OPTIMISING MAIZE PLANT POPULATION AND IRRIGATION STRATEGY ON THE DARLING DOWNS: A SIMULATION ANALYSIS

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Abstract

Optimum plant population and irrigation strategies for maize grown in the Dalby district of the Darling Downs in Queensland were investigated using the APSIM crop simulation model, which was validated against three seasons of experimental data. Three simulated irrigation experiments were conducted across two soil types with plant available water capacities (PAWCs) of 146 mm and 220 mm, and plant populations ranging from 20,000 to 80,000 plants/ha. All soil type × plant population × irrigation strategy scenarios were simulated using the historical climate record for Dalby in order to obtain long term average yield data and calculate gross margins (GMs) for each scenario. Soil water was reset to two-thirds of PAWC at sowing in each year. Plant populations required to achieve maximum long term average GMs ranged from 50,000 to 80,000 plants/ha across the range of scenarios. The use of higher plant populations increased season-to-season variability in grain yield and GM, and may not be a suitable strategy for growers who do not want to increase their risk of crop failure. Economic gains were achieved by varying the timing and amount of irrigation within a limited available irrigation volume, with a single 1 ML/ha irrigation giving greater long term average GMs than two 0.5 ML/ha irrigation events on both soil types, when the irrigation events were scheduled to fill a soil water deficit equal to the effective irrigation volume. However, under full irrigation the use of smaller irrigation events increased GMs on the 146 mm PAWC soil, demonstrating the importance of timely scheduling of irrigation events on low PAWC soils.

Introduction

In semi-arid, subtropical Australia irrigated maize is grown across a range of soil types, farming systems and climatic zones, and response to the quantity and timing of irrigation events is difficult to predict. Assessment of the response to irrigation based on water use efficiency may be inaccurate under water-limiting conditions because in maize the timing of water deficit around flowering is crucial to yield determination.

Mechanistic crop growth models that are capable of quantifying the contribution of different physiological processes, climatic, soil and management factors to yield have been used to examine irrigation management and investment (e.g. Boggess and Ritchie 1988, Robertson et al. 1997). Provided that soil properties and long-term meteorological data are available, the modelling approach offers the possibility of conducting virtual “irrigation experiments” at contrasting locations over a large number of seasons.

Plant population density is a key parameter of maize production, primarily because grain yield is responsive to density but also because seed is a substantial component of the cost of production. Plant population densities required to achieve maximum grain yield vary with amounts and timing of rainfall and irrigation events. While industry recommendations for plant population densities exist for dryland and fully-irrigated production, no such recommendations are available for partially irrigated situations.

This paper examines the scope for improved density and irrigation management with variable seasonal irrigation supplies using the agricultural systems model Agricultural Production Systems SiMulator (APSIM, Keating et al. 2003). The focus environment for the study is the heavy clay soil irrigated farms of the Darling Downs where irrigation supplies vary from farm to farm, and season to season.
Materials and Methods

Validation experiments

Field experiments with varying populations and irrigation regimes were conducted over three seasons in order to generate experimental data with which to validate the APSIM model. Experiments were conducted on a farm approximately 10 km south-west of Dalby on a grey vertosol soil type, with a plant available water capacity (PAWC) of 146 mm. Low to moderate levels of subsoil constraint were observed through elevated levels of chloride below 90 cm. Drained upper limit (DUL), crop lower limit (CLL) and bulk density were determined for soil depth layers of 0-15 cm, 15-30 cm, then 30 cm layers to 180 cm, using the methods described by Dalgliesh and Foale (1998) for a shrink-swell soil.

Population density × irrigation field experiments were conducted in the summers of 2001/2002, 2002/2003 and 2003/2004. The population densities and irrigation treatments varied between seasons, and are listed in Table 1.

<table>
<thead>
<tr>
<th>Season</th>
<th>Treatment</th>
<th>Established Plant Populations (1000 plants/ha)</th>
<th>PAW at Sowing</th>
<th>1st Irrigation</th>
<th>2nd Irrigation</th>
<th>3rd Irrigation</th>
<th>4th Irrigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001/ 2002</td>
<td>1 × Irrigation</td>
<td>37, 55, 71</td>
<td>82 mm</td>
<td>0.75 (24/12/01)</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>2 × Irrigations</td>
<td>44, 54, 68, 84</td>
<td></td>
<td>0.75 (24/12/01)</td>
<td>0.75 (10/1/02)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>2002/ 2003</td>
<td>2 × Irrigation</td>
<td>21, 36, 45, 50, 61</td>
<td>153 mm</td>
<td>0.60 (26/10/02)</td>
<td>0.80 (25/11/02)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>3 × Irrigations</td>
<td>36, 45, 50, 61</td>
<td></td>
<td>0.60 (26/10/02)</td>
<td>0.80 (25/11/02)</td>
<td>0.75 (22/12/02)</td>
<td>NA</td>
</tr>
<tr>
<td>2003/ 2004</td>
<td>Delayed Irrigations</td>
<td>46, 57, 61, 74</td>
<td>84 mm</td>
<td>0.60 (19/11/03)</td>
<td>0.60 (3/12/03)</td>
<td>0.60 (4/1/04)</td>
<td>0.60 (28/1/04)</td>
</tr>
<tr>
<td></td>
<td>On-Time Irrigations</td>
<td>44, 53, 61, 74</td>
<td></td>
<td>0.50 (12/11/03)</td>
<td>0.60 (30/11/03)</td>
<td>0.60 (25/12/04)</td>
<td>0.60 (28/1/04)</td>
</tr>
</tbody>
</table>

Experiments were designed in a completely randomised block design, with each population density replicated twice within an irrigation experiment except in the 2 × irrigation treatment of the 2001-2002 season where population densities were not replicated. Different irrigation treatments within the same year were considered as separate experiments, and all experiments were flood irrigated. Experimental plots were 16 rows × 450 m in the first two seasons, and 16 rows × 300 m in the third season. Buffer plots of 16 rows were used to separate the irrigation experiments. The established plant populations from each irrigation experiment are listed in Table 1. Irrigation schedules for each experiment are also listed in Table 1 along with the plant available water (PAW) at sowing.

The maize variety Pioneer 3237 was used for all experiments. Two rows of maize were planted onto raised beds in 1m row spacings, with an irrigation furrow either side of each bed. Experimental plots were harvested with the same commercial grain harvester for all experiments. Grain yield (t/ha) was calculated from yield monitor estimates of the total maize grain yield of experimental plots corrected to 14% moisture, divided by plot area. Nitrate nitrogen was measured at sowing each year and not considered to be limiting, with 496, 894 and 345 kg N/ha available at sowing in the 2001-2002, 2002-2003 and 2003-2004 seasons, respectively. Insects, weeds, nutrition and disease were not considered to have limited grain yield in any year.

Simulation model validation

The three years of field experimentation were modelled using APSIM. Maximum and minimum temperature data for the validation simulations were obtained from the Dalby Airport records available on the Bureau of Meteorology SILO database, while rainfall data was obtained from farm records.

APSIM parameterisation

Soil type parameters used were as follows: USDA curve number was set at 80, and diffusivity constant and slope were set to 40 and 16 respectively. Stage 1 and stage 2 evaporation coefficients were set at 6 and 3.5 between October 31st and April 1st.
The internal drainage parameter, SWCON, was set to 0.2 for all soil layers. DUL varied from 0.436 to 0.465 mm/mm and LL from 0.306 to 0.440 mm/mm down the profile. Saturated soil water content was 0.486 to 0.515 mm/mm. Critical temperature during flowering for the maize module was set to 36.5°C. High levels of starting soil N meant that N was not simulated as limiting in any of the experiments.

The $k_l$ constant determines the maximum rate of crop water uptake from individual soil layers. In order to simulate the effect of plant population, $k_l$ values were assumed to decline linearly with population in each soil layer, because the $k_l$ values are operating on a crop basis not an individual plant basis, and proportionally less water extraction per day was anticipated from lower population densities. $k_l$ values for a population density of 65,000 plants/ha varied from 0.11 day$^{-1}$ near the soil surface decreasing to 0.023 day$^{-1}$ at the bottom of the soil profile. Roots were allowed to penetrate at the maximum rate to 120 cm, then slowing and reaching maximum rooting depth at 150 cm.

A cap was placed on soil water demand (APSIM parameter “eo_crop_factor” = 1.2) to combat the deficiencies of the transpiration efficiency method of determining soil water demand in arid environments as discussed by Bristow and Carberry (1991) and Wang et al. (2004).

### Long term simulation modelling

Three long-term simulation analyses were conducted using the same set of model parameters described in the simulation model validation section. When discussing these analyses, the term ‘irrigation supply volume’ (ISV) describes the amount of water leaving the on farm storage on a per hectare basis, while the term ‘effective irrigation volume’ refers to the amount of water incorporated into the soil profile on a per hectare basis. The APSIM parameter ‘irrigation efficiency’ is similar to the industry term ‘Distribution Efficiency’ (the amount of water received at field inlets, divided by the total outflow from on-farm storage ( Purcell and Currey 2003)), but is slightly smaller as it accounts for any runoff in addition to the channel losses described by Distribution Efficiency. Irrigation efficiency was set to 0.85, slightly lower than the worst case benchmark distribution efficiencies reported by Dalton (2000).

In the first analysis (referred to hereafter as Analysis 1), season total ISV was capped at four different levels, and 0.9 ML/ha was applied each time the soil water deficit (defined as PAWC-PAW) in the top 120 cm of soil was greater than 75 mm. This analysis was designed to determine if the plant population required for maximum grain yield and gross margin varies with the season total of ISV. The second analysis (Analysis 2) was designed to investigate the effect on grain yield and gross margin of different sized soil water deficits being used as a trigger for irrigation events. The third analysis (Analysis 3) was designed to investigate whether a set season total ISV can be better utilised by using different sized irrigation events. The major variables and their configurations for each long-term analysis are described in Table 2.

<table>
<thead>
<tr>
<th>Simulation Experiment</th>
<th>Season Total ISV (ML/ha)</th>
<th>Application ISV (ML/ha)</th>
<th>Trigger (mm deficit in top 120cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis 1</td>
<td>0.9, 1.8, 2.7, 3.6</td>
<td>0.9 for all treatments</td>
<td>75 for all treatments</td>
</tr>
<tr>
<td>Analysis 2</td>
<td>Unlimited</td>
<td>0.59, 0.73, 0.88, 0.103</td>
<td>85 × the application ISV</td>
</tr>
<tr>
<td>Analysis 3</td>
<td>1.0</td>
<td>0.5 and 1.0</td>
<td>85 × the application ISV</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>0.66 and 1.0</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>0.75 and 1.0</td>
<td>*</td>
</tr>
</tbody>
</table>

Each long term simulation experiment was set up to perform an automatic ‘flush’ irrigation (0.4 ML/ha ISV at an irrigation efficiency of 0.7) to promote nodal root development between 21 and 36 days after sowing, when the soil water deficit of the top layer was greater than 10 mm. This flush irrigation was not included in the season total ISVs listed in Table 3 for ease of reporting (as it was not used in each year), but was accounted for in any gross margin analyses performed on the long-term simulations. Therefore season total ISVs used in the simulations may be up to 1.5ML/ha lower than that required in reality in order to account for any pre-irrigation, and a subsequent flush irrigation.
All of the long-term analyses compared population densities of between 20,000 and 80,000 plants/ha at intervals of 10,000 plants/ha, for all irrigation treatments. Populations higher than 80,000 plants/ha were not investigated as we do not believe the relationship between kf value and plant population discussed earlier would apply to such high populations. Historical climate data (1889 to 2004) for Dalby Airport was used for each simulation to simulate a maize crop planted on October 4th of each year.

Soil water was reset to have each soil type holding two-thirds of PAWC one week before planting in each year. Two soil types were compared for all long-term simulations. The first soil was the same soil used for the validation exercise (PAWC=146 mm), and the second soil was parameterised to have a PAWC of 220 mm.

Gross margins were calculated for the long-term simulations using simulated grain yield at 14% moisture, a price of $170/t (on-farm) for maize grain, irrigation water costed at $40/ML (Harris 2002) and a seed cost of $32 for 10,000 seeds. The gross margin included the amount of nitrogen used by the crop, costed at $1.00 per unit of nitrogen that was removed from the paddock. Other variable costs were assumed to equal $366/ha, an estimate provided by Graham Harris (pers. comm.) based on his gross margin analysis for irrigated maize on the Queensland Department of Primary industries website (Harris 2002) but updated using a diesel price of $1.14/litre.

Results

Validation experiments

High correlation was observed between simulated and observed grain yield for all irrigation experiments except the delayed irrigation experiment in 2003-2004. An r² value of 0.71 was obtained from a linear regression of all observed vs simulated data (results not shown), but an r² of 0.94 was observed when the 03-04 delayed experiment was not considered in the regression (Fig. 1a). The success of the model in predicting grain yield across multiple population densities is further illustrated in Figure 1(b), where observed and simulated grain yield from the 2002-2003 validation experiments is plotted against population density.

Figure 1: (a) Observed vs simulated grain yield for all validation experiments and linear regression on all data points except those generated in the 2003-2004 delayed irrigation experiment (b) Simulated and observed response of grain yield to plant population density in the 2002-2003 validation experiments.

*Linear regression does not include data from 2003-2004 delayed irrigation experiments. **No standard error bars presented as they are smaller than the symbols (1 irrigation treatment) or not available due to single replication (2 irrigation treatments).

Analysis 1: Population density response to four season total ISVs

On the 146 mm PAWC soil a simulated maximum grain yield of 14.2 t/ha was achieved at a plant population of 80,000 plants/ha in the 3.6 ML/ha treatment (Fig. 2a). This estimate of maximum grain yield is greater than the farmers estimate of yield potential of 12-13 t/ha, and greater than the highest observed grain yield (12.8 t/ha) in the validation experiments.
On the 146 mm soil, the population required to achieve maximum mean long term grain yield ($\text{LGY}_{\text{max}}$) varied slightly between different season total ISVs, being 70,000 plants/ha for the 0.9 ML treatment, and 80,000 plants/ha for the 1.8, 2.7 and 3.6 ML/ha treatments. Populations required to achieve maximum mean long term gross margin ($\text{LGM}_{\text{max}}$) were similar to those needed to achieve $\text{LGY}_{\text{max}}$, being slightly different for only the 0.9 and 1.8 ML/ha treatments (60,000 and 70,000 plants/ha respectively) (Fig. 2b). The gross margins (GM) analysis indicates that at 70,000 plants/ha the increase in GM ($\$45$/ha) from the addition of a fourth 0.9 ML/ha application is small relative to the increases seen by the application of the second and third applications (increases of $\$355$/ha and $\$192$/ha respectively).

On the 220 mm soil in the range of investigated populations, $\text{LGY}_{\text{max}}$ was achieved at a population density of 80,000 plants/ha for all season total ISVs. $\text{LGM}_{\text{max}}$ was achieved at 70,000, 70,000 and 80,000 plants/ha for the 0.9, 1.8 and 2.7 ML/ha treatments respectively. The application of a fourth 0.9 ML/ha gave only a negligible increase in long term average grain yield, and no increase in LGM in comparison to the simulations with three applications, indicating that when there was 140 mm of PAW (2/3rd of 220 mm) at sowing, 2.7 ML of season total ISV was sufficient to achieve $\text{LGM}_{\text{max}}$.

For all treatments on both soil types, variation in season-to-season grain yield and GM increased with the larger population treatments, although the degree of increase was less marked as season total ISV increased.

For example, in the 0.9 ML/ha treatment on the 146 mm PAWC soil, one standard deviation for the simulated long term mean GM (LGM) ranged from $\pm \$188$ to $\$569$ (Fig. 3a) while in the 3.6 ML/ha treatment, one standard deviation ranged from $\pm \$193$ to $\$409$ (Fig. 3b).
Figure 3: LGMs and their standard deviations for all population densities on the 146 mm PAWC soil in (a) the 0.9 ML/ha total season ISV treatment and (b) the 3.6 ML/ha total season ISV treatment.

Analysis 2: Grain yield response to the use of varying deficit sizes as irrigation event triggers

Simulations using smaller trigger deficit sizes with unconstrained season total ISV on the 146 mm soil had the highest yields across the range of population densities (Fig. 4a), although the differences were less noticeable at 80,000 plants/ha where only the 100 mm deficit trigger had a negative impact on grain yield. This was probably related to the effect of high \( k_l \) parameter values for these high populations causing faster rates of soil water extraction, which caused irrigation events to be triggered sooner for the higher populations and experienced decreased duration of water stress as a result. On the 220 mm soil, the trigger deficit had little impact on LGY, with all treatments having similar LGY for all populations (Fig. 4b), demonstrating that soils with higher PAWC and higher starting soil water buffer the crop against periods of low water input. Gross margin analysis of the same simulations had similar trends, with smaller deficit sizes giving higher LGMs on the 146 mm PAWC soil, and little difference between LGMs across the range of populations on the 220 mm PAWC soil (results not shown).

Figure 4: Grain yield response to varied irrigation trigger deficit size over a range of population densities for (a) the 146 mm PAWC soil and (b) the 220 mm PAWC soil.

Analysis 3: The effect of different irrigation application sizes on grain yield for the same season total ISV.

Smaller application ISVs had lower LGMs for the smallest season total ISV of 1 ML/ha in both the 146 mm and 220 mm PAWC soils (Fig. 5) at the population densities required to achieve LGM\(_{max}\). However, when the season total ISV was increased to 2 ML/ha or greater, there was little effect of application size at the economic optimum plant population in the 146 mm PAWC soil, and no effect of application size in the 200 mm PAWC soil.
The APSIM crop simulation model accurately simulated 5 out of the 6 validation experiments, giving confidence that it could be used to investigate scenarios of population × irrigation management. The low degree of correlation between simulated and observed grain yield in the 03-04 delayed irrigation experiment possibly resulted from incorrect recording of the amount or timing of irrigation events, or from the interaction between the irrigation event on 3/12/03 and a large rainfall event on 5/12/03 that may have caused the simulation to over-estimate infiltration from this rainfall event.

The population density required to achieve maximum simulated grain yields varied with the amount of irrigation water available to the crop, and soil PAWC (analysis 1). Population densities required to maximize simulated gross margins were different to those needed to maximize grain yield in the supplementary irrigation scenarios. The results indicate that the population size necessary to achieve maximum long term average gross margin when a single 0.9 ML/ha ISV was applied through the season, was 60,000 plants/ha on the 146 mm PAWC soil and 70,000 plants/ha on the 220 mm PAWC soil, when a 2/3 full profile was available at sowing. These simulated optimum populations are similar to the current recommended plant population for full irrigation on the Darling Downs (65,000 plants/ha). The increased risk of crop failure from using such a high population for supplementary irrigation is compensated for in the long term, with greatly increased returns available from seasons with good rainfall. The flat response around the optimum population suggests that variations from the optimum population of up to 10,000 plants/ha on the 146 mm PAWC soil, and 20,000 plants/ha on the 220 mm PAWC soil should not impose a large economic penalty in the long term.

The simulated maximum long term grain yield from this experiment was 1.4 t/ha higher than the highest grain yield observed in the validation experiments, and at a higher population than that used on the property where validation experiments were carried out. The use of improved irrigation scheduling (by using smaller deficit sizes as the trigger for irrigation events), larger season total ISVs and increased starting soil water may allow the grower to improve their yield potential. However, it is also possible that the estimated APSIM $k_l$ values may not be accurate for populations above 70,000 plants/ha, and the maximum simulated grain yield may not be achievable in reality.

Comparison of irrigation timing strategies (analysis 2) indicated that under fully irrigated conditions, irrigation trigger deficits of 75 mm or smaller were necessary to achieve maximum long term average grain yields and gross margins. However, the simulation analyses assumed an almost immediate irrigation event once the trigger soil water deficit was reached. Therefore, soil water deficits of 62.5 mm or smaller may be more appropriate in reality, in order to allow additional time to apply the irrigation water. Further analysis of the variable cost of each irrigation event would need to be undertaken in order to determine the cost effectiveness of such a high frequency of irrigation.

In situations where full irrigation is not possible due to limited water supply, simulation analysis indicated that varying the amount and timing of irrigation events can be used to maximize profitability on both the 146 mm and 220 mm PAWC soils (analysis 3). When only 1ML/ha of season total ISV was available, LGM_max was higher when the entire ISV was applied at once, when deficit size was nearly as high as the ISV. However, when season total ISV was > 2 ML/ha, larger application ISVs did not have an advantage over smaller applications at the population required to achieve LGM_max.
Conclusions

The results of the simulation analyses indicate plant population density can be varied in order to maximize profitability in response to variations in water supply. Population densities similar to those currently used under full irrigation were simulated as giving maximum long-term profitability for supplementary irrigation, when PAW at sowing was 96 mm or more. However, the use of higher population densities increased season-to-season variability of grain yield and may not be a suitable strategy for growers who do not want to increase their risk of crop failure. Additionally, the analyses demonstrated the importance of timely scheduling of irrigation events on low PAWC soils, where small soil water deficits were used as a trigger for irrigation events in order to maximize long-term profitability. However when total season water supply was limited, the use of smaller deficit sizes as a trigger for irrigation events did not maximize long-term profitability in all circumstances.

Acknowledgements

This research was financially supported by GRDC. Mr Glenn Fresser and his staff at Mayfield Farming Company are gratefully acknowledged for hosting and managing the validation experiments. Mr Neil Huth (CSIRO Sustainable Ecosystems) is gratefully acknowledged for his valuable comments on the simulation analyses. We thank Dr Lisa Brennan and Dr Shaun Lisson (CSIRO Sustainable Ecosystems) for their valuable comments on the manuscript.

References


