CSIRO PUBLISHING
Australian Journal of Experimental Agriculture, 2008, **48**, 296–303 www.publish.csiro.au/journals/ajea

Analysis of high yielding maize production – a study based on a commercial crop

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Abstract. This paper reports on the use of APSIM – Maize for retrospective analysis of performance of a high input, high yielding maize crop and analysis of predicted performance of maize grown with high inputs over the long-term (>100 years) for specified scenarios of environmental conditions (temperature and radiation) and agronomic inputs (sowing date, plant population, nitrogen fertiliser and irrigation) at Boort, Victoria, Australia. It uses a high yielding (17 400 kg/ha dry grain, 20 500 kg/ha at 15% water) commercial crop grown in 2004–05 as the basis of the study. Yield for the agronomic and environmental conditions of 2004–05 was predicted accurately, giving confidence that the model could be used for the detailed analyses undertaken. The analysis showed that the yield achieved was close to that possible with the conditions and agronomic inputs of 2004–05. Sowing dates during 21 September to 26 October had little effect on predicted yield, except when combined with reduced temperature. Single year and long-term analyses concluded that a higher plant population (11 plants/m^2) is needed to optimise yield, but that slightly lower N and irrigation inputs are appropriate for the plant population used commercially (8.4 plants/m^2). Also, compared with changes in agronomic inputs increases in temperature and/or radiation had relatively minor effects, except that reduced temperature reduces predicted yield substantially. This study provides an approach for the use of models for both retrospective analysis of crop performance and assessment of long-term variability of crop yield under a wide range of agronomic and environmental conditions.

Additional keywords: irrigation modelling, nitrogen optimisation, plant population, radiation, sowing date, temperature, yield, yield reliability, *Zea mays*.

Introduction

Production of high yields of any crop depends on optimisation of agronomic inputs and practices within the environmental characteristics (e.g. thermal, photoperiod and rainfall) and resource constraints (principally soil fertility and water holding capacity) of the crop location. Nielsen (2003) explored the concept of yield influencing factors, with a 'target' yield of 28 t/ha and observed that the number of potential factors is very high and related to environmental and resource constraints, agronomic inputs and practices and other decisions that may affect the crop, and noted that there is an abundance of agronomic choices available. The incidence and effects of yield influencing factors vary on farms and across regions (Nielsen 2003). This author proposed that management solutions to mitigate negative and enhance positive yield influencing factors were possible and argued that the solutions depended on detailed knowledge of environmental and resource constraints, and close monitoring and accurate recording of crop development and performance.

Experimental yields in Australia listed in Birch *et al*. (2003) showed that higher yields were achieved in southern than northern areas, with the more moderate temperatures in areas such as Gatton, Liverpool Plains and Riverina than in northern areas being at least a partial explanation for yield trends in rain grown and irrigated crops. Modelling studies for rain grown environments in the northern region of Australia show similar trends, and emphasise the importance of time of sowing (which influences thermal and radiation environment and water availability), plant population and water availability at sowing (Birch *et al*. 2008). Understanding of combinations of environmental conditions, agronomic and management inputs that achieve high yields is vital to providing information to managers of crop production enterprises so they can optimise inputs to consistently produce high yields, whether for current or future climates. High commercial yields have been reported in Australia, with the Australian record being from a commercial crop of 20 500 t/ha (at 15% water) (Hutchins 2005) grown near Boort (36.1°S, 143.7°E; elevation 90 m), Victoria. This crop was used as the basis of the present study.

Modelling is a powerful tool for both retrospective analysis of agricultural systems or individual inputs to explain performance of the system or input, and for assessing outcomes of changes to agronomic practices (Lyon *et al*. 2003; Robertson *et al*. 2003), provided the model is underpinned by sound scientific principles and is well validated (Lyon *et al*. 2003).

 10.1071/EA06103 0816-1089/08/30296

The purposes of this paper are to undertake a case study in which: (i) retrospectively analyse agronomic inputs to the high yielding maize crop above to assess the potential for further improvements to yield for current and historical environmental conditions by changes to agronomic practices; and (ii) undertake several 'what if?' scenarios to assess the impact of differing environmental conditions for a range of agronomic conditions.

Site and crop cultural details

The commercial crop was grown in the 2004–05 on Sawers Farms near Boort, Victoria, Australia. The average annual rainfall (373 mm) at Boort and nearby Kerang (36.7°S, 143.9°E; elevation 78 m) is relatively evenly distributed (44% and 46% October to March, 56% and 54% April to September), and temperatures are moderate during October to March though exceeding 38°C in 10% of years and occasionally exceeding 40°C (Bureau of Meteorology 2004, 2007). The soil, a vertosol (locally known as a Boort clay), is dark brownish-grey with light to medium clay topsoil and heavy clay subsoil that tends to brownish yellow-grey in colour. It has a self-mulching surface, is friable when moist (Skene 1971; Ashcroft *et al*. 2001), has a pH of 7.8 (to 30 cm) (Stork *et al*. 2003) and exceeds 5 m depth. Plant available water holding capacity exceeds 200 mm to 180 cm deep, and there are no subsoil constraints to root proliferation.

The cultivar grown was Pioneer 3335, which has a comparative relative maturity (CRM), a measure of time from emergence to grain moisture content being suitable for harvest (Lauer 1998; Yang *et al*. 2005), of 113 days, and has 'stay green' characteristics (Pioneer 2004). The crop was sown on 1 October 2004 at 84 000 seeds/ha on 167 cm wide beds, two rows to a bed, using a precision planter. Weeds and insects were controlled chemically. The soil profile was fully wet to field capacity by irrigation before crop sowing and subsequently irrigated by subsurface drip irrigation daily or twice daily, the volume applied being sufficient to compensate for estimated evapotranspiration to maintain non-limiting water supply conditions. Soil water was also checked daily using a moisture probe to ensure non-limiting water supply. Irrigation totalled 7.5 ML/ha. Fertiliser application was 46 kg N/ha and 82 kg P/ha [375 kg/ha monoammonium phosphate (12.3% N, 22% P)] applied close to the sowing row before sowing plus 350 kg N/ha as urea (46% N) through the irrigation system according to guidance in Pioneer (2004), providing nitrogen ~7–10 days before expected plant uptake to allow for nitrification. The crop was harvested on 27 April 2005; the yield being assessed in three areas harvested under supervision (Hutchins 2005).

Analysis

To carry out the modelling, APSIM (Keating *et al*. 2003) was used. There is extensive information on scientific underpinnings, model structure, information flow, inputs required and parameterisation of functions for maize on the APSIM website under 'Documentation' (APSRU 2003). It has been validated for maize in Australia and the United States (Robertson *et al*. 2003; Lyon *et al*. 2003; Madhiyazhagan 2005). Whopper Cropper (Nelson *et al*. 2002; Cox *et al*. 2004) was used for storage, analysis and presentation of output, as described in Birch *et al*. (2008). Model output was stored and processed using the data capture and analysis system in Whopper Cropper. Predictions that illustrate the main findings are presented as box and whisker plots, which show the range (vertical bars), 70 and 30 percentiles (top and bottom of box), predicted mean and median yields (broken and solid horizontal lines) for each scenario.

Two groups of simulations were completed, first using weather data for 2004–05 to assess model and crop performance, and second long-term analyses using 100 years of weather data for nearby Kerang (Kerang data were used as weather data are more comprehensive and cover a longer period than at Boort). The simulations provided estimates of crop phenology, leaf number and leaf area index (LAI), yield and components of yield and incidence of water stress. This paper concentrates on prediction of yield, with predictions of phenology, leaf area and water stress indices being used to explain trends in simulated yield.

In the simulations, the radiation use efficiency (RUE) was 3.8 g/MJ photosynthetically active radiation for maize grown under optimal conditions (Lindquist *et al*. 2005) (replacing 3.3 g/MJ photosynthetically active radiation used in APSIM maize). Soil parameters were based on those for a deep vertosol soil, modified according to data for the Boort clay in Skene (1971), Ashcroft *et al*. (2001) and Stork *et al*. (2003), to produce plant available water of 200 mm to 180 cm deep. For simulations using Pioneer 3335, the phenology routine produced 18 leaves with cultivar parameters used in current modelling research for Pioneer 3335 (commercial in confidence values provided by Pioneer Hi Bred Pty Ltd, S. R. Wilson, pers. comm.). Different values were used in those simulations where phenology was modified by increasing or decreasing the number of leaves produced. Also, in sowing date simulations, the model was allowed to predict variation in final leaf number, based on parameters for Pioneer 3335.

The following simulations were completed:

(i) Nitrogen rates of 0, 75, 150, 200, 250, 300, 350, 400 and 500 kg N/ha (all applied at sowing) assuming 60 kg/ha NO_3-N in the soil at sowing.
(ii) Phenology – using plants with 16, 18, 20 and 22 leaves (set in input files).
(iii) Sowing dates from 21 September to 26 October in 5-day intervals.
(iv) Irrigation based on deficits from 10 to 60 mm assuming 100% plant available water capacity (PAWC), of 250 mm H_2O to 180 cm at sowing (2004–05 analysis only). PAWC was estimated as in Dalgleish and Foale (1998).
(v) Irrigation schedules from 10 to 60 mm deficit assuming 15, 30, 45, 60, 75 and 100% of PAWC at sowing. (At the 15% and 30% initial PAWC, the 40 and 60 mm deficits were overridden and irrigated when 10% of PAWC remained).
(vi) Daily radiation changed in 5% intervals to produce values from 15% below to 15% above observed daily values.
(vii) Daily mean temperature from 4°C below to 4°C above observed values in 1°C intervals, by changing maximum and minimum temperatures to simulate cooler or warmer locations, with 75% of the increase being in minimum temperatures and 25% being in maximum temperature consistent with reduced diurnal range in temperatures under global warming conditions (IPCC 2001; Bureau of Meteorology 2007).

Table 1. Summary of predicted dry grain yield and grain yield of maize at 15% water (in parentheses) using 2004–05 weather data for variations in nitrogen application, crop phenology, sowing date and changes in radiation and temperature from daily data

Simulation	Range used	Range in predicted yield (kg/ha)	Predicted optimum[A]
Phenology	16–22 leaves	16 900–19 000 (19 900–22 400)	20 leaves
Sowing date	21 September to 26 October	17 200–19 100 (20 200–22 500)	11 October
Plant population	5–12.5 plants/ha	11 600–21 400 (13 600–25200)	11 plants/m^2
Nitrogen rate	0–500 kg N/ha	5300–18 700 (6200–22 000)	Near 350 kg N/ha
Irrigation	Deficit of 10–60 mm	All near 18 700 (All near 22 000)	Any could be used
Radiation	–15 to 15%	18 100–18 700 (21 300–22 000)	–5 to 15%
Temperature	–4 to 4°C	0–18 900[B] (0–22 200)	–1

[A]Optimum was defined as where maximum yield occurred.
[B]Includes values of –3°C and –4°C from 2004–2005 observed data.

(viii) Using Pioneer 3335 (18-leaf cultivar), factorial combinations of temperature × sowing date and temperature × radiation.

Simulations (i) to (v) were included to represent tactical decisions that can be taken as part of crop management, and can therefore be considered inputs to optimise crop cultural practices. Simulations (vi) to (viii) were included to represent cooler or warmer conditions at the same latitude due to altitude in current climates and warmer conditions due to climate change (Bureau of Meteorology 2007). Similarly, differences in radiation were included to represent changes in incoming radiation that may occur with changes in cloudiness, which has generally increased (hence, less radiation reaches the ground) globally since the 1950s, but with substantial local variation (Bureau of Meteorology 2007); hence, the need to consider both increases and decreases in radiation. In simulations, factors not varied were retained at those used in the commercial crop, or for water and nutrient supply, set to non-limiting conditions.

Results are presented as dry grain yield (t/ha), with commercial grain yield at 15% moisture in the grain shown in parenthesis.

Results

2004–05 simulations

The predicted dry grain yield (PY) of 18 700 kg/ha (22 000 kg/ha at 15% water in grain) was within 8% of the commercial crop yield (17 400 kg/ha dry grain, 20 500 kg/ha at 15% moisture) for similar conditions. The analysis showed that the crop was grown at or close to predicted optima for nitrogen rate, phenology and sowing date, but that a higher plant population could have been used (Table 1). Varying radiation had little effect except when reduced by >5%, which reduced PY. Lower temperatures would mean the cultivar used could fail, while higher temperatures would reduce yield by up to 1500 kg/ha (Table 1).

Long-term predictions

Crop phenology

Altering crop phenology by using 16 to 22 leaves, produced median PY near 18 000 kg/ha (21 000 kg at 15% water) for all with a narrow range from the 30 to 70 percentile for 16 and 18 leaves (Fig. 1). However, the range in the 30 to 70 percentile and from minimum to maximum PY was large for 20 and 22 leaves, indicating greater variability, though the probability of exceeding 12 000 kg/ha (14 100 kg/ha) was near 100% for all options.

Sowing date

All sowing dates produced median PY between 17 000 and 18 000 kg/ha (20 000–21 100 kg/ha at 15% moisture) (Fig. 2), though mean PY was lower for sowing between 6 and 21 October. This sowing period also had greater range from 30 to 70 percentile and from lowest to highest PY. However, sowing on 26 October had similar median and mean PY, range and range from 30 to 70 percentile as sowing between 21 September and 1 October. The probability of producing above 12 000 kg/ha (14 100 kg/ha at 15% moisture) exceeded 85% for all sowing dates assessed.

Plant population

Using long-term weather data and plant populations from 5 to 12.5 plants/m^2 maximum median PY was simulated near 11 plants/m^2 (110 000/ha), exceeding that at 8 plants/m^2 by ~3 t/ha with greater reliability (Fig. 3). At 12.5 plants/m^2, reliability but not PY was improved, while populations below 8 plants/m^2 showed substantial yield penalty.

Nitrogen rate

Rates of N up to 500 kg/ha produced an expected curvilinear response, with maximum simulated mean PY of 18 000 kg/ha

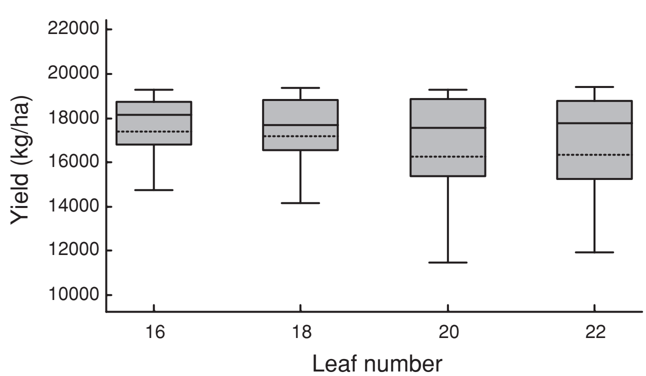

Fig. 1. The effect of leaf number on predicted yield of maize at Boort under non-limiting conditions of water and nitrogen supply using long-term weather data.

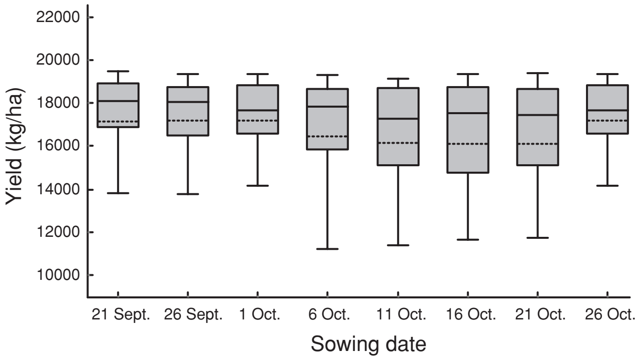

Fig. 2. The effect of sowing date on predicted yield of maize at Boort, Victoria, Australia, under non-limiting conditions of water and nitrogen supply using long-term weather data.

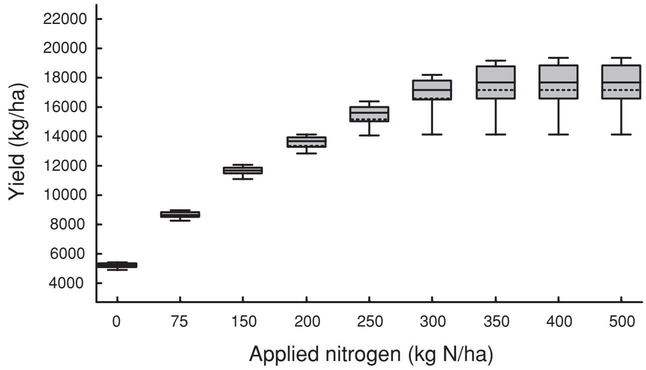

Fig. 4. The effect of nitrogen rate (kg/ha) on predicted yield of maize at Boort, Victoria, Australia, under non-limiting conditions of water supply using long-term weather data.

(21 200 kg/ha at 15% water) at 350 kg N/ha or more. The range in PY was small at rates up to 250 kg N/ha, but greater at higher N rates (Fig. 4).

Irrigation

The analysis for the 2004–05 season, assuming a full or near full profile of water at sowing showed only a limited effect of reduced irrigation frequency until quite substantial deficits were reached. In the long-term analysis, there was little if any difference in median PY (near 18 000 kg/ha, 21 100 kg/ha at 15% water) for starting water conditions of 60, 75 or 100% PAWC when irrigated at up to 60 mm deficit and refilled to the starting water supply (Fig. 5*a*). Using 45% of PAWC and irrigating at 10, 20, 40 or 60 mm deficit produced some reduction in PY and small increase in risk. However, at starting water storage of 15 and 30% of PAWC, there were substantial reductions in median PY (8000 and 15 300 kg/ha, 9400 and 18 000 kg/ha at 15% water) and substantially greater risk of low yield (Fig. 5*a*). Investigation of predicted water use over the long-term showed the highest input to be at starting conditions of 60% of storage capacity or above, with the median total requirement being near 650 mm, (6.5 ML/ha) (Fig. 5*b*), there being virtually no short-term water stress in these and no restriction on leaf area production.

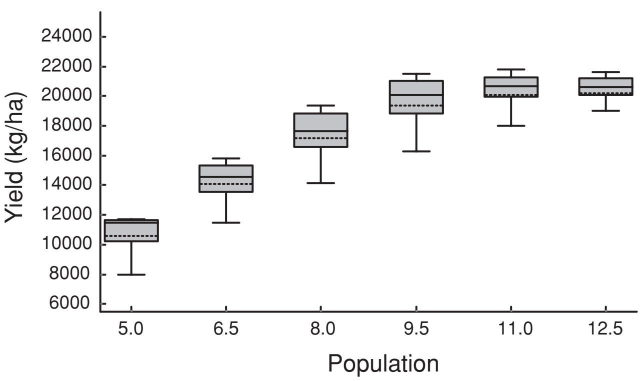

Fig. 3. The effect of plant population (plants/m^2) on predicted yield of maize at Boort, Victoria, Australia, under non-limiting conditions of water and nutrient supply using long-term weather data.

Temperature and radiation

Over the long-term, predicted median and mean PY for Pioneer 3335 were in the range 17 000 to 18 000 t/ha (20 000 to 21 200 kg/ha at 15% water) for observed temperature plus or minus 1°C. For 2004–05, mean temperature 1°C below observed values increased PY slightly (Table 1). However, at 2°C below observed temperatures mean PY declined by ~3000 kg/ha (3500 kg/ha at 15% water) and at 3°C below observed temperature, median PY was 0 kg/ha. Temperatures 2°C or more above observed values produced small but steady

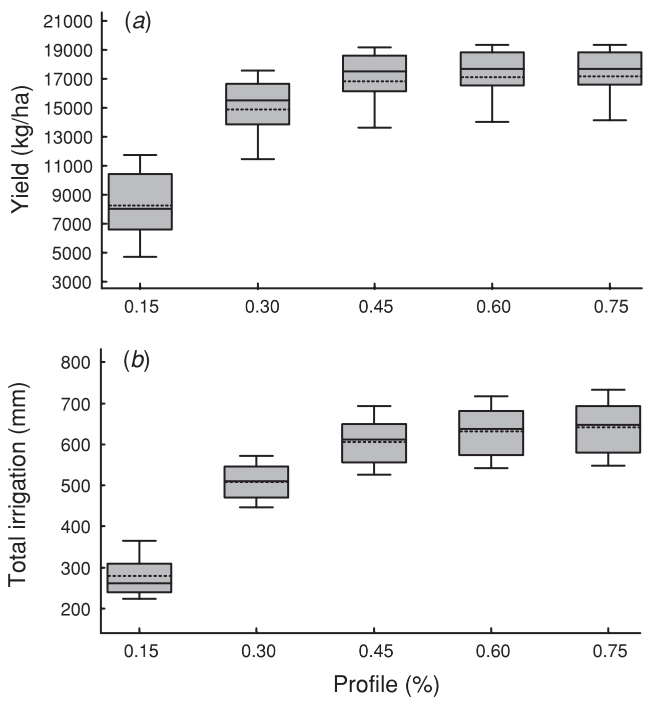

Fig. 5. The effects of starting soil water storage of 0.15 (15%) to 0.75 (75%) of capacity and refilling to these values, assuming no more than 60 mm of water deficit, and no less than 25 mm remaining in the profile on (*a*) predicted maize grain yield, and (*b*) amount of irrigation water (mm) used at Boort, Victoria, Australia, under non-limiting conditions of nitrogen supply using long-term weather data.

declines in both mean and median PY, with increased variability. There was little effect of varying radiation from 5% below observed to 15% above observed, but 10 or 15% reduction lowered PY somewhat (<1000 kg/ha). Investigation of the combined effects of temperature and radiation confirmed that temperature was the dominant factor in reductions in mean and median PY.

Combined effects of sowing date and temperature

Regardless of sowing date, temperatures more than 2°C lower than observed data produced major reductions in PY and at 4°C lower, median and mean PY were either very low or zero. Even at 2°C lower than observed, early sowing (21 September) would be very risky and the crop could fail. With later sowing, mean and median PY declined as temperature was increased above observed values, with greater decreases in all assessments with progressively later sowing date. Nevertheless, most mean and median PY were quite high (>13 000 kg/ha, 15 300 kg/ha at 15% water).

Discussion

Analysis of the 2004–05 crop year revealed that the yield produced was unlikely to be exceeded by changes to agronomic practices other than plant population, or environmental conditions. The analysis also showed that green leaf area index (LAI) was maintained at high levels from anthesis (LAI >5.0) to physiological maturity (LAI remained >3.5), levels required for full or nearly full light interception. The accuracy of predictions for 2004–2005 based on environmental conditions and production inputs used in that year provide confidence that the model performs well for the environmental and agronomic conditions of northern Victoria, and add to the already substantial validation of the model for a range of locations, cultural conditions and cultivars (APSRU 2003; Lyon *et al*. 2003; Robertson *et al*. 2003; Madhiyazhagan 2005). In effect, the model has been validated for higher yield environments than those for which it has previously been used (for example, Lyon *et al*. 2003; Robertson *et al*. 2003; Birch *et al*. 2008). Therefore, the output from the analyses for variation in inputs and environmental conditions for 2004–05 and in the long-term can be used with confidence.

Crop phenology

It was not possible to assess accuracy of phenological predictions for the 2004–05 crop as observed data were not available for comparison of predicted time to anthesis and physiological maturity (80 and 144 days from sowing). In the model, time to anthesis is based on completion of leaf expansion and physiological maturity is based on thermal time schedules, the completion of which coincides to black layer formation at which grain remains at around 30% water. However, the accuracy of prediction of grain yield and components of yield (grain size and grain number) is some evidence that the phenological predictions are reasonable, as prediction of dry matter accumulation and yield relies principally on crop duration, radiation interception and use and dry matter distribution according to physiological principles (APSRU 2003). As there was little improvement in predicted yield in 2004–2005 and no yield improvement but a greater risk of lower yield using later maturity types in long-term simulations due to lower temperatures and less radiation during the predicted grain filling period, there is no justification for selecting longer season cultivars. The shorter season cultivar type (less leaves) had similar PY to Pioneer 3355. Hence, the cultivar used in 2004–05 was around the optimum for the sowing date used, but using a slightly shorter season cultivar can be justified.

Sowing date

As sowing date did not affect yield to any extent until after 16 October 2004 in the single season assessment, temperature and radiation conditions provided a relatively wide sowing window in 2004. However, over the long-term, sowing between 21 September and 1 October for cultivars of CRM near 113 days are indicated, though sowing on 26 October produce similar predicted yields and should also be considered. Less favourable outcomes for the remaining sowing dates appear to be related to exposure to a greater number of days on which high temperatures occur during late vegetative and reproductive stages during January and February when highest maximum temperatures at Boort occur (10% of years maximum temperature exceeds 38°C, Bureau of Meteorology 2007). For cultivars of shorter or longer duration, reassessment of optimum sowing time would be necessary. It would be unlikely to be earlier, unless cold tolerant cultivars were introduced, due to low temperatures in early spring but could extend later for shorter season cultivars only.

Plant population

The higher optimum plant population than used in 2004–05 and in recommendations for irrigated maize (Serafin and McCaffery 2002; New South Wales Department of Primary Industries 2004) suggests that available resources were not fully exploited by 8.4 plants/m^2. The higher PY at the higher plant population reflects higher early LAI and extended period of LAI sufficient for full light interception. Higher plant population could partly compensate for adverse effects of high temperature, and would be needed for shorter season cultivars, provided all other inputs were non-limiting.

Nitrogen rate

The optimum rate, assuming 60 kg NO_3-N/ha in the soil at sowing is around 350 kg/ha. The limited variation in PY at each N rate reflects variation in temperature and radiation, not an inherent N effect. However, PY at suboptimal N inputs will have been over predicted as RUE was not reduced for low concentration of N in the leaf (Muchow and Davis 1988; Vos *et al*. 2005), while leaf area and hence light interception has been maintained by the model. The latter is reasonable except for severe N deficiency, as maize is conservative of leaf area under suboptimal N supply conditions (Vos *et al*. 2005). The analyses indicated that some reduction in N rate from that used in 2004 was possible provided management practices favoured high N use efficiency. However, for a higher plant population with higher potential yield, an N rate near 400 kg N/ha would be required to meet the extra demand. An issue though is nitrogen use efficiency, which, while beyond the scope of the analysis completed here, must be considered. Also, economic optima could differ according to nitrogen fertiliser price and value of grain, and would need to be assessed in each crop year. The analyses completed here indicate that additional analyses with differing N application strategies than used here are required to provide guidance on those that may both improve nitrogen use efficiency and economic returns for N fertiliser use.

Irrigation

The limited effect of differing starting soil water conditions and irrigation scheduling on the basis of water consumption to 60 mm deficit for starting soil water conditions of 45% PAWC or more can be explained by the high water holding capacity of the soil. The lowest of the starting water conditions (15%) and only irrigating to rewet to this level produced frequent short-term stress despite frequent irrigation, detailed output showing inadequate water supply from 50 to 130 days after sowing restricting LAI and final yield. It is an unrealistic option for the site, but could indicate crop performance in soils with low PAWC or restricted rooting depth.

With initial PAWC at 30% of profile capacity and irrigating to this level, frequent irrigation produced quite a high median PY, with only short periods of inadequacy of water supply. Overall, provided the profile is filled to 45% or more, irrigation on schedules up to 60 mm deficit had little effect on PY. At the higher initial PAWC and irrigating at the deficits shown, only limited short-term water stress was predicted, mostly after 60 days after sowing, hence leaf expansion and processes that rely on leaf area were not restricted much if at all. Consequently, there was a relatively narrow range from 30 to 70 percentile PY, which also include effects of environmental conditions over the long-term as well as any short-term water stress. Therefore, ensuring PAWC exceeds 45% at sowing by irrigating to this level, if necessary, would be a sound production strategy, but total irrigation requirement would exceed the long-term requirement of around 7.5 ML/ha for sowing to maturity.

Further, for a higher plant population, increased transpiration would occur earlier in crop life due to higher LAI and earlier canopy closure. Also, higher LAI may persist for longer during grain fill in cultivars with ‘stay green’ characteristics, adding to water consumption and irrigation requirement.

Temperature and radiation

Temperature and radiation were examined independently and in combination to generate differing thermal and/or radiation environments. Differing thermal environments could represent cooler or warmer locations or global warming, while differences in radiation could represent seasonal differences due to cloud cover or differing latitudes.

Predicted crop failure when daily mean temperatures were reduced by 3°C or more could be attributed to frost damage or low soil temperatures preventing germination and establishment, as predicted crop duration was <45 days, with predicted biomass insufficient to indicate successful crop establishment when using changes to 2004–05 temperature data. Long-term analyses showed increasing risks at temperatures more than 1°C lower than observed values, with crop failure for the reasons proposed above being the most likely outcome at 3°C or more below the observed values. Even in current climates, there is an occasional frost during September and October (Bureau of Meteorology 2007); hence, moving to a lower temperature environment and sowing during September (especially) and October will increase the risk of frost and low temperatures during establishment. Clearly, in cooler environments, a cultivar of shorter duration and, if possible, greater cold tolerance would be needed. Alternatively, maize could be sown later and grown for silage as in northern Europe which has a very short season and completion of grain filling unlikely due to temperature limitations (Birch and Vos 2000). Higher than observed temperature reduced real time duration of the crop, hence less total radiation can be intercepted leading to lower total dry matter accumulation and lower PY. Other factors would include reduced individual and total plant leaf area (Thiagarajah and Hunt 1982), In this study, changes in daily mean temperatures did not include potential changes in diurnal patterns of temperature – different predictions may ensue if, for example, the proportional change in minimum and maximum temperatures differed from those used here.

The lack of improvement in PY when higher radiation was used indicates that radiation conditions were non-limiting under the agronomic and other environmental conditions of 2004–05. When examined in long-term factorial simulations, temperature effects dominated those of radiation, indicating that higher radiation did not compensate for the impact of higher or lower temperature. It may be argued that higher RUE could partly or wholly compensate for changes in temperature. However, RUE used here was high for optimum input conditions (Lindquist *et al*. 2005), so increasing RUE may need to be a long-term plant improvement objective. It may also be possible to partly compensate for temperature effects by increasing plant population to increase total plant leaf area.

Temperature and sowing date

Temperature was dominant of these factors, and showed increasing production risks under increasing temperature for all sowing dates. This effect and the greater reductions in yield than for sowing date only are attributed to shortening of real time duration of the crop at higher temperatures, and again point to the need for higher plant populations to compensate.

Conclusions

The ability of the model to predict grain yield accurately for 2004–05 based on environmental conditions and production inputs used in that year means that the model has effectively been validated for high input, high yield conditions, and can be used with confidence for such circumstances, for both single year and long-term analyses with confidence.

The analysis showed that the yield achieved commercially in 2004–05 was close to the maximum possible for the plant population and other agronomic practices used and the environmental conditions of that year. Higher yield may have been achieved if a higher population had been used. The analysis indicated that a slightly lower rate of nitrogen could have been used (assuming 60 kg NO_3-N/ha available in the soil at sowing), but would of course depend on initial soil supply. It also indicated that ~1 ML/ha less water than used in 2004–05 (7.5 ML/ha) would be required in 50% of years, the use in 2004–05 being in the upper end of predicted irrigation requirements. That higher optimum plant populations than used in 2004–05 were indicated also indicates that additional analyses using higher plant populations combined with other single factor effects investigated are required. It would be expected that higher inputs, particularly of nitrogen and irrigation would be required to meet the demands of the higher yields and higher transpiration that would occur earlier in a higher population crop. Also, in the irrigation analysis, the deficits used were chosen to represent those that could represent trickle irrigation. Additional analyses with greater deficits designed to represent other methods of irrigation would be informative. Predicted yields declined sharply for lower temperatures, but less so for higher temperatures, while changing radiation had little effect. Additional analyses with a wider range in values of some variables and more combinations of inputs are indicated to gain further understanding of optimisation of inputs.

Further, the analysis demonstrates the utility of modelling as a tool for retrospective analysis and identifying where improvements in a production system could be achieved, and for prediction of the impact of changes to production practices. There are also opportunities for additional analyses to enhance understanding of the response of the production system to changes that might be made. The output could then be used in other applications, for example to assess differing irrigation and nitrogen application strategies and in economic analyses of options.

Finally, the retrospective analysis of a crop system by use of the model provides insights into production practices that can be used in future decision making. Meanwhile, the long-term analyses provide measures of variability, thus quantifying risk and identifying boundaries to the production system that can be incorporated in enterprise and industry management, or even point to where adaptations through, for example, plant breeding for cooler or warmer environments as indicated here could be made.

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Manuscript received 16 March 2006, accepted 7 August 2007