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Prediction of weather damage of mungbean seed in tropical Australia. I. Relation between seed quality, weather, and reproductive development

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Abstract. Assessment of the potential for mungbean cropping in the Australian monsoon tropics required a model that could predict pre-harvest seed quality from long-term climatic data. Empirical relations between seed quality and pre-harvest weather were developed from field-grown mungbean using 22 sowings over 3 seasons. 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 decreased proportionally until a maximum was reached whereby all susceptible seed was weather damaged. The percentage of unweathered seed was best predicted as a function of the cumulative duration of rainfall events. Exposure to at least 300 min of rainfall was required before seed quality was downgraded. Exposure to 4000 min of rainfall was required to reach the maximum threshold. The linear decline in the percentage of unweathered seed was accurately predicted with independent data (r^2 = 0.84) by a function that combined the cumulative duration of rainfall and the standard deviation of evaporation. This function reflected the weathering process, that is, cumulative exposure to moisture and the extent of drying of the atmosphere between rainfall events. Alternatively, where pluviograph data were unavailable, combining the sum of rainfall events (>0.5mm) with the standard deviation of evaporation and mean daily solar radiation was also highly correlated with the proportion of unweathered seed; accurate predictions were made using independent data during crop ripening (r^2 = 0.93) and after ripening (r^2 = 0.72). Weather damage was sensitive to the timing of reproductive development relative to rainfall; adjusting climate variables for cohort-specific exposure removed the confounding effects caused by the daily ripening of pods. Time to flowering was accurately predicted, 2–3 days from observed, using mean daily photoperiod and temperature. As expected, rate of progress from flowering to the first ripe pod and crop maturity was dependent on photoperiod, temperature, and moisture availability. The proportion of pods ripe on any day was highly (P < 0.01) correlated with the proportion of the pod-ripening phase completed.

Additional keywords: climatic risk, crop simulation models, operational research.

Introduction

Mungbean (*Vigna radiata* L. Wilczek) is a potential crop for the Australian monsoon tropics. It is adapted to the 600–1100 mm annual rainfall areas and there is good consumer demand for mungbean products in nearby Asia (Garside *et al.* 1985). Good seed quality is important in order to maximise profits from mungbean, as human food is the major use for the crop (Williams *et al.* 1995*a*). However, the expansion of mungbean production into the Australian monsoon tropics is seriously constrained by the risk of pre-harvest weather damage, which reduces seed quality (Imrie and Putland 1982; Yeates 1991).

In a controlled environment, where temperature was constant, weather damage to mungbean seed was caused by the cumulative effect of cycles of atmospheric wetting and drying between physiological maturity and harvest (Williams *et al.* 1995*a*, 1995*b*). However, in the field environment, for most crops, little is known of how different meteorological measures of atmospheric moisture contribute

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to pre-harvest weather damage. High temperature, relative humidity, and rainfall have been associated with weather damage in a range of crops (Woodruff *et al.* 1967; Mondragon and Potts 1974; TeKrony *et al.* 1980; Andrews 1982; Powell *et al.* 1984; Keigley and Mullen 1986), including mungbean (Lawn and Russell 1978; Imrie 1983; Lassim *et al.* 1984).

There are no cultivars adapted to the Australian monsoon tropics that have resistance to weather damage (Yeates 1991). Therefore, the optimum date for maturity is a balance between sowing early to ensure rainfall for grain production and sowing sufficiently late to avoid poor seed quality due to rainfall and high humidity prior to harvest (Putland and Buchanan 1988*b*; Yeates and Imrie 1993). However, as the end of the wet season is a period of extreme rainfall variability (Mollah 1986), many seasons of field experimentation are required before it is known if this strategy can reliably produce stable yields of high quality seed. Such an analysis is possible using an operational research approach, whereby crop simulation models are used in conjunction with historic climatic data to predict economic returns and their associated risks (McCown 1989). This approach has been used elsewhere (Huda *et al.* 1991; Carberry *et al.* 1996). A seed quality model of mungbean was not available, although a crop growth model had recently been developed and tested (Robertson *et al.* 2000*a*, 2000*b*).

A predictive model of seed quality should relate measures of atmospheric moisture (e.g. rainfall, relative humidity) to the progress and degree of seed weathering. A model of seed quality should also use a measure of weather damage that reflects the market value of the seed. Within a mungbean genotype there is a strong association between visual changes in seed morphology and exposure to a weathering environment (Lassim *et al.* 1984; Williams *et al.* 1995*a*, 1995*b*). However, the quality of mungbean seed is determined using a combination of seed morphology and vigour (Law and Law 1991).

In mungbean, pod ripening is not synchronous and flowers, developing pods, and ripe pods can occur on a plant at the same time (Matsunaga *et al.* 1988). The extent of weather damage is dependent on the proportion of pods that are mature when exposed to a weathering environment (Imrie 1983). Therefore, a model to simulate weathering must be able to predict the timing and duration of reproductive development.

Mungbean is classified as a quantitative short-day plant in which both temperature and photoperiod combine to influence time to flowering (Summerfield and Lawn 1987, 1988; Imrie and Lawn 1990). The time from flowering through pod ripening to harvest maturity is known to be modulated by temperature and photoperiod (Lawn 1979; Matsunaga *et al.* 1988) and available moisture (Lawn 1982; Muchow 1985; Pandey *et al.* 1988; Sadasivam *et al.* 1988). However, attempts to account for the effect of moisture when predicting time to maturity have been empirical and confined to a few studies with other legume crops such as peanuts and soybeans (Brown and Chapman 1960; Dwyer and Stewart 1987; Ketrig and Wheless 1989).

Thus, the primary objective of the work reported here was to develop relations that could be used with historic climatic records to simulate the pre-harvest seed quality of field-grown mungbean. These could later be combined with a crop growth model to predict economic returns for potential production regions within the Australian monsoon tropics. A secondary objective was to predict the timing of reproductive development with sufficient accuracy to demonstrate the seed quality model independently of a growth model if needed. Therefore, our approach to predicting reproductive development was empirical because we had assumed the proposed growth model would incorporate a solid physiological basis for predicting reproductive development.

Materials and methods

Relation between seed quality and weather

Experiments were located at the CSIRO Katherine Research Station, 4 km east of Katherine (14°28′S, 132°18′E), Northern Territory (NT), Australia. The soil was a loamy red earth of the Tippera family (Gn 11) (Aldrick and Robinson 1972). Mungbean was sown on 22 occasions over 3 wet seasons (1989, 1990, 1992). A range of sowing dates was selected covering the period from 11 December to 28 February. The mungbean cultivars King and Putland were sown on all occasions. King was selected because it has been the most commonly grown cultivar in the NT since 1982 (Yeates 1991). It is early-maturing and has a large seed (Cook 1982). Putland was a newer cultivar bred for tropical Australia. It is late-maturing and small-seeded (Yeates *et al.* 1992).

Experiments were sown with a cone seeder, with seed inoculated with mungbean inoculum at sowing. There were 3 replications of each variety at each sowing date. Plot area was at least 14.5 m^2 and included a minimum of 4 rows (36 cm wide). Land preparation was by conventional tillage in the first season. In the second and third seasons zero tillage was used. Crop husbandry was as recommended for mungbean grown at Katherine (Yeates *et al.* 1988; Yeates and Imrie 1993).

Wherever possible, harvests for seed weathering were made prior to and following precipitation events. In the absence of rain, harvests were made from the centre rows of each plot at 7–10-day intervals. Harvests commenced when 10% of pods per plot were ripe. Plants (3, 10, 5) were harvested from each plot in Seasons 1, 2, and 3, respectively. Ripe pods were defined as having all of their surface black and starting to desiccate (i.e. pods were brittle). Post rainfall harvests were made between 10 00 and 14 00 hours, the exact time being recorded. After harvest all pods were inspected and pods with mechanical damage to walls (e.g. insect or bird damage) were discarded. Ripe undamaged pods were then removed from plants and placed in a drier at 30°C for 48 h prior to threshing. In Season 1, mature pods were removed from each plant in the field and each replicate was placed in individual paper bags and the percentage of ripe pods recorded. Pods were hand threshed after drying in the laboratory. In Seasons 2 and 3, whole plants were harvested then threshed mechanically with a stationary thresher fitted with rubber beaters. The drum speed was 100 rpm, and splitting of seed was negligible (<1 %). Samples were cleaned in a laboratory seed cleaner.

During crop ripening, individual fruit cohorts experience different environmental conditions. Thus, to account for the addition of newly ripe pods, the value for each climatic variable was adjusted so that its cumulative effect was in proportion to the number of pods that were ripe each day. That is, the adjusted value (C_A) for a climatic variable (C) at any day (n) is calculated as follows:

$$C_A = {}_1^n\Sigma\, C{*}P_1/PPR + \ldots\ldots\ldots\ldots + {}_n^n\Sigma\, C{*}P_n/PPR \qquad (1)$$

where P_1......P_n are the percentages of the total pods that ripen on each day and PPR is the percentage of pods ripe on day n.

Only seed from the first flush of pods was used to develop relationships between weather parameters and damage. The pods from the second flush of flowers commenced ripening approximately 15 days after the first flush of pods had competed ripening. The yield of the second flowering is usually considerably less than the yield from the first flowering; however, it varies considerably and cannot be predicted (Yeates and Imrie 1993).

Measurements

The following phenological stages were recorded for each plot: days from sowing to 50% plants having an open flower; first ripe (black) pod on 10% and 30% of plants; 95% of plants with all pods mature from the first flush of flowers; 50% of plants having an open first flower from the second flush of flowers; 10% of plants having a first mature pod from the second flowering; 95% of pods from the second flowering mature. The percentage of ripe pods per flowering was estimated for each plot.

The percentage of weather damaged seed was determined from 50–100 seeds/plot. The method of Williams *et al.* (1995*a*) was used to identify symptoms of weather damage based on changes in seed morphology. All wrinkled, discoloured, cracked, mouldy, and germinated seed was deemed to show weather damage. Seed that was obviously damaged by insects was removed prior to counting the weathered seed. There were only a few instances of insect damage to seed and these were the result of pod sucking insect species (*Nezara viridula* and *Riptortus serripes*). During periods where rainfall occurred over many consecutive days, harvests were frequent and immediate assessment was not possible. Therefore, all samples were dried and stored in a dehumidified seed room at 9°C and visual assessment was made 5 months after each harvest date.

To relate seed quality to changes in seed morphology, seed from 34 harvests of cv. King and 20 of cv. Putland was selected from Season 3. The harvests selected represented a wide range in the proportion of weather-damaged seed. Approximately 300 seeds were taken from each harvest and each visually assessed for seed weathering using the criteria described previously. After visual assessment, samples were immediately (within 4 days) tested using the 'Australian Mungbean Association Methods for Export Quality Assessment' relevant to each cultivar (Anon. 1991). Tests were conducted in the Berrimah Agricultural Research Centre Seed Laboratory, Berrimah, NT.

Daily precipitation data were collected at the site, while daily measurement of pluviograph, maximum and minimum temperature, air relative humidity at 09 00 hours, radiation, and evaporation (Class A pan) were collected by staff of CSIRO at a site 700 m from the experimental site.

Validation

Independent data collected separately to this study (Putland and Buchanan 1988*a*, 1988*b*) could be not be used to validate predictions because seed quality was determined from yield samples that combined the first and second flowerings. Consequently, 3 sowings from Season 3 of this study (11 and 30 December, 18 February) were used for validation purposes. These sowing dates were selected because they covered the important weathering scenarios: seed weathering during early pod ripening, seed weathering commencing midway through pod ripening, and weathering that commenced only after all pods were ripe. These sowings were exposed to different rainfall events. No data from these sowings were used in model development.

Prediction of time to flowering and maturity

The methodology described by Summerfield *et al.* (1991) was applied to derive simple linear functions that relate rate of progress to flowering with mean daily temperature and/or photoperiod. The SAS system for regression was used to fit equations (Freund and Littell 1991). Functions were developed from 18 sowings made with cultivars King and Putland at Katherine covering 4 seasons (1987–1991) sown over the period from 21 December to 27 March. Nine sowings were from Seasons 1 and 2 of this study; the remaining 9 were from other studies (Yeates and Kahl 1987, 1988; S. J. Yeates unpubl. data). First flower was defined as being when 50% of plants in each plot had at least one open flower. Temperature was collected at the site. Photoperiod (sunrise to sunset plus civil twilight) was calculated using the equations of Jones and Kiniry (1986).

If models incorporating photoperiod accounted for significant proportions ($P < 0.05$) of the variation in rate of development to flowering, then it was necessary to determine whether critical photoperiod (P_c, defined by Roberts and Summerfield 1987) was transgressed. A flowering model was built using 2 equations, where at photoperiods less than P_c, time to flowering is a function of temperature only, and at photoperiods greater than P_c, time to flowering is a function of temperature and photoperiod. The equation was derived using an iterative least squares minimisation routine in conjunction with GENSTAT (Genstat V Committee 1987). The value of P_c was determined for each genotype as descibed by Summerfield *et al.* (1991). Eleven sowings of cv. King and 9 sowings of cv. Putland made at Katherine, with accurate flowering records, were used to validate the flowering models (Putland 1986; Putland and Buchanan 1988*a*, 1988*b*; Season 3 of this study).

Time to maturity was predicted using 13 of 18 sowings described above, where the occurrence of maturity stages had also been accurately recorded. The appearance of the first ripe pod was defined as when 30% of plants had at least one ripe pod per plot. Crop maturity was defined as when, for 95% of individual plants in a plot, all the pods produced by the first flush of flowers were ripe. Daily rate of progress (1/day) to the maturity stages first ripe pod and crop maturity was calculated from flowering.

In the sowings used in this analysis, soil moisture content was not measured. It was, therefore, necessary to use variables that may have an empirical association with the soil moisture and atmospheric conditions that could modulate the duration of pod ripening. Two steps were taken to minimise co-linearity between independent variables. Firstly, simple linear regression analysis was made between all climatic variables. Where each variable was compared in a pair-wise fashion, variables that were correlated ($P < 0.05$) were removed from step-wise analysis. Secondly, the Mallows statistic (Freund and Littell 1991) was used to indicate co-linearity between independent variables included in the multiple linear regression analysis. Maturity stage predictions were validated using independent data collected from the 12 sowing dates in Season 3. Sowings where either insect damage or plant lodging may have interfered with pod development were not used in the analysis.

The rate of ripening of pod cohorts was measured from harvests made in Season 3: 5 sowings of cv. King (11 and 16 December, 20 January, 4 and 10 February) and 4 of cv. Putland (6 and 20 January, 4 and 25 February). All harvests were made between 11 00 and 14 00 hours. Samples of 5 and 3 consecutive plants were taken from the 4 centre rows per plot of cv. King and cv. Putland, respectively. Harvests were made at 2-day intervals commencing when 30% to 50% of plants had at least one mature pod per plot, and concluding when all pods from the first flush of flowers were ripe. Following harvest, the proportion of ripe pods (defined as pods having at least 90% of their surface black) was determined. A comparison was then made between the actual percentage of mature seed and the estimated percentage of mature seed.

Results

Prediction of first flower

For cv. King, the combination of mean daily temperature and photoperiod accounted for the greatest proportion of variation in rate of progress to flowering and predicted flowering with a mean deviation from observed of <1 day (Table 1). For cv. Putland, the greatest proportion of variation in days to flowering was explained by the transgression of the critical photoperiod model (Table 1). The temperature-dependent critical photoperiod for this genotype ranged between 12 86 hours and 13 02 hours for the sowing dates used. Time to flowering was predicted with a mean deviation from observed of <2 days (Table 1).

Prediction of crop maturity

The sowing dates used in this analysis covered 4 wet seasons and included 7 dryland and 6 supplementary irrigated sowings. This range of seasonal conditions, combined with the application of irrigation on selected sowings, allowed time to maturity to be compared under different pre-flowering environments, e.g. drought compared with non-drought conditions. The post-flowering environment also varied, in terms of high and low preflowering biomass and maturity under different levels of atmospheric moisture and photothermal range.

Table 2 shows that measures of moisture availability accounted for a greater proportion of the variation in the rate of progress to maturity than did temperature or photoperiod. Either cumulative rainfall events or cumulative days with relative humidity ≥75% were highly correlated ($P < 0.01$) with rate of progress to all development stages. In fact, photothermal variables only contributed to the rate of progress from flowering to first ripe pod (Table 2).

For both cultivars, the time from sowing to first ripe pod and to crop maturity was predicted with a mean deviation from observed of <5 days using independent data (Table 3). For cv. King the time to crop maturity may have been more accurately predicted where crops that received irrigation after flowering were removed. Prediction of time to maturity is dependent on the sum of days where relative humidity was at least 75%. In Season 3, irrigation was applied to 2 crops (sown on 18 and 28 February) between flowering and first ripe pod. At the time of application, air relative humidity was very low, a situation that differs from natural rainfall, which is usually associated with high air relative humidity. Removal of these crops reduced the mean deviation from observed to 2.3 days.

Table 1. Derived equations and regression coefficients relating rate of development to flowering (1/d), where d = days to flowering, to one or more of mean daily temperature (T) and mean daily photoperiod (P) above the critical photoperiod (P_c)

The residual mean square deviation (RMSD) and mean deviation of predicted from observed days to flower using independent data

Cultivar	Equation	R^2 (%)	RMSD	Mean deviation from observed (days)
cv. King	1/d = –0.0300 + 0.00109T	38**	0.90	0.7
	1/d = –0.0170 + 0.00016T – 0.00252P	61**	0.89	0.7
cv. Putland	1/d = 0.1110 + 0.00145T – 0.00983P	83**	2.28	1.8
	$P < P_c$ 1/d = 0.0034 + 0.00082T	89**	1.90	1.7
	$P > P_c$ 1/d = 0.1640 + 0.00153T –0.01399P			

** $P < 0.01$, * $P < 0.05$, degrees of freedom corrected.

Table 2. Regression coefficients (as percentages, degrees of freedom adjusted) relating rate of progress to mean daily temperature (T), photoperiod (P), the number of days where relative humidity at 09 00 hours exceeded 75% (RH75), and the number of rainfall events ≥1 mm (CRD)

Phase	Cultivar	T	P	T + P	RH75	CRD
Flowering to first ripe pod	King	62**	<1	60**	70**	66**
	Putland	57**	4	54**	62**	63**
Flowering to crop maturity	King	27*	<1	27*	53**	46**
	Putland	23	<1	20	73**	76**
First ripe pod to crop maturity	King	2	<1	10	30*	2
	Putland	<1	5	<1	43*	26

* $P < 0.05$; ** $P < 0.01$.

Table 3. Maturity stage prediction commencing at first flower, fitted equations, their regression coefficients, and mean deviation from observed (MDO) when tested using independent flowering and maturity data

Symbols for variables as for Tables 1 and 2

Cultivar	Growth stage	Equation	r^2 (%)	MDO (days)
cv. King	First ripe pod	1/d = – 0.0290 – 0.00082*CRD + 0.00348*T	76	0.90
	Maturity	1/d = 0.0529 – 0.00069*RH75	53	2.86
cv. Putland	First ripe pod	1/d = – 0.4074 – 0.00281*CRD + 0.00348*P	76	2.19
	Maturity	1/d = 0.1606 – 0.00736*RH75	76	4.63

Prediction of the proportion of mature seed during crop ripening

There was a highly significant ($P < 0.01$) linear relationship between the percentage of the pod ripening phase completed and the percentage of seed mature on the same day. The fitted lines can be used to calculate the proportion of seed or pods ripe in a crop at any time during pod ripening:

cv. King $Y = -0.019 + 0.948X$ $(r^2 = 0.95)$

cv. Putland $Y = 6.55 + 0.94X$ $(r^2 = 0.88)$

The transition of individual pods from physiologically mature (yellow) to ripe (black) took at most 24 h in both cultivars. Visual assessment was an accurate method of determining the number of seeds mature at any time during the ripening phase. For cv. King and cv. Putland, the correlation between visual assessment of the percentage of pods mature and the measured percentage of mature seed at each harvest was highly significant ($P < 0.01$; $r^2 = 0.93$ and 0.92, respectively).

Table 4. Summary of the Australian seed quality grades for mungbean and their associated percentage of unweathered seed, determined by visual assessment

The relative value of export grades is also presented. These figures are averages taken over a 5-year period and are based on data provided by H. Remalli (pers. comm.) and Lawn and Imrie (1991)

Australian seed quality grade	Percent unweathered seed cv. King	cv. Putland	Relative value
Premium	>87	>89.9	1.0
No. 1	76–87	80–89.9	0.85
Processing	56–75.9	56–79.9	0.5–0.6
Stockfeed	26–55.9	26–55.9	0.3–0.5
Unsaleable	<26	<26	Nil

Relation between seed quality and visual weather damage

Seed quality measured using the Australian export grades was related to changes in seed morphology caused by weathering as found by Williams *et al.* (1995*a*). Each export grade covered a reasonably wide range of the percentage of visually unweathered seed (Table 4). Where more than one export grade was placed within the same range of visually unweathered seed, these samples were close to the point of delineation between grades.

Effect of cultivar and rainfall on proportion of weather damaged seed

The cultivars differed in the frequency and severity of weather damage. Economic weather damage was more frequent in cv. King: 12 sowings compared with 5 sowings for cv. Putland. In part, this difference was because cv. Putland avoided rainfall due to later maturity. The severity of weather damage was also less in cv. Putland. It is difficult to directly compare cultivars because their reproductive ontogeny must overlap exactly for comparisons to be valid (Imrie *et al.* 1988). However, as Fig. 1 shows, where this did occur, cv. Putland was more tolerant of rainfall than cv. King.

Fig. 1 also shows that weather damage was associated with rainfall events. However, the severity of weather damage following an event did not appear related to the volume of rainfall. The later observation is confirmed in Table 5, where cumulative measures of exposure to rainfall had a higher correlation with the proportion of unweathered seed than the volume of precipitation per day. Adjustment of weather data to allow for the daily ripening of individual pod cohorts improved correlations over unadjusted data (Table 5). Except for standard deviation of evaporation and rainfall per day, regression coefficients for adjusted data were similar in magnitude to the situation where weathering occurred after all the pods had ripened (Table 5).

It was considered unlikely that a reliable model to predict weathering in cv. Putland could be developed from this study, for 2 reasons. Firstly there were insufficient data; weather damage that was severe enough to reduce seed quality (<10% seed weather-damaged) was only observed in 10 of the 63 harvests made following rainfall. Secondly, the proportion of hard seed present during and after ripening could not be predicted. The proportion of hard seed at harvest maturity ranged from 7.4% to 64.5%, which was much greater than expected. Hard seed was also found to develop as the seed desiccated (data not presented, see Yeates 1994); consequently, the susceptibility of seed to weathering changed over time. Because hard seed can confer some resistance to weather damage (Williams *et al.* 1995*b*), an ability

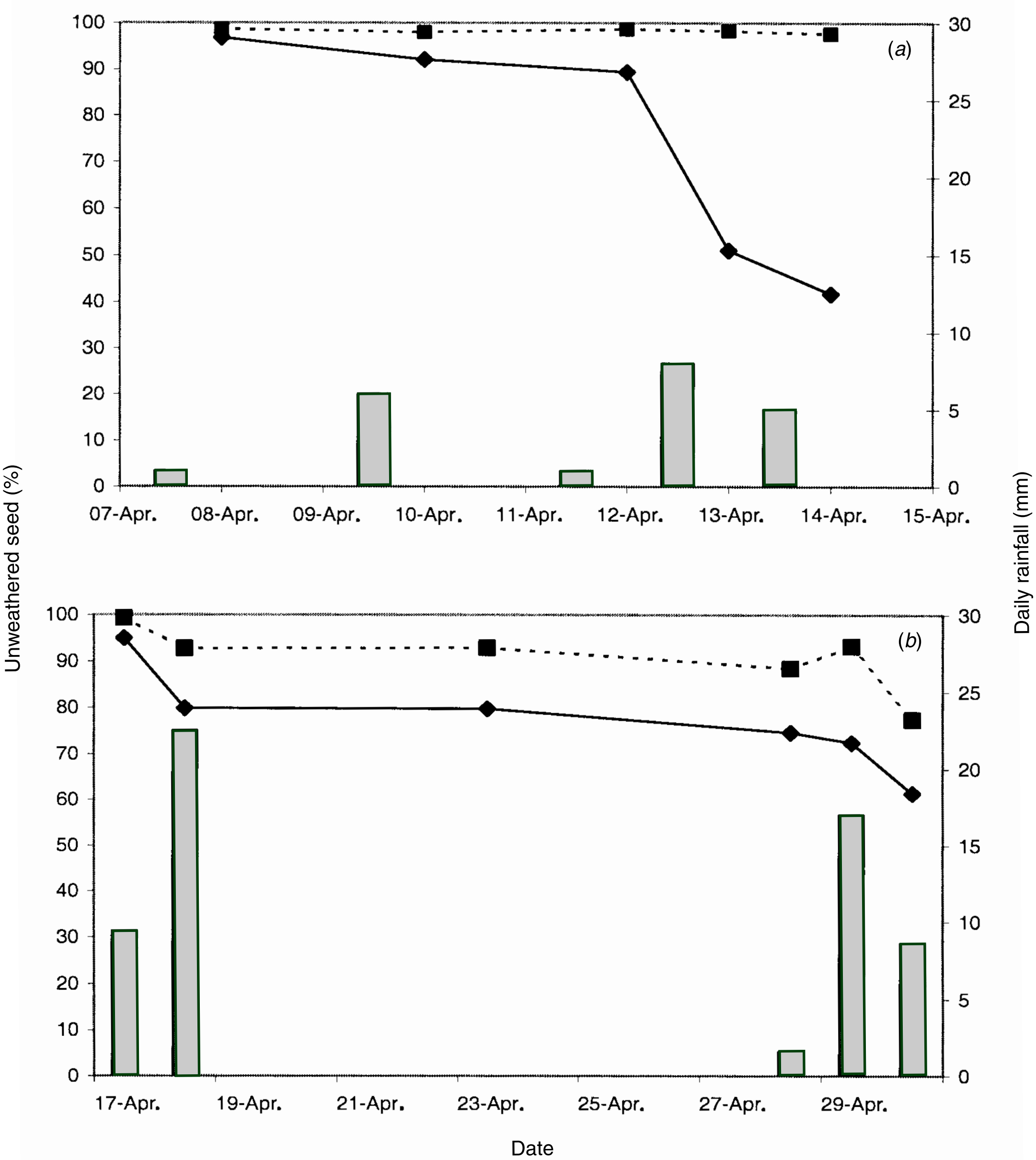

Fig. 1. Effect of daily rainfall (shaded bars) on cultivar susceptibility to seed weathering, for periods where reproductive ontogeny overlapped: (*a*) cv. King sown 10 February 1992 (l.s.d. = 6.8), and cv. Putland sown 27 January 1992 (l.s.d. = ns), (*b*) cv. King sown 4 February 1989 (l.s.d. = 12.5), and cv. Putland sown 23 January 1989 (l.s.d. = 9.5). ◆, cv. King; ■, cv. Putland.

to predict the proportion of hard seed would be essential in predicting weather damage in this cultivar.

Model development, cv. King

Adjustment of rainfall variables for the ripening of individual pod cohorts permitted the cumulative effects of rainfall on the proportion of unweathered seed to be interpreted independently of the stage of reproductive development (Fig. 2). A minimum exposure to rainfall was required before seed quality was reduced. After this exposure was exceeded, the proportion of unweathered seed declined with additional rainfall until a maximum exposure was reached where the proportion of unweathered seed was effectively zero. The minimum previous exposure to rainfall could be quantified and is shown by a vertical line on Fig. 2. This was equivalent to approximately a cumulative rainfall duration of 300 min, greater than one rainfall event ($\geq$0.5 mm) or accumulating 10–15 mm of precipitation (Fig. 2). To determine the maximum exposure required extrapolation because the maximum value observed exceeded what was required to weather all susceptible seed and would also be considered a leverage point in fitting a curve to these data. The maximum

Table 5. Regression coefficients (as percentages, degrees of freedom adjusted) between the percentage of unweathered seed and weather parameters for separated sowing dates where rainfall first occurred during pod ripening and after all pods were ripe

+ adjust, weather variables adjusted for the proportion of pods ripening each day; – adjust, not adjusted

Variable	After ripening		During ripening		
	King (n = 31)	Putland (n = 35)	King – adjust (n = 50)	King + adjust (n = 50)	Putland + adjust (n = 35)
Cumulative rainfall volume (mm)	56.1**	47.3**	61.2**	74.7**	31.4**
Rainfall events ≥0.5 mm	70.1**	18.1*	39.7**	72.2**	<1
Precipitation per day	45.9**	13.2	<1	6.9	1.4
Cumulative duration of rainfall (min)	75.3**	31.6**	38.0**	67.2**	45.5**
Mean relative humidity	10.9	11.3	1.0	14.4*	16.9*
Standard deviation of evaporation	11.1	6.4	28.6**	47.7**	11.6
Mean daily temperature	<1	17.3*	14.9*	16.1*	16.0*

* $P < 0.05$; ** $P < 0.01$.

exposure was equivalent to ≥4000 min of rainfall duration, >15 rainfall events, and about 250 mm of precipitation (Fig. 2).

In the context of developing a model of field weathering, quantifying the minimum previous exposure necessary for weathering to become cumulative is useful; less than the minimum there is no economic damage to seed. Between this minimum and the maximum previous exposure required to damage all seed, the decline in the percentage of unweathered seed may be explained by simple linear functions dependent on the cumulative effect of rainfall.

Duration of rainfall directly measures the period that seed is exposed to atmospheric moisture and was the variable having the greatest correlation with the proportion of unweathered seed (Fig. 2*a*). However, to be of practical value a model of field weathering must use meteorological data that are commonly recorded. Unfortunately, pluviograph readings have been recorded at very few meteorological stations in tropical Australia and where data do exist they have not been tabulated (H. Nicholson, White Rocks Computing Consultancy, Jimboomba Qld, pers. comm.). An alternative to the cumulative duration of rainfall may be the cumulative number of rainfall events. The sum of rainfall events was the next most highly correlated variable with seed weathering after rainfall duration (Fig. 2*b*) and was highly correlated with rainfall duration ($r^2 = 0.76$).

Further examination of Fig. 2 shows a considerable range in the percentage of unweathered seed between the minimum and maximum exposure, i.e. 300–4000 min or 2–15 rainfall events. Greater exposure appeared associated with larger standard deviations of evaporation (70–250% higher) and slightly higher mean temperatures (0.5–2.0°C). Consequently, multiple regression that combined rainfall variables with the standard deviation of evaporation was more highly correlated with the percentage of unweathered seed than was simple regression based on rainfall variables alone (Table 6).

Model selection and validation for cv. King

Between the maximum and minimum thresholds for exposure to rainfall, fitted equations giving the highest correlations with the percentage of unweathered seed are shown in Table 7. Where rainfall duration was a variable, a Kruskal-Wallis test (SAS 1990) found the relationship with weather damage was independent of the stage of crop ripening when first exposed to rainfall (Table 7). However, where the number of rainfall events was the dependent variable, the relationship with weather damage was crop-stage dependent.

Regression coefficients between observed and predicted percentage of unweathered seed were calculated by applying these equations between a maximum and minimum threshold (taken from Fig. 2) for each rainfall variable (Table 7). The maximum threshold, assumes only 2%, the average proportion of hard seed in cv. King (S. J. Yeates unpubl. data), of seed remains unweathered after exposure to >4000 min cumulative rainfall duration or >15 rainfall events. The minimum threshold value, that is $DP \leq 60$ min, $60 < DP \leq 300$ min and ≤1 SE, assumes 95.5%, 91.5%, and 95% of seed is unweathered below these values, respectively.

Weather damage and seed quality grades were accurately predicted using the equations selected above. At worst, predictions were one grade higher than observed (Tables 7, 8).

Discussion

This study measured the effect of rainfall on changes in preharvest seed quality of field-grown mungbean. The effect of rainfall was cumulative once a minimum threshold was exceeded. We were able to quantify this threshold using known meteorological measures of rainfall (Fig. 2). The minimum threshold may equate to the initial imbibition of water that predisposes the mungbean seed to weather damage found in a controlled environment (Williams *et al.* 1995*a*, 1995*b*). The decline in seed quality after this thresh-

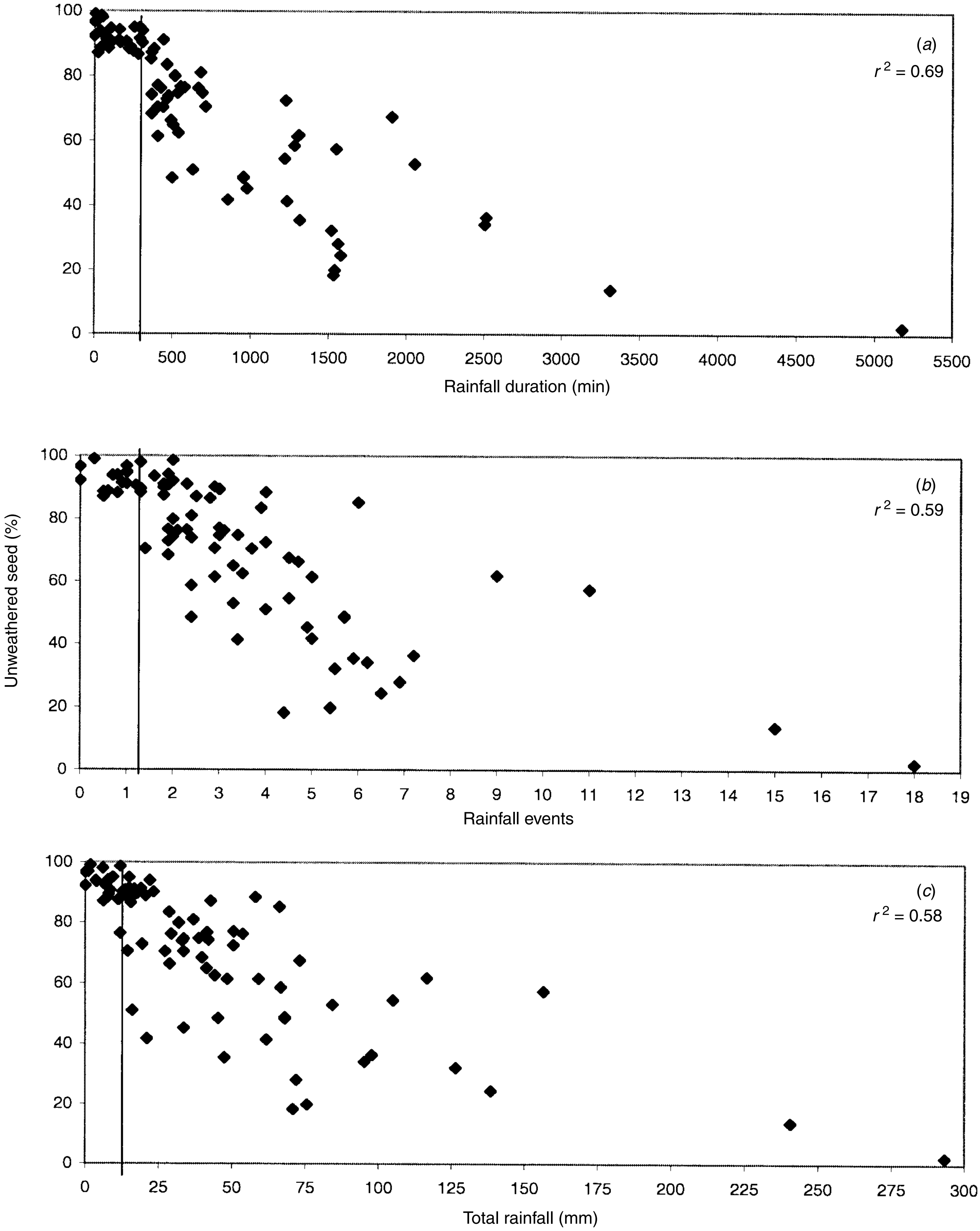

Fig. 2. Cumulative effect of rainfall measured as (*a*) rainfall duration (min), (*b*) rainfall events (⩾ 0.5 mm), and (*c*) rainfall volume on the percentage unweathered seed for cv. King. Data are independent of the stage of reproductive development when rainfall first occurred and are adjusted for the proportion of ripe pods (n = 81). Vertical line is minimum required for economic weathering.

Table 6. Comparison of weather variables in multiple and simple regression (degrees of freedom adjusted) for cv. King

Regression calculated for seed exposed to 1–15 rainfall events ≥0.5 mm (RE) or a cumulative duration of rainfall of 300–4000 min (DP) with and without the standard deviation of daily evaporation (SDE) and mean solar radiation (RN). $P < 0.01$ for all coefficients

Climatic variables	*n*	R^2 (%)
DP	53	56
DP + SDE	53	76
RE	66	51
RE + SDE	66	58
RE + SDE + RN	66	66

old was exceeded could largely be predicted by the combined effects of the cumulative exposure to rainfall and the standard deviation of evaporation, which reflect the likely causes of weather damage to mungbean seed. That is, cumulative exposure to moisture and the extent of drying of the atmosphere between rainfall events (Williams *et al.* 1995*a*, 1995*b*).

While the effect of the number of cycles of wetting and drying on the degree and severity of weather damage has been studied for mungbean in a controlled environment (Williams *et al.* 1995*a*), the effect of the rate of change of seed moisture content has not. Future research could attempt to simulate this process by predicting the daily changes in seed moisture. Such research may provide the basis for a more mechanistic model to predict seed quality.

The pre-harvest seed quality of cv. King was reliably predicted with independent data using inputs of either the cumulative duration of rainfall or the number of rainfall events to which seed was exposed (Table 8). However, the cumulative duration may be the only measure of rainfall that could be used in a model to predict weathering across a range of environments outside those used here, because it directly measures the period of exposure to atmospheric moisture.

Visual assessment, based on changes in seed morphology known to be associated with weather damage, could effectively partition seed into the seed quality grades currently used for cvv. King and Putland (Table 4). Visual assessment was a rapid method to measure seed quality because it removed the requirement for the vigour and oversoakes tests that form part of the procedure used to measure seed quality (Law and Law 1991). However, the relationships between changes in seed morphology and weathering are cultivar-specific (Williams *et al.* 1995*b*) and, therefore, will require validation for cultivars not tested in this study.

Over the 3 years of this study, mean radiation was significantly ($P < 0.01$) correlated ($r^2 = 0.4$) with mean temperature and duration of rainfall. Thus, in a function that combines radiation with rainfall events, radiation may approximate temperature and rainfall duration effects. That is, low mean radiation was associated with prolonged rainfall and cloud cover.

Where reproductive development overlapped, cultivar differences in susceptibility to weather damage (Fig. 1) were consistent with comparisons of seed morphology made by Williams *et al.* (1995*b*), where a large-seeded cultivar imbibed moisture faster and had a lower proportion of hard seed than a small-seeded cultivar. A model to predict seed quality in a cultivar capable of producing hard seed, such as cv. Putland, would need to account for both the variation in the proportion of hard seed formed at maturity and the time required for each seed to desiccate before becoming hard.

This study also highlighted the interaction between reproductive development and weather damage in an indeterminate crop such as mungbean. Because weather damage was found to occur in as little as 3 days, the timing of the crop ripening period required accurate prediction. Moreover, the daily ripening of individual pod cohorts confounded relations between the proportion of weather-damaged seed and climate. Adjusting weather variables to account for the cohort-specific exposure to environmental conditions was successful in removing these confounding effects (Table 5).

The relationships developed here used only seed produced by the first flush of flowers. The proportion of the total seed yield contributed by a second flowering, although low, could not be predicted. Therefore, predicting the contribution of the seed produced by the second flowering to the total seed quality would require a growth model that can simulate the yield of the second flush of flowers.

The prediction of the time to flowering to within a maximum deviation of 2–3 days, using the procedures of Summerfield *et al.* (1991), approaches the limit of reading

Table 7. Selected equations for cv. King and their regression coefficients for rainfall between the maximum and minimum thresholds

Validation data showing regression coefficients and slopes for the correlation between observed and predicted percentage of unweathered seed (Uw) using independent data. Symbols for variables as for Table 6 . Weather variables are calculated from first ripe pod

Growth stage	R^2 (%)	Selected equation (%)	Validation *n*	r^2 (%)	Slope
Any	76.0	Uw = 103.2 – 0.020*DP – 14.46*SDE	23	84.0	1.198
During pod ripening	75.2	Uw = 116.3 – 8.08*RE – 17.84*SDE	17	93.1	0.997
After pod ripening	74.2	Uw = 129.2 – 5.65*RE – 9.7*SDE – 0.98*RN	6	72.3	1.870

Table 8. Observed and predicted seed quality grades at harvest maturity for cv. King using independent data

Percentage visually unweathered seed in brackets; two harvest dates were possible for the 18 February 1992 sowing date, predicted and actual grades for both are shown

Sowing date	Observed seed quality	Predicted seed quality	
		Rainfall duration	Rainfall events
11 Dec. 1991	Unsaleable (11)	Stockfeed (32)	Unsaleable (8)
30 Dec. 1991	Stockfeed (47)	Stockfeed (39)	Stockfeed (42)
18 Feb. 1992 (1)	Premium (93)	Premium (98)	Premium (96)
18 Feb. 1992 (2)	Stockfeed (38)	Stockfeed (49)	Processing (63)

observed values in these experiments, as differences within replicates were at least 1 day. Predicting flowering within 2 days of observed is, at worst, equivalent in accuracy to the models derived for other crops (e.g. Angus *et al.* 1981; Hammer *et al.* 1989; Loss *et al.* 1990; Jones *et al.* 1991; Sinclair *et al.* 1991). However, for cv. King the selection between model types (e.g. temperature only or temperature and photoperiod) was difficult due to the small temperature and photoperiod ranges observed to derive the functions. Consequently, extrapolation to determine base temperatures and photoperiods are subject to error (Ritchie and NeSmith 1991).

The commencement and the completion of crop ripening were predicted to within a mean of 3 and 5 days from observed in cv. King and cv. Putland, respectively. This was at least comparable with other studies concerned mainly with grain yield (Vanderlip and Arkin 1977; Angus *et al.* 1981; Hodges and French 1985; Jones *et al.* 1991). It was expected that rate of development from flowering to either maturity stage would be dependent on temperature, photoperiod, and available moisture. This was the case between flowering and first ripe pod. However, after pods commenced ripening, moisture availability appeared to be the most important factor affecting time to crop maturity. It is likely that temperature effects may have been accounted for indirectly due to autocorrelation with rainfall events. Temperature and photoperiod may have a greater influence on the rate of crop ripening at higher latitudes (Lawn 1979).

The validation data suggested that, provided the models selected are not used outside the rainfall regime and photothermal range wherein they were derived, accurate prediction of the timing of pre-harvest seed quality and reproductive development is possible. Areas of the Australian monsoon tropics (13 to 17°S) receiving between approximately 600 and 1600 mm of rainfall are unlikely to deviate from the photothermal range or rainfall regime observed in this study (Slatyer 1960; Mollah 1986).

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