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Prediction of weather damage of mungbean seed in tropical Australia. II. Model application

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Abstract. To demonstrate a model to simulate the risk of weather damage of mungbean, application studies were undertaken using 27 years of climatic data collected at Katherine, Northern Territory, Australia. In terms of the risk of weather damage, the transition from high risk to low risk occurred after mid-February but before 20 March. High quality seed could be expected in 70% of seasons for a crop that matured after 20 March. For planting dates prior to 25 January, the chance of producing premium quality seed was enhanced to 40–70% of seasons by sowing a cultivar that matured 2 weeks later and by harvesting promptly (4 days after maturity). There was no benefit from later maturity or harvest promptness where sowing was made after 25 January, because maturity occurred after the wet season was complete. In contrast, yield was optimised at early January sowing dates. Calculating gross margins by combining yield and weather damage simulations identified an optimum sowing date between the optimum for yield and seed quality. It was shown that later maturity combined with photoperiod sensitivity increased the sowing window from 10 to 29 days compared with a short duration variety that was insensitive to photoperiod. The relative merits of modelling and field experimentation in assessing the cropping potential for mungbean in a new region are discussed. The need to be able to simulate the yield of the second flush of flowers was acknowledged as a future research requirement.

Additional keywords: crop simulation models, seed quality, climatic risk.

Introduction

The areas of the Australian monsoon tropics that could potentially grow dryland mungbean, *Vigna radiata* (L.) Wilczek, have an annual rainfall between 600 and 1100 mm, and distinct wet and dry seasons (Garside *et al.* 1985; Yeates 1991). Between the wet and dry seasons, there is a transition period where the frequency of rainfall either declines or increases with time, depending on which season has finished (Slatyer 1960). To avoid weather damage to seed, a mungbean crop must be sown so that it matures toward the end of the transition from the wet to the dry season. However, to maximise yield, grain fill must occur early in the seasonal transition, a time when the likelihood of rainfall is good. Therefore, to optimise the conflicting requirements for yield and quality in this variable climate, economic returns need to be calculated for different maturity dates and cropping seasons. Combining the simulation of weather damage with yield using historic weather data should better permit the calculation of likely economic returns.

It has been proposed that a late-maturing, photoperiod-sensitive cultivar should avoid weather damage and permit earlier sowing in the Australian monsoon tropics (Imrie and Putland 1982; Yeates and Imrie 1993). However, in a variable climate, it will take many seasons of field experimentation to quantify the effects of later maturity on seed quality and yield. A challenge for simulation models capable of predicting weathering and grain yield for varieties of differing phenology is to demonstrate that, when combined with historic climatic data, the need for prolonged field experimentation is reduced.

The previous paper in this series (Yeates *et al.* 2000) determined the way in which weather affects both preharvest seed quality and the timing of crop maturity in mungbean. For tropical Australia, a model was developed which

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enabled the prediction of reproductive development and seed quality from weather data inputs. This model can now be combined with a yield simulation model developed independently for mungbean (M. J. Robertson *et al*. unpublished data) and the likely economic loss through poor yield and weather damage measured.

In Part 1 of this series (Yeates *et al.* 2000), it was hypothesised that the over- or under-prediction of weather damage, due to errors in the prediction of crop maturity, would be counter-balanced by making simulations over a large number of years provided that no consistent over- or under-prediction occurred. The maximum error in predicting maturity was 5 days. To test the above hypothesis, the percentage of weathered seed can be simulated for crops maturing at consecutive 5-day periods over the growing season. The hypothesis can be assumed to be valid if the variation in the mean percentage of weathered seed is similar between adjacent 5-day periods.

In this paper, the sensitivity of the weather damage model to maturity date prediction is tested. The model is also applied to determine the duration of the seasonal transition at one location. The weather damage model is then combined with a yield simulation model to show the effect that selected management practices, such as sowing date, cultivar maturity, and harvest promptness, might have on mungbean seed quality, grain yield, and economic return.

Materials and methods

Description of pre-harvest weather damage model

The methods for predicting seed quality of cv. King as a result of pre-harvest weather damage are described in detail in the previous paper of this series (Yeates *et al.* 2000). In summary, seed was susceptible to damage by weather after physiological maturity (pods black). Seed quality reflected visual symptoms of weather damage expressed as the percentage of undamaged seed. A minimum exposure to rainfall was required before seed quality was reduced. After this minimum was exceeded, the effect of additional rainfall was cumulative and the percentage of unweathered seed declined proportionally until a maximum exposure where all susceptible seed was weather damaged. The percentage of unweathered seed could be expressed as either a function of the cumulative duration of rainfall events (min) or the sum of rainfall events ($\geq$ 0.5 mm) calculated from the first ripe pod. The linear decline in the percentage of unweathered seed was predicted using multiple regression combining the cumulative duration of rainfall and the standard deviation of evaporation. Alternatively, combining the sum of rainfall events with the standard deviation of evaporation and mean daily solar radiation and was also highly correlated with weather damage.

Asyncronous ripening of pods necessitated prediction of the proportion of ripe pods when rain occurred. This required the prediction of two growth stages, the occurrence of the first ripe pod and when all pods were ripe. In the first paper of this series (Yeates *et al.* 2000), our approach to predicting the timing of these development stages was empirical because we had assumed the seed quality model could adopt functions that were being developed separately for the mungbean yield model. This was not the case; only time-to-flowering and harvest maturity were predicted and these used thermal time summations (M. J. Robertson *et al.* unpublished data). Consequently, reproductive development was predicted using the functions developed previously (Yeates *et al.* 2000). The duration of the development phases, sowing to first flower, first flower to first ripe pod, and first flower to the end of crop ripening, was predicted for seed formed by the first flush of flowers using a combination of photothermal and moisture variables. The duration of each phase (n) was calculated by integrating the daily rate of development over the phase (1/d) where the last day of the phase is:

$$\int_1^n (1/d)\,dt = 1$$

The percentage of seed that was ripe on any day during ripening was then calculated as a proportion of the pod-ripening phase completed.

Climatic data

The simulation of crop grain yield and seed weather damage required daily records of maximum and minimum temperature, relative humidity, daily rainfall, class A pan evaporation, solar radiation, and/or duration of rainfall. Except for duration of rainfall, data covering 27 wet seasons (1966–67 to 1992–93) recorded at Katherine Research Station (latitude 14º28′ S, longitude 132º18′ E), Northern Territory (NT), Australia, were available to demonstrate the weather damage model. However, because pluviograph data had not been collected the weather damage model used the functions dependent on rainfall events as described in paper I of this series (Yeates *et al.* 2000).

Application studies

(i) Model sensitivity to the prediction of time to maturity

Simulation of the percentage of seed that was unweathered was made for consecutive 5-day periods from 22 January to 28 April, for the 27 seasons on record. It was assumed that the first exposure to rainfall occurred after the completion of ripening, and harvest occurred at the end of the fifth day.

(ii) Identifying the optimum maturity date for seed quality

The objective of this analysis was to identify the optimum date for the commencement of crop maturity. Crop development was not predicted. It was assumed that it took 10 days for the crop to ripen (the average for cv. King, Yeates *et al.* 2000), and that harvest was made 4 days after the completion of ripening. Eight ripening dates were compared from 18 January to 12 April. The wet-to-dry seasonal transition is most likely during March at Katherine (Mollah 1986). Therefore, during March weather damage was simulated for crops maturing at weekly intervals. The analysis was simplified by reducing the 5 export quality grades to 3. That is, the Premium and No. 1 grades were combined, as seed of either grade is sold for sprouting. Moreover, the price discount is not large (Yeates *et al.* 2000). For similar reasons, the Processing and Stockfeed grades were combined. Unsaleable seed was the third category.

(iii) Evaluation of strategic and tactical crop management practices

Two strategic practices were compared, sowing date and cultivar maturity. Sowing dates were selected such that ripening would commence prior to, during, and after the optimal maturity date identified in the previous analysis. Tactically, the advantage of prompt harvest was assessed. The proportion of unweathered seed was simulated for harvests made 4, 10, and 20 days after maturity (pods from the first flush of flowers).

Grain yield and seed quality were simulated by combining the weather damage model with the crop growth model APSIM-mungbean (M. J. Robertson *et al.* unpublished data). The APSIM model framework is described by McCown *et al.* (1996), and requires soil characterisation data. The soil type used in these simulations was the same as described in the previous paper of this series (Yeates *et al.* 2000) and is typical for the area. Essential soil characterisation data, plant-available

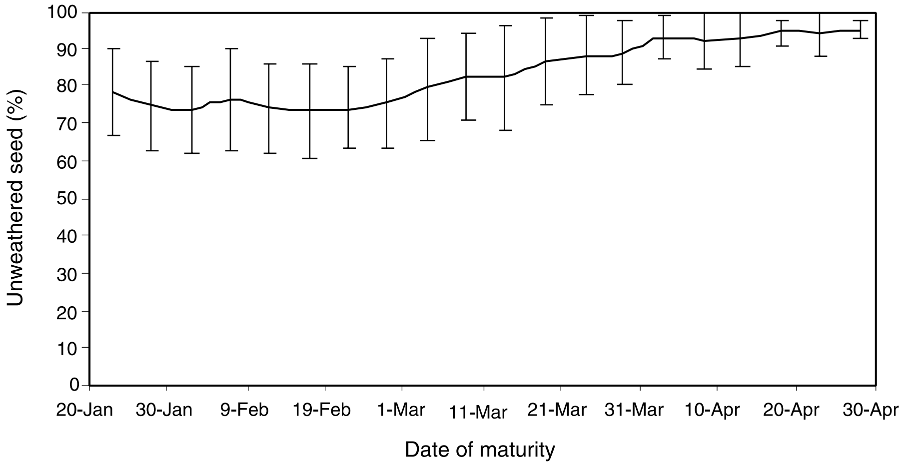

Fig. 1. Sensitivity of the weather damage model to errors of 5 days in the prediction of maturity. The mean unweathered seed (%) and standard deviation (error bars) are shown for simulations made for the 27 years from 1967 to 1993 at Katherine. For each year, the unweathered seed (%) was simulated for seed exposed to weather for 5 days after the date of crop maturity.

water content, and bulk density were measured by Carberry *et al.* (1996). Planting was simulated by assuming as a sowing criterion that planting occurred any day within each 10-day window, if at least 30 mm of accumulated rainfall occurred over the previous 3 days. For each sowing window and season of yield simulation, it was assumed that sorghum was sown in the preceding season and mungbean was sown zero-till into 1.5 t/ha of stubble. Soil water was initialised at 10% of plant-available, 4 weeks prior to each sowing window. Each variety was sown at its recommended density, 40 plants/m^2 for cv. King (Yeates *et al.* 1988) and 20 plants/m^2 for cv. Putland (Yeates *et al.* 1992). Row spacing was 0.36 m. Weather damage simulations were made using the SAS programming language. To compare cultivars of differing maturity, weather damage and yield were simulated for the early-maturing cv. King and for the late-maturing cv. Putland. For cv. Putland, seed weather damage was simulated assuming susceptibility to weather damage identical to cv. King.

Gross margins were calculated by combining simulated yield and quality. A grading loss of 15% and a harvest loss of 12% were assumed. Prices for each quality grade were: sprouting $AU700/t; number 1 $595/t; processing $450/t; and stockfeed (including grading loss) $220/t. All prices were delivered to Brisbane except for stockfeed which was sold locally. Variable costs were $188/ha, and per tonne costs $173/t for export grades and $30/t for stockfeed (from Hirstova 1998 and Kirby *et al.* 1996).

Validation of yield model

APSIM-mungbean (M. J. Robertson *et al.* unpublished data) had been previously validated for south-east Queensland (Robertson *et al.* 2000) and in the NT for both cultivars using data independent to this study (Carberry 1996). To confirm the effect of sowing date on yield, a further validation was made using additional independent data collected at Katherine over the period 1984–1990, which is described by Yeates and Imrie (1993). For each sowing date, grain yield was simulated using the same climatic data and crop husbandry as the field experiments.

Results

Sensitivity analysis – prediction of time to maturity

Where maturity occurred prior to mid-April, variation in the percentage of unweathered seed was similar for consecutive 5-day ripening periods (Fig. 1), suggesting that it is unlikely that seed weathering predictions would be sensitive to errors of 5 days in the prediction of time to ripening.

Optimum maturity date selection

In terms of the risk of weather damage to seed, the seasonal transition occurs over a 3–4 week period between the middle of February and 20 March (Fig. 2). Where crop ripening commenced prior to 8 March, the probability of weather damage to seed was high, and seed was more likely to be downgraded to stockfeed or processing quality (Fig. 2). Where ripening commenced on or after 8 March, sprouting quality seed would be the most likely outcome. However, ripening must commence on or after 22 March for at least a 70% chance of producing seed of the highest quality (Fig. 2). It is clear that if maturity commences at the end of this period, that is 22 March, there would be considerable reduction in the risk of weather damage to seed. However, reduced grain yields are likely if sowing date is delayed such that maturity occurs after 22 March (Yeates and Imrie 1993).

Yield model validation

The effect of sowing date on yield was predicted with acceptable accuracy (Fig. 3). Simulated yields of cv. King at late January sowing dates were higher than observed, although the difference was within the average least significant difference ($P < 0.05$) measured for the observed data (Fig. 3). The model may slightly under-predict yields of cv. King at an early January sowing because yield from the second flush of flowers is not simulated by APSIM-mungbean (M. J. Robertson *et al.* unpublished data). Under-prediction of yield is not likely to have occurred in the seasons used in this analysis because end-of-season rainfall (March) was below

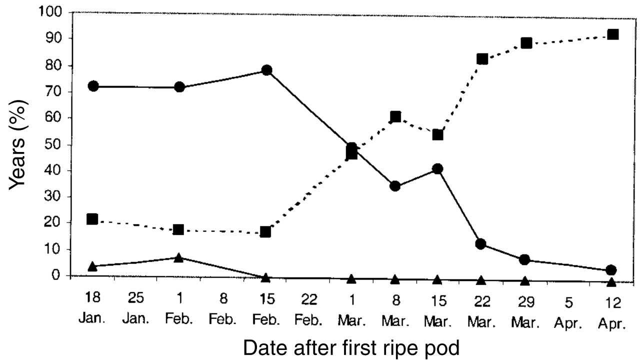

Fig. 2. Effect of the date when the first pod ripens on the likelihood of producing high quality (premium and No. 1 grade, --■--), marketable lower quality (processing and stockfeed —●—, and unsaleable seed —▲—).

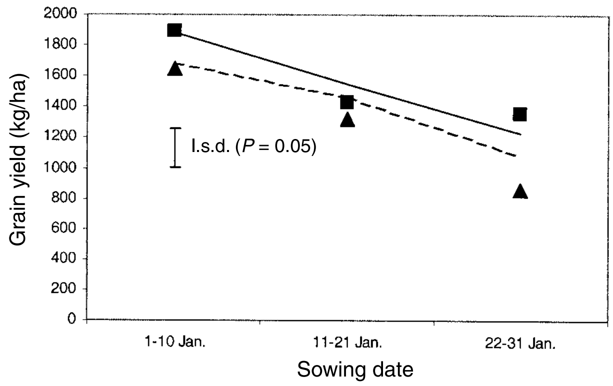

Fig. 3. APSIM-mungbean model validation for the effect of sowing date on yield at Katherine. Observed yields as shown in Yeates and Imrie (1993). cv. King: observed yield ▲, predicted yield (--); cv. Putland: observed yield ■, predicted yield (—). Least significant difference for the observed data is shown.

Table 1. Percentage of years where sowing was possible at Katherine for the 27 years from 1967 to 1993

A sum of 30 mm of precipitation over 3 days was defined as the sowing 'rule'

Sowing period	Years where sowing rule was met (%)
26 December–4 January	74
5–14 January	67
15–24 January	70
25 January–3 February	67
4–13 February	89
14–23 February	63

average. Consequently, growth of the second flush of flowers would have been constrained by moisture stress.

Evaluation of strategic and tactical crop management practices

For the majority of planting times, conditions defined as suitable for sowing were met in approximately 2 of 3 years

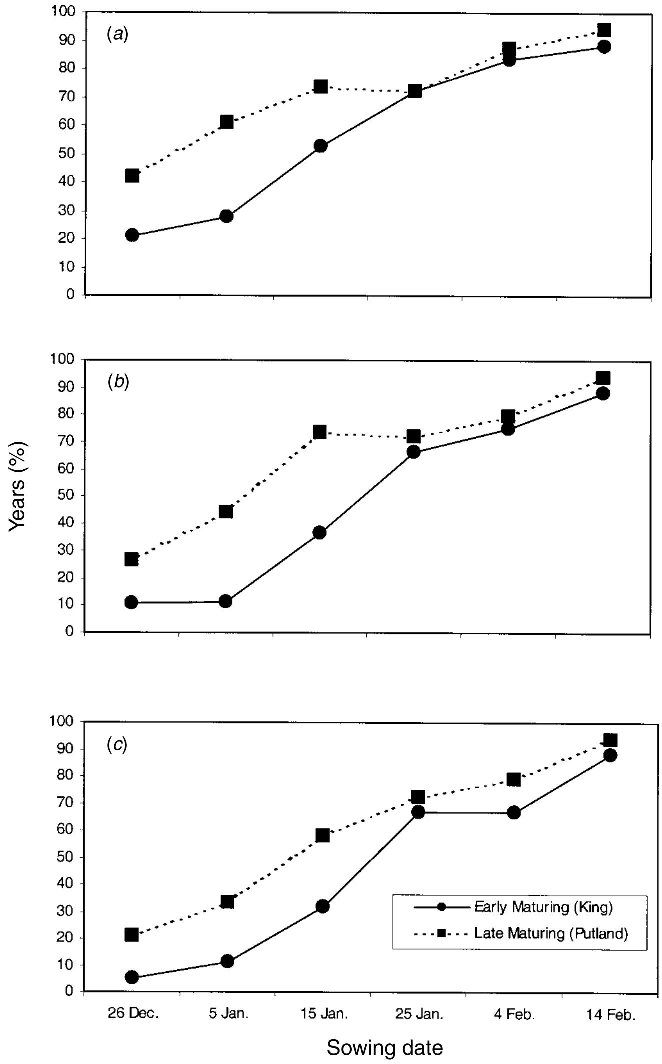

Fig. 4. Effect of sowing date and cultivar maturity on the percentage of years where simulated seed quality was unaffected by pre-harvest weather for harvests made (*a*) 4 days, (*b*) 10 days, and (*c*) 20 days, after the maturity of the pods from the first flush of flowers at Katherine for the period 1967–1993.

(Table 1). In years where sowing was not possible, a later planting date would have to be considered. That is, seed weathering or grain yield was not simulated separately in the years where sowing was delayed. In the present analysis, seed quality and yield were only simulated in the years where the sowing rule was met. However, it could be assumed that the probabilities of weather damage or yield outcomes would be similar in each analysis.

The effect of planting date, cultivar maturity, and harvest promptness on the likelihood of producing high quality mungbean seed is presented in Fig. 4. Where sowing was made on or after 25 January, the effect of cultivar maturity or harvest promptness was minimal. This is because a crop sown at this time would mature after 20 March, when the probability of weathering is low (Fig. 2). Where sowing was undertaken prior to 25 January, cultivar maturity and harvest promptness were of greater importance. A late-maturing cultivar greatly improved the chance of producing premium quality seed. The consequence of harvest delay was more dependent on sowing date than cultivar maturity. Harvest promptness was most beneficial where maturity occurred during the seasonal transition (early to mid-March), that is, sowing during 5–14 January for the late maturing cv. Putland, and 15–24 January for cv. King. During the seasonal transition, rainfall events can be interspersed with dry weather (Slatyer 1960), and therefore, it is possible for a crop to ripen between rainfall events. In this situation only a delay in harvesting will result in weather damage to seed.

The effect of sowing date on simulated yields was, as expected, the reverse of seed quality (Fig. 5) and in agreement with experimental data (Fig. 3). That is, yield was maximised at early January sowing dates and declined roughly linearly as sowing progressed to late February. Variability of yield in cv. Putland was generally greater than cv. King due to a combination of later maturity and a higher yield potential.

Gross margins calculated by combining yield and seed weathering simulations for each season and sowing date are shown in Fig. 6. Calculation of gross margins permits evaluation of the trade-off between yield and quality when selecting a sowing date. For cv. Putland gross margin was maximised at sowing dates (5 January–3 February) that were between the optima for yield and seed weathering (Figs 3 and 5). A similar result was observed for cv. King except that the optimum sowing period was smaller, 25 January–3 February. Interestingly, for cv. King this optimum sowing period is 10 days later than that recommended for the variety based on the results of small plot trials (Yeates *et al.* 1988). Lower yields and a high likelihood of severe weather damage, due to early maturity, dramatically reduced gross margins for cv. King sown during late December and early January compared with cv. Putland. The longer sowing window found for cv. Putland is due to the combined effects of later maturity and photoperiod sensitivity that reduce the chance of seed weathering (Fig. 4), and a higher yield potential at sowing dates prior to 24 January (Fig. 5).

Prompt harvest produced the greatest increases in gross margin at sowing dates prior to 24 January (Fig. 6). By accounting for yield, simulation of gross margins produced a different interpretation of the effect of harvest delay than did simulation of seed quality alone (Figs 4 and 6). Harvest promptness was of most benefit where maturity occurred prior to the seasonal transition, that is, sowing prior to 5 January.

Discussion

This analysis demonstrated the utility of the seed weathering model in quantifying the climatic risks associated with the production of high quality mungbean seed. Combining seed quality and grain yield simulations is novel and permitted an economic analysis of strategic and tactical aspects of mungbean production in a variable climate such as tropical Australia.

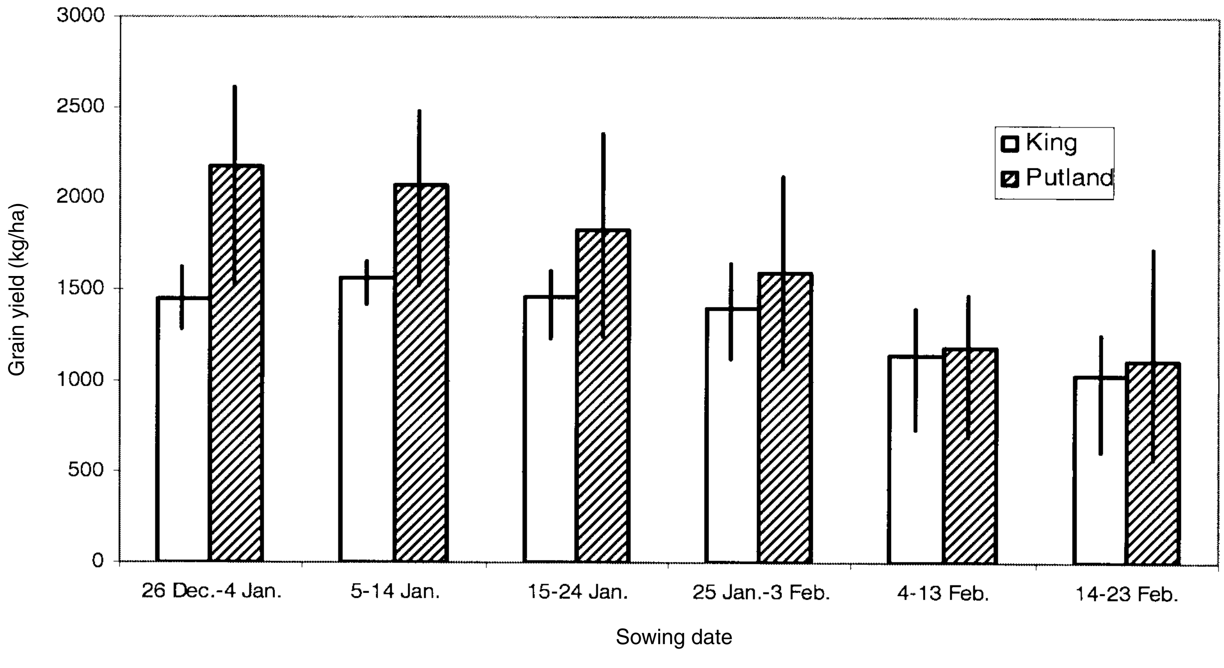

Fig. 5. Effect of sowing date on mean simulated grain yield at Katherine, from 1966 to 1993. Bars show yield range for middle 20–80% of seasons.

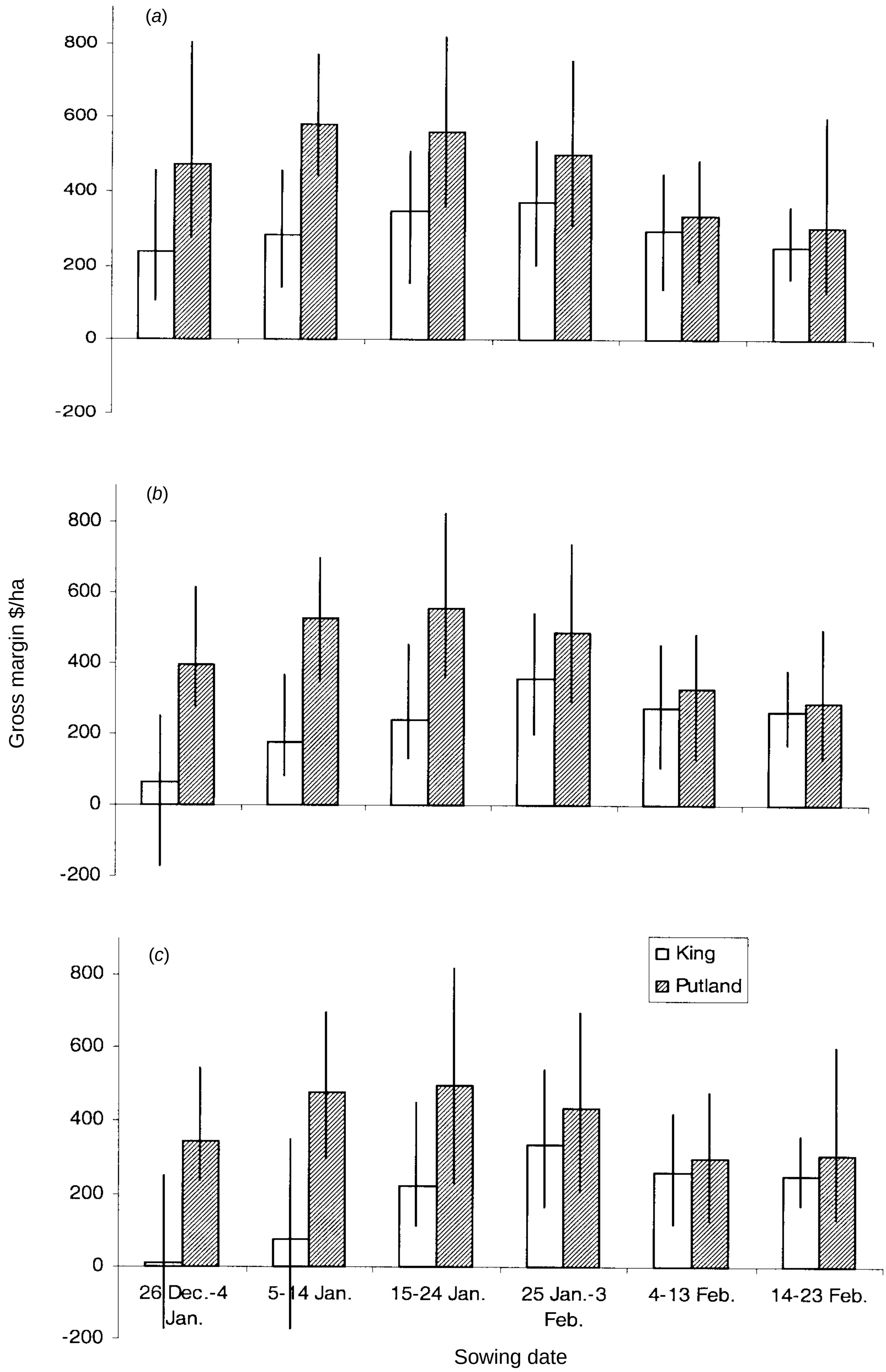

Fig. 6. Effect of sowing date and harvest promptness on simulated gross margin at Katherine from 1966 to 1993 inclusive for harvests (*a*) 4 days, (*b*) 10 days, and (*c*) 20 days, after the maturity of the pods from the first flush of flowers. Bars show yield range for middle 20–80% of seasons.

This study forms part of a broader objective to assess the cropping potential for mungbean production in a new growing region, tropical Australia. The analysis described above showed that operational research, based on simulation models, was effective in optimising sowing date, crop phenology, and potential economic returns. This type of analysis can also complement field experimentation in a variable climate. The discrepancy between the optimum sowing date identified by the simulation analysis compared with field experimentation highlights this point. The sowing date recommendation for Katherine (Yeates *et al.* 1988) was based on field experiments conducted over 3 consecutive wet seasons (Putland and Buchanan 1988). It would appear that 3 seasons of field experimentation was insufficient to account for long-term seasonal climate variability. However, simulation analysis could not replace the requirement to breed a late-maturing and photoperiod-sensitive variety, which required field experimentation over many years (Yeates *et al.* 1992).

The sensitivity of seed quality simulation to the accuracy of prediction of time to maturity was not critical where simulations were made over many seasons using historic climatic records. Larger differences between the variability in weather damage simulated for consecutive 5-day exposure periods reflected the high seasonal variability that is associated with the low frequency of rainfall late in the wet season (Fig. 1). On average, there are only 2 wet days during April (Slatyer 1960; Cook and Russell 1983). Therefore, these errors would have only a minor consequence because, in all but a few seasons, seed would be unweathered on a crop that matures at this time of year (Fig. 1). Moreover, simulation using climatic data covering a longer period than was used in this analysis would be expected to further reduce variability between 5-day periods.

Seed quality and yield was not simulated for seed formed by the second flush of flowers. Omission of the seed from the second flush of flowers would have no effect on the above simulation studies where harvest was prompt, because the seed from the second flowering would be unlikely to commence ripening until about 15 days after the pods from the first flush of flowers had ripened (Yeates *et al.* 2000). However, where harvest occurred 20 days after the seed from the first flush of flowers had ripened, some seed from the second flowering could be expected to have ripened, and the simulations would slightly under-predict the proportion of unweathered seed and the grain yield. The yield contributed by the second flush of flowers would be expected to be greater in cv. Putland than cv. King (Yeates and Imrie 1993). Inclusion of the seed produced by the second flush of flowers in simulation studies would require enhancement of the APSIM-mungbean yield simulation model.

The weather damage model requires class A pan evaporation to simulate seed quality. The class A pan is the most common method used to measure evaporation and is frequently used in the simulation of crop water use (Hatfield 1990). However, at the same location, the correlation between different pans has been found to be poor (Watts and Hancock 1985). Therefore, the simulation of seed quality using evaporation data collected from pans other than the one used in this study may produce errors. To overcome the poor correlation between evaporation pans would require simulation of evaporation as measured by the Katherine pan (e.g. Hearn and Constable 1981), or the calculation of evaporation directly using a formula (e.g. Doorenbos and Pruitt 1977).

Expanding this analysis throughout tropical Australia (13° to 17°S) would be of considerable value to farmers and planners. For farmers, the model analysis would assist the strategic and tactical decision-making process. For planners, the potential for expansion of a mungbean industry in the Australian monsoon tropics could be assessed, identifying new regions where expansion might occur, and the location and provision of infrastructure (e.g. grading plants, roads) could be planned for.

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