Sciences, Gatton, Qld, 4343, Australia;*
[2]*Department of Primary Industries and Fisheries, Toowoomba, Qld, 4350, Australia;*
[3]*The University of Queensland, Centre for Biological Information Technology, Brisbane, Qld, 4072, Australia;*
[4]*The University of Tasmania, Burnie Campus, Burnie, Tas, 7320, Australia)*

**Abstract: It is essential to provide experimental evidence and reliable predictions of the effects of water stress on crop production in the drier, less predictable environments. A field experiment undertaken in southeast Queensland, Australia with three water regimes (fully irrigated, rainfed and irrigated until late canopy expansion followed by rainfed) was used to compare effects of water stress on crop production in two maize (*Zea mays* L.) cultivars (Pioneer 34N43 and Pioneer 31H50). Water stress affected growth and yield more in Pioneer 34N43 than in Pioneer 31H50. A crop model APSIM-Maize, after having been calibrated for the two cultivars, was used to simulate maize growth and development under water stress. The predictions on leaf area index (LAI) dynamics, biomass growth and grain yield under rainfed and irrigated followed by rainfed treatments was reasonable, indicating that stress indices used by APSIM-Maize produced appropriate adjustments to crop growth and development in response to water stress. This study shows that Pioneer 31H50 is less sensitive to water stress and thus a preferred cultivar in dryland conditions, and that it is feasible to provide sound predictions and risk assessment for crop production in drier, more variable conditions using the APSIM-Maize model.**

**Key words: APSIM, Crop production, Drought, Model, Rainfed, *Zea mays* L.**

Maize (*Zea mays* L.) is an important crop that provides cereal grains and ensilaged forage. Water shortage is a critical limitation to maize production in non-irrigated areas. The effects of water stress on maize growth and development vary with severity and timing of stress and are well documented (e.g. Grant et al., 1989; Muchow and Carberry, 1989; NeSmith and Richie 1992a, b, c; Abrecht and Carberry, 1993; Otegui et al., 1995; Singh and Singh, 1995; Çakir, 2004). Generally, phenological effects such as delaying completion of canopy development by several days are relatively small, though reductions in leaf area, biomass, grain yield and yield components can be quite substantial, including total crop failure (Muchow and Carberry, 1989; NeSmith and Ritchie, 1992a, b; Otegui et al., 1995). The most critical period of water supply is between 2 wk before and 2–3 wk after silking (Singh and Singh, 1995), during which final grain number is determined (NeSmith and Richie, 1992a, b, c; Otegui et al., 1995), with longer durations of water stress causing near total crop failure (Ne Smith and Ritchie, 1992c; Madhiyazhagan, 2005).

The ability to predict the effects of water stress on crop production is vital to improve risk assessment in water-limited conditions. Crop modelling that provides a robust framework on interaction of crop and environments can be used to improve the prediction of maize growth and yield under water-limited conditions (Boote et al., 2001; Hammer et al., 2002). Agronomists and crop modellers use existing crop models to predict the effects of water stress. They also assess the accuracy and sensitivity of the models to identify areas where revision may be required (Birch, 1996; Nouna et al., 2000; Madhiyazhagan, 2005; Raes et al., 2006) to improve the scientific basis of the models and improve their applicability across environments and genotypes (Carberry et al., 1989; Muchow and Sinclair, 1991; Birch, 1996). Improvement in terms of specific aspects of modelling required for use under water stressed conditions have been identified. For instance, Cavero et al. (2000) found that leaf area production in the EPICphase model and evapo-transpiration in CROPWAT need to be revised to improve accuracy of prediction of yield reductions due to water stress. Xie et al. (2001) found that leaf area index and kernel weight were overly sensitive to drought stress in

CERES-Maize. Nouna et al. (2003) subsequently revised CERES-Maize for semi-arid Mediterranean areas by introducing a new leaf area module and water stress function. These revisions improved predictions for the semi-arid Mediterranean environment, but have not been tested widely.

Water for irrigation is becoming more scarce and expensive because of the combined effects of climate change and competition for water among agricultural, urban, industrial and environmental demands. Consequently, water shortage will increasingly limit crop growth and yield and reduce reliability of production. Therefore, partially irrigated or even completely rainfed production will be increasingly dominant (Farré et al., 2000; Çakir, 2004; Passioura, 2006; Payeroa et al., 2006; Birch et al., 2008b). Breeding new cultivars that can be used in drier, less predictable environments is essential (Bolanos et al., 1993; Chapman et al., 2003; Campos et al., 2004; Hammer et al., 2006). The objectives of this paper are to (i) examine the effects of water stress on maize growth for two recently released cultivars; (ii) compare and assess the sensitivity of the cultivars to water stress; and (iii) model the effects of water stress on maize production in dryland conditions using APSIM-Maize.

### Materials and Methods

#### 1. Cultural details

A field experiment was carried out at The University of Queensland, Gatton Campus, Australia (Latitude 27°34′ S, longitude 152°20′ E) in 2006–2007, which was in one of a series of years with below average rainfall (Birch et al., 2008b). The field experiment has been described in Song et al. (2008a) and is briefly as follows. The field site has a moderately fertile Typic Chromustert soil (Vertosol, Lawes series (Schafer et al., 1986)) which holds 195 mm plant available water (PAWC) to 1.8 m (Dalgleish and Foale, 1998), providing conditions that are favourable for rainfed maize production in north eastern Australia (Birch et al., 2008b). Sufficient fertilizer was applied to prevent nutrient stress, and weeds and pests were controlled rigorously. Irrigation was implemented by trickle application using T-tape at 2.0 mm hr$^{-1}$.

A randomized split-plot design was applied, with water regime as the main plot and cultivar as the subplot in two replicates. Individual plots were 20 m long by 9 m wide (12 rows 0.75 m apart). A 2 m gap between main plots was used to minimize the edge effects of irrigation regimes, and 2 m at each end and 2 rows on each side of sub-plots were used as guard areas. Chemically treated seeds were sown on September 6, 2006 for a population density of 60,000 plants ha$^{-1}$ (equivalent to 6 plants m$^{-2}$) for both cultivars. Three water regimes were imposed by combining rainfall and irrigation: (i) fully irrigated (FI), irrigated until late in grain filling, after which the crop relied on stored

Table 1. Irrigation timing (days after sowing, DAS) and amount (mm) for irrigated rainfed (IRF) and fully irrigated (FI) water regimes for both maize cultivars.

| Days (DAS) | FI (mm) | IRF (mm) |
|---|---|---|
| 37 | 15 | 15 |
| 40 | 45 | 45 |
| 48 | 45 | 15 |
| 77 | 30 | Nil |
| 90 | 30 | Nil |
| 91 | 30 | Nil |
| 92 | 30 | Nil |

soil water; (ii) rainfed (RF), in which crops were not irrigated at any time during the season; and (iii) irrigated rainfed (IRF), irrigated till late canopy development, then followed by reliance on rainfall only.

#### 2. Cultivars used

Pioneer 34N43 with 'erect' leaves (i.e. angle between stem and leaves being relatively smaller than Pioneer 31H50) and Pioneer 31H50 with leaves at a greater angle and having a greater leaf area in upper positions (referred to as 34N43 and 31H50 in this paper) were used. Both are medium maturity cultivars, with comparative relative maturity (Lauer 1998) of 110 and 118 d respectively (Pioneer 2007a, b). 34N43 is recommended for irrigated and favourable raingrown conditions and 31H50 for irrigated and for a wider range of dryland conditions in Queensland and New South Wales (O'Keefe 2006; Pioneer, 2007a), having excellent stay green and stress tolerance characteristics (Pioneer, 2007b).

#### 3. Plant data collection

Phenological events i.e., emergence, tassel initiation, tasselling, anthesis, silking, physiological maturity were recorded when 50% of the plants reached the stage as described in Abrecht and Carberry (1993). Canopy morphology (the length of lamina–LL, sheath, internode, and lamina maximum width–LW) and fresh biomass of individual organs were destructively measured at 1–3 d intervals by referring to non-destructive reference sampling of the canopy characteristics as in Song et al (2008a). Leaves, sheath and internodes were weighed and then dried in the oven at 65ºC for 4 d and weighed. Individual leaf area was calculated as LL×LW×0.75 (Muchow and Carberry, 1989; Birch et al., 2003a), and total leaf area per plant was calculated by summation of individual leaf areas. The number of visibly expanding (leaf tip out of the whorl), invisibly expanding (leaf tip still inside the whorl), fully expanded (ligule visible), and senesced leaves (more than 50% of leaf being dead) were recorded at each sampling so that total leaf number and
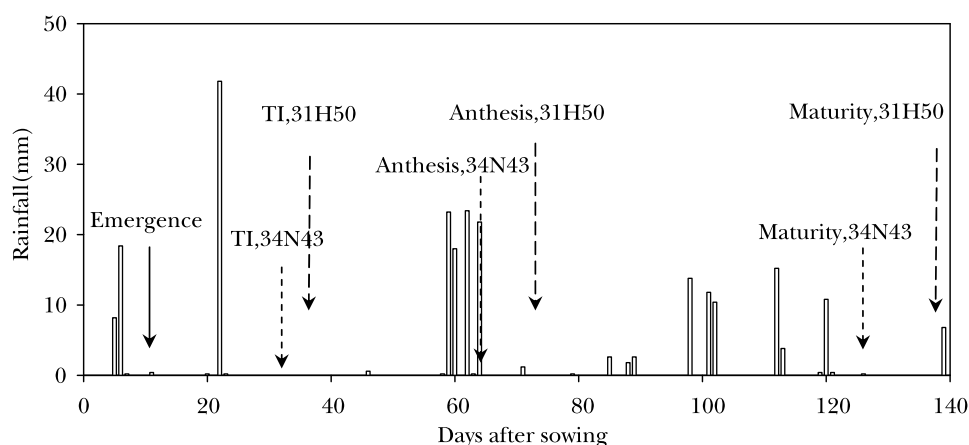
Fig. 1. Rainfall distribution from sowing to physiological maturity. Solid arrow indicates emergence for both maize cultivars, dashed arrows indicate tassel initiation (TI), anthesis and physiological maturity.

total and green leaf area could be calculated. Several ears randomly selected from the centre of the plot were harvested at physiological maturity and the number of grains per ear was counted. Dry weight of grains in each ear was recorded after oven drying at 65℃ for 4 d. The mean grain yield per plant and individual kernel weight were calculated, and grain yield per hectare was estimated as the product of mean yield per plant and plant population per hectare.

### 4. Environmental data

Daily weather data were recorded at a nearby weather station. Field capacity of the soil was 0.39 mm mm$^{-1}$ measured using a pressure plate (Ceramic Plate, USA). Soil water status was monitored using a T-bug sensor (SM200, UK) installed 15 cm deep in IRF and RF treatment plots.

Fig. 1 presents rainfall events totaling 238.8 mm over the crop duration of both cultivars–26.6 mm before emergence, 41.8 mm at 2 wk after emergence, 86.6 mm over 5 days in late canopy expansion (around 60 d after sowing, DAS), and three rainfall during grain filling–36 mm over three days (around 100 DAS), 19 mm (112 and 113 DAS) and 11 mm (120 DAS). A total of 225 mm of irrigation was applied in FI over the whole crop life, and 75 mm in IRF prior to anthesis. The difference in irrigation before anthesis was 30 mm.

### 5. Modelling approach
#### (1) Model description

APSIM was developed to provide a sound platform to model cropping production systems (Keating et al., 2003) by incorporating a generic crop model template and configuring for specific crops (Wang et al., 2002). The description of model structure and parameterization for APSIM-Maize is described fully at www.apsim.info/apsim/Publish/apsim/maize/docs/maize_science.htm.

Table 2. Observed timing (days after sowing, DAS) of phenological events in fully irrigated (FI) and rainfed (RF) treatments for both maize cultivars.

| Cultivars | 34N43 | | 31H50 | |
|---|---|---|---|---|
| Water regimes | FI | RF | FI | RF |
| Emergence | 10 | 10 | 10 | 10 |
| Tassel initiation | 33 | 33 | 37 | 37 |
| Tasseling | 59 | 60 | 72 | 73 |
| Silking | 62 | 63 | 72 | 73 |
| Anthesis | 64 | 66 | 74 | 76 |
| Maturity | 126 | 113 | 138 | 134 |

#### (2) Model calibration

The APSIM-Maize model (APSRU, 2003) provides an interface to allow extending genetic and environmental control on maize growth and development for various cultivars. As this model requires input parameters for phenology, leaf development and growth, these were calibrated using data from the FI treatment for both cultivars to ensure accurate fitted values for crop growth and development.

#### (3) Simulation studies

Environmental data on minimum and maximum temperature, solar radiation and rainfall, potential evaporation, vapour pressure and management information on sowing date, population density, row spacing and irrigation were supplied as input to the model. Soil characteristics for a vertosol (Lawes series) were also provided from the APSIM soils data base (APSRU, 2003). Simulations were performed for both cultivars in different water regimes, and results were compared to observations in phenology, temporal leaf area index (LAI), temporal biomass accumulation and final grain yield.

#### (4) Data analyses and presentation

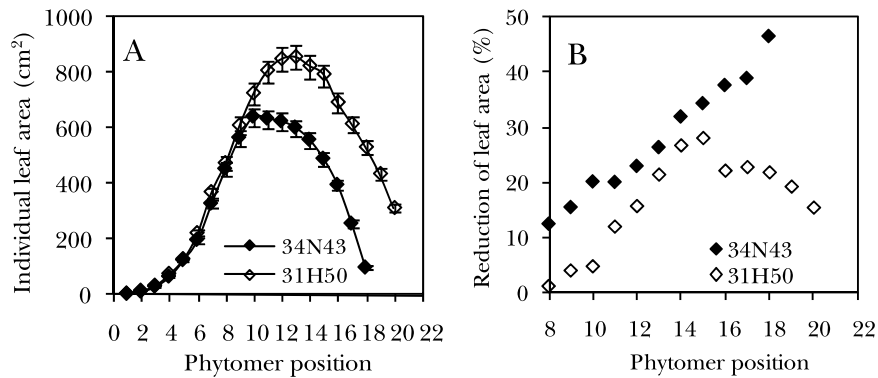Data analyses were carried out using Microsoft Excel

Fig. 2. (A) Individual leaf area and (B) reduction of individual leaf area (%) in rainfed (RF) relative to fully irrigated (FI) as a function of maize phytomer position for 34N43 and 31H50. Vertical bars indicate 95% confidence intervals.
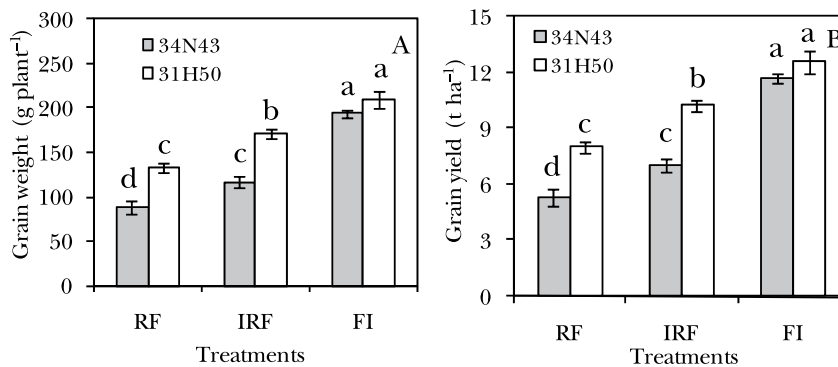


Fig. 3. (A) Mean grain weight (g plant$^{-1}$) and (B) mean grain yield (t ha$^{-1}$) for both maize cultivars under fully irrigated (FI), irrigated rainfed (IRF) and rainfed (RF) water regimes. a,b,c and d indicate statistical difference, the same letters are not significantly different at 0.05 probability level; vertical bars indicate ± standard error.

2003 (Microsoft Inc., Seattle, WA, USA). Statistical analyses were conducted using a general linear model (GLM) in Minitab 15 (Minitab Inc., Pennsylvania, PA, USA). ANOVA was done to test the difference among treatments, least significant difference (LSD) at P=0.05 being used.

### Results

### 1. Effects of water stress on crop growth and development

### (1) Phenology

Time to emergence was similar in both cultivars, however in 34N43 tassel initiation occurred 4 d sooner, anthesis 10 d sooner, and physiological maturity 12 d sooner than 31H50 (Table 2). In RF, there were small delays in tassselling, silking and anthesis (1–2d) in response to water stress but maturity was advanced by 13 d (34N43) and 4 d (31H50). There were no differences in time to tasselling, anthesis, and silking between IRF and FI.

### (2) Individual leaf area

Figure 2 presents individual leaf area for the FI treatment and percentage reduction in individual leaf area in RF as a function of phytomer position. Both cultivars

had similar individual leaf area for the first 9 leaves, but 34N43 had smaller leaves for higher positions (Fig. 2A). The reduction in leaf area in RF increased almost linearly from 13% (phytomer 8) to more than 35% for phytomers 17–19 (34N43), and from 0% (phytomer 8) to more than 25% (phytomers 13–15) but was progressively less for higher phytomers in 31H50 (Fig. 2B). The lower reduction for the last few phytomers (31H50) followed relief of water stress by rainfall during late canopy development (Fig. 1), but was too late to affect leaf area in 34N43. Overall, the reduction of individual leaf area in 34N43 was consistently greater than that in 31H50 (Fig. 2B), indicating that leaf area production in 34N43 was more sensitive to water stress. Leaf areas in FI and IRF were similar as both had similar irrigation until full expansion of leaf 12 (48 DAS), and water stress was not sufficiently severe during the remainder of leaf expansion to affect leaf area.

### (3) Grain yield and yield components

Grain yield of both cultivars was similar in FI treatments, and was significantly reduced in RF and IRF, more so in 34N43 than in 31H50 (Fig. 3A). Reductions of 54% and
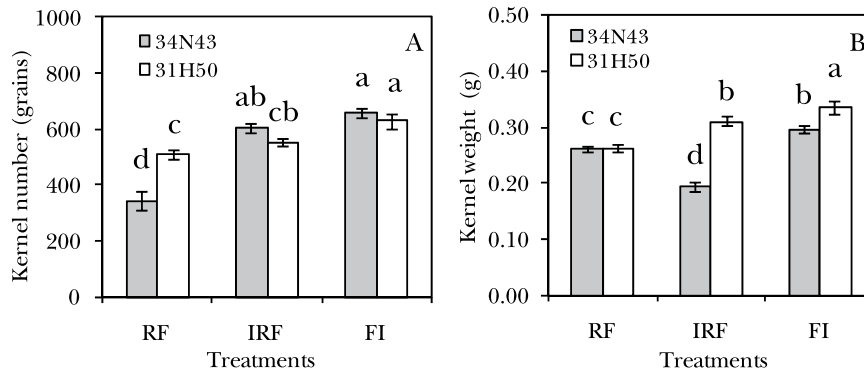
Fig. 4.   (A) Mean kernel number and (B) mean kernel weight of yield components for both maize cultivars under fully irrigated (FI), irrigated rainfed (IRF) and rainfed (RF) water regimes. a,b,c and d indicate statistical difference, the same letter are not significantly different at 0.05 probability level. Vertical bars indicate ± standard error.

Table 3.   Coefficient of variation (CV, %) for grain weight and components for maize cultivars of 34N43 and 31H50 in fully irrigated (FI), irrigated rainfed (IRF) and rainfed (RF) water regimes.

| Cultivars | 34N43 | | | 31H50 | | |
|---|---|---|---|---|---|---|
| Treatments | FI | IRF | RF | FI | IRF | RF |
| Grain weight | 8 | 20 | 36 | 14 | 13 | 16 |
| Kernel number | 11 | 10 | 38 | 16 | 11 | 16 |
| Individual kernel weight | 9 | 16 | 9 | 11 | 11 | 12 |

Table 4.   List of APSIM-Maize model parameters fitted from FI treatment

| Model parameters | 34N43 | 31H50 |
|---|---|---|
| Rate of leaf initiation | $0.034°C^{-1}d^{-1}$ | $0.038°C^{-1}d^{-1}$ |
| Rate of leaf appearance | $0.024\ °C^{-1}d^{-1}$ (first 12 leaves); $0.033\ °C^{-1}d^{-1}$ (last 6 leaves) | $0.020°C^{-1}d^{-1}$ (first 14 leaves); $0.028°C^{-1}d^{-1}$ (last 7 leaves) |
| Leaf area of largest leaves | $650\ cm^2$ | $850\ cm^2$ |
| Thermal time from flowering to maturity | $900\ °Cd$ | $1050\ °Cd$ |
| Kernel number | 660 | 630 |
| Kernel weight | 0.30 g | 0.33 g |

40% (34N43) and 37% and 19% (31H50) were induced in RF and IRF respectively, indicating that for grain production, 34N43 was more sensitive to water stress than 31H50.

There was no significant difference in kernel number between 34N43 and 31H50 (Fig. 4A). In 34N43, kernel number in IRF was similar to FI, but much lower in RF (with 48% reduction); in 31H50, kernel number was reduced in IRF by 12%, but only by a further 12% in RF (Fig. 4A). Kernel weight in 34N43 was slightly lower than in 31H50 in FI (Fig. 4B) and was lower in IRF and RF than in FI for both cultivars (Fig. 4B).

The variation of grain yield and yield components was assessed using the coefficient of variation (CV, %) (Table 3). In 34N43, the greater CVs for grain yield and kernel number but not individual kernel weight in RF and IRF than FI indicated that variation in grain yield under water stress was mostly due to reduced kernel number (Table 3). In 31H50, CVs for grain yield and its components were all between 11% and 16%, further indicating that 31H50 was less sensitive to water stress, or that the onset of water stress earlier in crop development resulted in a different pattern of response.

## 2.   Modelling of water stress effects

Leaf development (leaf initiation rate and leaf appearance rate), leaf area production (leaf area of largest leaf) and yield components (kernel number and kernel weight) in APSIM-Maize were calibrated from data from FI for both cultivars. The fitted model parameters are shown
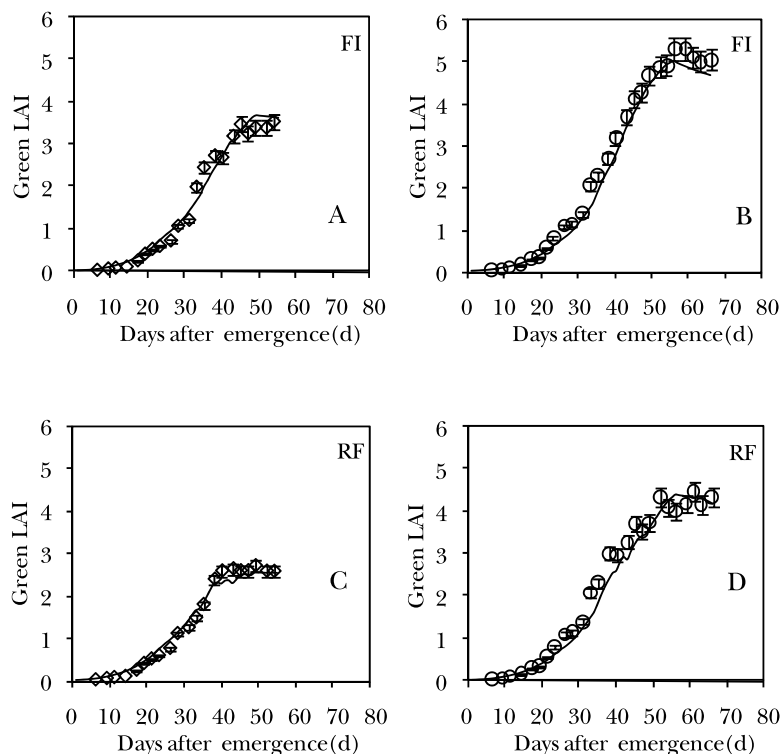
Fig. 5. Comparisons of (A, B) fitted (line), (C, D) simulated (line) and observed (open circle) leaf area index (LAI) growth overtime in fully irrigated (FI) and rainfed (RF) water regimes for maize cultivars of (A, C) 34N43 and (B, D) 31H50 (Song et al., 2008b). Vertical bars indicate 95% confidence interval.

in Table 4. Simulation of development, leaf area and yield of IRF and RF was then completed.

**(1) Phenology in IRF and RF treatments**

Predictions of tassel initiation, silking and anthesis were quite accurate (within 1–2 d), though the advanced maturity in IRF and FI was not predicted accurately (data not shown).

**(2) LAI**

Fig. 5 presents fitted, simulated and observed LAI during the vegetative stage in FI and RF water regimes for both cultivars (IRF was very similar to FI and is not shown). The close agreement between fitted, simulated and observed LAI dynamics across water regimes indicated that the calibration of leaf appearance rate and leaf area parameters using FI was successful, and stress indices used by APSIM produced appropriate adjustments to leaf area growth.

**(3) Biomass accumulation**

Fig. 6 presents fitted (for FI), simulated (RF) and observed biomass accumulation during the vegetative stage for both cultivars, again IRF was similar to FI. The fitting of biomass growth agreed with observation, indicating that procedures used in the model to calculate the biomass were effective. The simulation was in agreement with observation for RF treatments, though there was a slight over-prediction during rapid canopy development for both

cultivars, indicating that water stress indices used by APSIM-Maize were suitable for modelling biomass production. The over-prediction was mainly because of greater stem biomass under water stress, laminae and sheaths being well predicted (data not shown).

**(4) Grain yield**

Table 5 presents fitted, simulated and observed final grain yields in differing water regimes. The fitted values were within 10% of observation for the FI treatment. The simulation of grain yield in IRF and RF was in fair agreement with the observation for 34N43, but it was significantly lower in IRF (24.5%) and RF (17.5%) for 31H50. In addition, grain yield components (kernel number and kernel weight) were not well predicted in RF though final grain yield simulation was acceptable (data not shown).

**Discussion**

**1. Comparative effects of water stress**

The responses to water stress in two recently released cultivars differing in plant morphology and maturity, were compared. Tasseling and anthesis were slightly delayed by 1–2 d due to water stress in both cultivars, but physiological maturity in 34N43 was advanced more than in 31H50 in RF treatment indicating greater sensitivity to water stress or its timing. Also the greater reductions in grain yield per
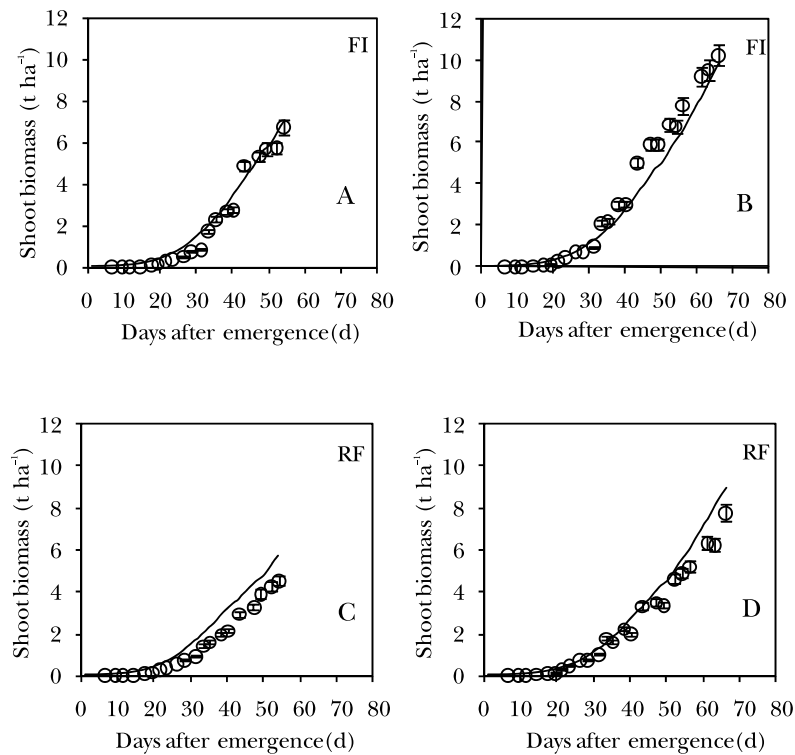
Fig. 6.   Comparisons of (A, B) fitted (line), (C, D) simulated (line)  and observed (open circle) shoot biomass accumulation overtime in fully irrigated (FI) and rainfed (RF) water regimes for maize cultivars of (A, C) 34N43 and (B, D) 31H50 (Song et al., 2008b). Vertical bars indicate 95% confidence interval.

Table 5.   Fitted, simulated and observed maize grain yield and relative difference (RD) between fully irrigated (FI), irrigated rainfed (IRF) and rainfed (RF) water regimes.

| Water regimes | 34N43 | | | 31H50 | | |
|---|---|---|---|---|---|---|
| | Fitted or simulated (t ha$^{-1}$) | Observed (t ha$^{-1}$) | RD (%) | Fitted or simulated (t ha$^{-1}$) | Observed (t ha$^{-1}$) | RD (%) |
| FI | 10.7 | 11.7 | 8.5 | 13.4 | 12.6 | −6.3 |
| IRF | 6.2 | 7.0 | 7.1 | 7.7 | 10.2 | 24.5 |
| RF | 5.4 | 5.3 | −1.9 | 6.6 | 8.0 | 17.5 |

plant, kernel number per plant, kernel weight, and leaf area of individual laminae in 34N43, and greater coefficient of variation for grain weight and kernel number in RF treatment, indicated that 34N43 was more sensitive to water stress than 31H50. The alternative explanation that the effects were due to timing of water stress is untenable, since leaf expansion in both cultivars occurred under similar water supply conditions, and IRF treatment did not affect kernel number in 34N43 (Fig. 5A) but advanced physiological maturity with greater proportional loss of grain yield than in 31H50. Thus, 34N43 was more sensitive to the mild water stress experienced in this study than 31H50. More severe water stress would cause greater reductions in leaf area production and grain yield, as in Grant et al. (1989),  Muchow and Carberry (1989) and NeSmith and Ritchie (1992b, c), and the relative sensitivity

of the cultivars may change if timing of stress was different.

## 2.   Cultivar assessment in dryland conditions

Both cultivars produced grain yield in FI and IRF treatments (Fig. 3B) that were similar to the reports for maize grown in a range of locations and conditions (e.g. Grant et al., 1989; Muchow and Sinclair, 1991; NeSmith and Ritchie, 1992a, b, c; Abrecht and Carberry, 1993; Stone et al., 2001; Xie et al., 2001; Çakir, 2004; Farré and Faci, 2006). Grain yield under RF conditions particularly in 31H50 (8.0 t ha$^{-1}$) was in the high end of yield of rain-grown maize in southeast Queensland (Birch et al., 2003b).

34N43 had a smaller total leaf area (Fig. 2) and shorter time to maturity (Table 2) than 31H50, but both cultivars had a similar potential yield ('FI' in Fig. 3), indicating that

34N43 is more efficient and as a shorter duration cultivar, would be expected to consume less water. However, 34N43 was more sensitive to water stress than 31H50, suggesting that 31H50 may be a preferable cultivar for limited irrigation or favorable rainfed conditions. It is likely, though, that it would not be preferred for marginal dryland conditions due to its longer crop duration and larger leaf area (Birch et al., 2008b). Further study using field experiments over a number of years and or locations to assess the impact of timing, duration and severity of water stress, and planting densities would be informative.

### 3.    Crop modelling

Leaf area index during the vegetative stage was predicted accurately, and predicted values of biomass accumulation generally agreed with observation except for a slight overestimation during rapid canopy development for 34N43. Grain yield prediction was accurate for 34N43 and acceptable for 31H50. Fraction of extractable soil water (FESW) across all the treatments can be estimated by this model to further assess crop response to water stress and thus assess the  risk of crop failure under drought conditions (Madhiyazhagan, 2005; Song et al., 2008a). The accuracy of predictions in this study confirms that APSIM-Maize model could be used as a tool to assess maize production with new cultivars in drier, less predictable environmental situations, provided parameterisation of the cultivars to be used and soil characteristics are accurate. It has already been used to assess cropping risk by conducting sensitivity analysis with a wide range of cultivars and water supply conditions (Lyon et al., 2003; Robertson et al., 2003; Madhiyazhagan, 2005; Birch et al., 2008a, b).

However, predictions of yield were lower than observed in both FI and RF, especially in 31H50 for which predictions were quite inaccurate as shown by Relative Difference (Table 5). This does not invalidate the previous use of the model, but does highlight the need to quantify adjustments for water stress for newly released cultivars that have advanced characteristics including higher levels of stress adaptation and stay green characteristics. In this experiment, 31H50 consistently showed less sensitivity to water stress than 34N43, and it is therefore not surprising that a model with generic rather than genotype-specific adjustments for the effects water stress on growth parameters may under-predict yield if the adjustments produce more severe reduction, as appears to have happened here, or over-predict if the adjustments are not severe enough. The results achieved here are consistent with recommendations of Pioneer (2007a), who recommend 34N43 for irrigated conditions and 31H50 for both irrigated and dryland conditions in Queensland, but neither for conditions where severe water stress is likely. This study indicates that adjustments for water stress in APSIM-Maize may need to be calibrated for cultivar

characteristics. However, before this can be done, specific experiments to quantify responses by individual cultivars are needed.

Prediction of LAI and biomass accumulation after anthesis has not been tested since data were not available. Leaf senescence and physiological maturity in water-stressed treatments were not predicted well. Also, grain yield components were not predicted well, but acceptable predictions of final grain yield were obtained, indicating compensating errors in prediction of yield components. Therefore, further model revisions by addressing the above limitations are necessary to provide more precise predictions for new cultivars in dryland conditions.

### Conclusion

Phenology, leaf production and grain yield in both cultivars were affected by water stress, but the specific influence varied with the cultivar. Water stress had greater adverse effects on leaf area production, maturity and grain yield in Pioneer 34N43 than in Pioneer 31H50. The experimental results were then placed in the context of a production system using the APSIM crop model to predict effects of water stress on maize growth and development. This study indicates that Pioneer 34N43 is more sensitive to water stress than Pioneer 31H50, and the latter may be preferable in dryland cropping. Furthermore, it is possible to produce sound predictions of the effects of water stress on maize production using APSIM-Maize, though evidence was obtained that cultivar-specific adjustments for water stress may enhance the accuracy and thus usefulness of the model.

### References

Abrecht, D.G. and Carberry, P.S. 1993. The influence of water deficit prior to tassel initiation on maize growth, development and yield. *Field Crops Res.* 31: 55-69.

APSRU 2003. The APSIM Maize Module. [Online]. http: //www.apsim.info/apsim/Publish/apsimui/types.xml. Agricultural Production Systems Research Unit, Toowoomba, Australia.

Birch, C.J. 1996. Testing the performance of two maize simulation models with a range of cultivars of maize (Zea mays) in diverse environments. *Environ. Software.* 11: 91-98.

Birch, C.J., Vos, J. and van der Putten, P.E.L. 2003a. Plant development and leaf area production in contrasting cultivars of maize grown in a cool temperate environment in the field. *Eur. J. Agron.* 19: 173-188.

Birch, C.J., Robertson, M.J., Humphreys, E. and Hutchins, N. 2003b.

Agronomy of maize in Australia - in review and prospect. *In* C.J. Birch and S. Wilson eds., 'Versatile Maize, Golden Opportunities' Proc. 5th Australian Maize Conference, Toowoomba. Maize Association of Australia. 45-57.

Birch, C.J., McLean, G. and Sawers, A. 2008a. Analysis of high yielding maize production–a study based on a commercial crop. *Aust. J. Exp. Agric.* 48: 296-303.

Birch, C.J., Stephen, K., McLean, G., Doherty, A., Hammer, G.L. and Robertson M.J. 2008b. Reliability of production of quick to medium maturity maize in areas of variable rainfall in north-east Australia. *Aust. J. Exp. Agric.* 48: 326-334.

Bolanos, J., Edmeades, G.O. and Martinez, L. 1993. Eight cycles of selection for drought tolerance in lowland tropical maize. lII. Responses in drought-adaptive physiological and morphological traits. *Field Crops Res.* 31: 269-286.

Boote, K.J., Kropff, M.J. and Bindraban, P.S. 2001. Physiology and modelling of traits in crop plants: Implications for genetic improvement. *Agric. Syst.* 70: 395-420.

Çakir, P. 2004. Effect of water stress at different development stages on vegetative and reproductive growth of corn. *Field Crops Res.* 89: 1-16.

Campos, H., Cooper, M., Habben, J.E., Edmeades, G.O. and Schussler, J.R. 2004. Improving drought tolerance in maize: a view from industry. *Field Crops Res.* 90: 19-34.

Carberry, P.S., Muchow, R.C. and McCown, R.L. 1989. Testing the CERES-Maize simulation model in a semi-arid tropical environment. *Field Crops Res.* 20: 297-315.

Cavero, J., Farre, I., Debaeke, P. and Faci, J.M. 2000. Simulation of maize yield under water stress with the EPICphase and CROPWAT models. *Agron. J.* 92: 679-690.

Chapman, S.C., Cooper, M., Podlich, D. and Hammer, G.L. 2003. Evaluating plant breeding strategies by simulating gene action and dryland environment effects. *Agron. J.* 95: 99-113.

Dalgleish, N. and Foale, M. 1998. Soil matters - monitoring soil water and nutrients in raingrown farming. Agricultural Production Systems Research Unit, Toowoomba, Australia.

Farré, I. and Facia, J.M. 2006. Comparative response of maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L. Moench) to deficit irrigation in a Mediterranean environment. *Agric. Water Manage.* 83: 135-143.

Farré, I., van Oijen, M., Leffelaar, P.A. and Faci, J.M. 2000. Analysis of maize growth for different irrigation strategies in northeastern Spain. *Eur. J. Agron.* 12: 225-238.

Grant, R.F., Jackson, B.S., Kiniry, J.R. and Arkin, G.F. 1989. Water deficit timing effects on yield components in maize. *Agron. J.* 81: 61-65.

Hammer, G.L., Kropff, M.J., Sinclair, T.R. and Porter, J.R. 2002. Future contributions of crop modeling: from heuristics and supporting decision making to understanding genetic regulation and aiding crop improvement. *Eur. J. Agron.* 18: 15-31.

Hammer, G., Cooper, M., Tardieu, F., Welch, S., Walsh, B., van Eeuwijk, F., Chapman, S. and Podlich, D. 2006. Models for navigating biological complexity in breeding improved crop plants. *Trends Plant Sci.* 11: 1360-1385.

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V.,

Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M. and Smith, C.J. 2003. An overview of APSIM, a model designed for farming systems simulation. *Eur. J. Agron.* 18: 267-288.

Lauer, J. 1998. The Wisconsin comparative relative maturity (CRM) system for corn. [Online]. http://corn.agronomy.wisc.edu/AA/1998/A021.html [Accessed 19 Sept. 2009].

Lyon, D.J., Hammer, G.L., McLean, G.B. and Blumentha, J.M. 2003. Simulation supplements field studies to determine no-till dryland corn population recommendations for semiarid western Nebraska. *Agron. J.* 95: 884-891.

Madhiyazhagan, R., 2005. Modeling approach to assess the impact of high temperature and water stress on dry land maize. PhD Thesis, the University of Queensland, Australia. February 2005.

Muchow, R.C. and Carberry, P.S. 1989. Environmental control of phenology and leaf growth in a tropically-adapted maize. *Field Crops Res.* 20: 221-236.

Muchow, R.C. and Sinclair, T.R. 1991. Water deficit effects on maize yields modeled under current and 'Greenhouse' climates. *Agron. J.* 83: 1052-1059.

NeSmith, D.S. and Ritchie, J.T. 1992a. Effects of soil water deficits during tassel emergence on the development and yield components of maize. *Field Crops Res.* 28: 251-256.

NeSmith, D.S. and Ritchie, J.T. 1992b. Short- and long-term responses of corn to a pre-anthesis soil water deficit. *Agron. J.* 84: 107-113.

NeSmith, D.S. and Ritchie, J.T. 1992c. Maize response to a severe soil water deficit during grain filling. *Field Crops Res.* 29: 23-35.

Nouna, B.B., Katerji, N. and Mastrorilli, M. 2000. Using the CERES-Maize model in a semi-arid Mediterranean environment. Evaluation of model performance. *Eur. J. Agron.* 13: 309-322.

Nouna, B.B., Katerji, N. and Mastrorilli, M. 2003. Using the CERES-Maize model in a semi-arid Mediterranean environment. New modelling of leaf area and water stress functions. *Eur. J. Agron.* 19: 115-123.

Otegui, M.E., Andrade, F.H. and Suero, E.E. 1995. Growth, water use and kernel abortion of maize subjected to drought at silking. *Field Crops Res.* 40: 87-94.

Passioura, J. 2006. Increasing crop productivity when water is scarce-from breeding to field management. *Agric. Water Manage.* 80: 176-196.

Payeroa, J.O., Melvinb, S.R., Irmakc, S. and Tarkalson, D. 2006. Yield response of corn to deficit irrigation in a semiarid climate. *Agric. Water Manage.* 84: 101-112.

Pioneer, 2007a. Corn 2007-08. Pioneer HiBred International Inc. [Online]. http://australia. Pioneer.com [Accessed 22 June 2009].

Pioneer, 2007b. Products - Corn - Silage. [Online]. http://australia. Pioneer.com [Accessed 27 June 2009].

Raes, D., Geerts, S., Kipkorir, E., Wellens, J. and Sahli, A. 2006. Simulation of yield decline as a result of water stress with a robust soil water balance model. *Agric. Water Manage.* 81: 335-357.

Robertson, M.J., Cawthray, S., Birch, C., Bidstrup, R., Crawford, M., Dalgleish, N.P. and Hammer, G.L. 2003. Managing the risk of growing dryland maize in the northern region. *In* C.J. Birch and S.R. Wilson eds, Proceedings of the 5th Australian Maize Conference (Versatile Maize - Golden Opportunities) Toowoomba, Maize Association of Australia. 16-28.

Schafer, B.M., Ritchie, A.M. and Strachan, D.B. 1986. Soils of the Queensland Agricultural College farm, Darbalara. Queensland Agricultural College, Technical Pap. No. 7, Queensland Agricultural College, Lawes, Queensland, Australia.

Singh, B.R. and Singh, D.P. 1995. Agronomic and physiological irrigation responses of sorghum, maize and pearl millet to irrigation. *Field Crops Res.* 42: 57-67.

Song, Y., Birch, C.J. and Hanan, J. 2008a. Analysis of maize canopy development under water stress and incorporation into the ADEL-Maize model. *Funct. Plant Biol.* 35: 925-935.

Song, Y., Birch, C.J., Qu, S. and Hanan, J. 2008b. Revising crop and architectural models of maize canopy production for rainfed conditions. *In* "Global Issues, Paddock Action". Proceedings of the 14th Australian Agronomy Conference, 21-25 Sept. 2008, Adelaide, South Australia. Australian Society of Agronomy.

Stone, P.J., Wilson, D.R., Reid, J.B. and Gillespie, R.N. 2001. Water deficit effects on sweet corn. I. Water use, radiation use efficiency, growth, and yield. *Aust. J. Agric. Res.* 52: 103-113.

Wang, E., Robertson, M.J., Hammer, G.L., Carberry, P.S., Holzworth, D., Meinke, H., Chapman, S.C., Hargreaves, J.N.G., Huth, N.I. and McLean, G. 2002. Development of a generic crop model template in the cropping system model APSIM. *Eur. J. Agron.* 18: 121-140.

Xie, Y., Kiniry, J.R., Nedbalek, V. and Rosenthal, W.D. 2001. Maize and sorghum simulations with CERES-Maize, SORKAM, and ALMANAC under water-limiting conditions. *Agron. J.* 93: 1148-1155.