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Analysis of line × environment interactions for yield in navy beans. 1. Components of variance

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Abstract. Multi-environment yield trials of navy bean (*Phaseolus vulgaris* L.) lines were grown over a diverse range of locations for the years 1983–1989 in Queensland, in an unbalanced set of line × location × year combinations. This is the first in a series of 3 papers reporting different perspectives on the genotype × environment (G×E) interactions in this series of experiments. In this paper, restricted maximum likelihood (REML) estimates of G×E components of variation were derived using trial means in both standard and extended models where concomitant genotype and location factors such as maturity, disease resistance, and experimental management regimes were investigated. Prior to estimating the variance components the heterogeneity of trial error variances was modelled. Several alternative trialing systems were compared using acceptance probabilities derived from the variance components. The interaction of genotype maturity with location considerably reduced the line × location × year variance component and further examination of the maturity × environment interaction suggested an advantage in stratifying the breeding program on maturity. There is no redundancy in the current trialing system and an increase in sampling locations can be justified.

Additional keywords: *Phaseolus vulgaris*, yield, REML, multi-environment trials, environments.

Introduction

A set of diverse genotypes for a crop, grown over a range of environments, typically will exhibit a range of genotype × environment (G×E) interactions for particular traits. An assessment of genotype performance in the presence of these interactions and periodic assessment of resource allocation is important for the efficiency and effectiveness of a plant improvement program. Whether such an assessment is based on cost considerations or purely statistical grounds, the relative magnitude of the sources of variation due to genotypes and their interaction with environments must be determined.

There is considerable literature in Australia on the analysis of multi environment trials (METs) conducted for plant improvement. This includes the work on joint regression (Finlay and Wilkinson 1963), pattern analysis (Mungomery *et al*. 1974; Byth *et al*. 1976; Brennan and Byth 1979; Basford 1982), and the estimation and use of variance components (Thomson and Cunningham 1979; Brennan *et al*. 1981; Williams *et al*. 1992; Cullis *et al*. 1996*a*, 1996*b*)

In the recently initiated program of navy bean (*Phaseolus vulgaris* L.) breeding in Queensland (Redden *et al.* 1985), regional variety trials included former Queensland Department of Primary Industries (QDPI) selections, new introductions from the USA and Columbia, and derived selections from crosses between and within these groups. These trials, grown over a wide geographic range, consisted of varying genotypic entries and test locations between years. This series of papers examines possible changes in adaptation pattern with newly bred selections, the most efficient choice of trialing system to characterise these differences in adaptation, and hence strategies to identify new varieties for the navy bean industry. This first paper reports the estimation of genotype and G×E interaction variance components and the use of covariates to partition the G×E interaction into known and unexplained components, and concludes with an assessment of the current navy bean trialing system using the method of Patterson *et al*. (1977). Subsequent papers focus on the pattern of G×E interactions firstly within years and finally across all years.

Materials and methods

Genotype and G×E variance components were estimated from a retrospective analysis of experiment means. These components were used to

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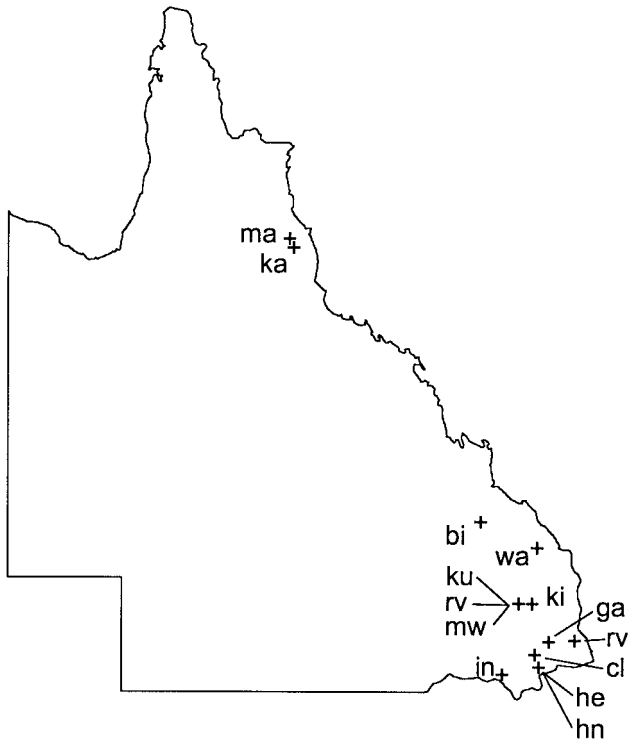

Fig. 1. Location of trial locations used for the Queensland navy bean regional trials from 1983 to 1989. Location codes are as given in Table 1.

assess the existing trialing system and compare a number of systems with various combinations of replicates, locations, and years. The standard 2-stage model (Patterson *et al*. 1977; Williams *et al*. 1992) was augmented with genotypic and location-specific factors such as maturity, disease resistance, irrigation, and row spacing, which can potentially contribute to G×E interactions. The consequences of changes to the trialing system on the risk of rejecting superior lines was assessed in terms of acceptance probabilities (Patterson *et al*. 1977).

Trial details

Regional navy bean METs were grown in Queensland for 7 years (1983–1989). The number of entries (lines) varied from 8 to 22 with partial substitution of entries between years. A subset of 17 entries and 43 environments provided grain yield data for an examination of G×E interactions. The 43 test environments, diverse in both management and geography (Fig. 1, Table 1), ranged from a minimum of 4 locations in 1983 to a maximum of 10 in 1987, with partial substitution between years (Table 2). Some locations, while geographically close, were considered as distinct environments because of differing management regimes.

The trials were sown in row widths from 17 to 90 cm at populations of approximately 200 000 plants/ha, rainfed at some locations, but irrigated at others (Table 1). Nitrogen levels of 40 (rainfed) to 80 (irrigated) kg/ha were supplied to trials, with varying supplements of phosphorus, potassium, and zinc according to location. Weed control was through pre-emergence herbicides [Treflan (a.i. trifluralin, Hoechst Australia Ltd) + Eptam (a.i. thiocarbamate, Cropcare) if nut grass present], inter-row cultivation, and manual chipping. Pest control involved 1–4 sprays of diomethoate for bean fly and jassid control, mainly pre-flowering, and 1–4 sprays with Methomyl (a.i. carbamate, Lannate Du Pont) and/or Endosulphan 350EC (a.i. endosulfan, Nufarm) post-flowering for *Heliothis* and *Nezara* control. Plots were mechanically harvested except at Kairi, Mareeba, and Biloela. The central 2 of 4 row plots were harvested, while at 17-cm row spacing, the central 7 out of 9 rows were harvested. Plot lengths varied from 5 to 10 m. Grain yields were adjusted to 12% moisture content if harvest samples were relatively moist. In all cases the trial design was a randomised complete block with 3 replicates.

Original plot data were not available and all analyses have been conducted using experiment means. For each trial, *i*, the general mean ($\bar{y}_i$), error degrees of freedom (df_i), and residual error variance (s_i^2) were available from the original analysis of variance for grain yield.

Trial entries included selections from the previous Queensland breeding program (Gallaroy, Kerman, Actolac, 2GA, W1401, Actosan Revenue, Selection 46), introductions from the USA and Columbia (Campbell series, Banker, Nep 2, Bac 125, Bac 134), and new genetic combinations (CH series, Table 3). Only lines that were tested for 2 or more years were included in the analysis. The 17 lines were also classified by maturity and bacterial blight resistance, 2 characteristics thought likely to contribute to any G×E interaction for grain yield (Table 3).

Statistical methods

Modelling trial error variance

Variance heterogeneity is a common problem encountered in the analysis of series of experiments. Assuming the analysis of the individual experiments is valid, a likely difficulty in interpreting any pooled analysis is heterogeneity of the (true) error variance, that is, σ_ε^2 is not constant (Kempthorne 1952). In the context of the regional navy bean trials, σ_ε^2 will vary from location to location and season to season because of heterogeneity in the experimental medium (that is, physical trial locations and their interaction with prevailing conditions). This can arise through purely natural means such as inherently different background variation (for example, soil properties, slope) or through extraneous sources such as disease incursion or management practices. For instance, Rocklea and Mt Wooroolin are subject to intermittent animal grazing effects not present at other locations, while Inglewood is prone to weed infestation. The problem is further compounded as the original analyses of these trials were as randomised blocks and are therefore quite likely to have differentially inflated estimates (s^2) of because of σ_ε^2 poor estimation of local (within trial) trend effects.

For the set of 43 trials there was a 79-fold difference between the smallest and largest observed trial error variance, clearly violating any assumptions regarding constant residual variance. An unweighted analysis would be statistically inefficient; this heterogeneity was accounted for in the analysis of grain yield through the use of weights derived from the s_i^2. Cullis *et al.* (1996*a*) argued that it is more efficient to model the structure of the observed error variances and form weights based on predictions from this model rather than directly from the observed errors. Specifically, we consider a generalised linear model (McCullagh and Nelder 1989) for predicting trial error variance using a number of explanatory variables. These include the logarithm of trial mean yield [$\log(\bar{y}_i)$], location, year, irrigation regime, and row spacing. The s_i^2 were regressed against the explanatory variables assuming Gamma errors and a log link function (McCullagh and Nelder 1989; Cullis *et al*. 1996*a*).

In addition to calculating appropriate weights for the subsequent estimation of variance components, this model (as would standard multiple regression) quantifies the relationship between trial error variance and continuous variates such as trial mean yield, and management practices such as irrigation regimes and row spacing. The model also allows an investigation of the consistency of trial error variance for variables such as location and year. Knowledge of these relationships is important for plant improvement programs.

Table 1. Date of sowing, water regime, row spacing, minimum and maximum temperature range and geographic location for the 16 locations used for the Queensland navy bean trials from 1983 to 1989

	Hermitage	Hermitage	Inglewood	Clifton	Gatton	Rocklea	Redvale	Redvale	Kingaroy	Mt Woorolin	Wallaville	Biloela	Mareeba	Kairi	Kumbia	Teakle
Location code	he	hn	in	cl	ga	rl	rv	rn	ki	mw	wa	bi	ma	ka	ku	te
Sowing date (day.month)																
1983	16.ii		19.i	16.ii	28.i											
1984	12.i		20.i	18.i			24.i					2.iii	18.vii		12.i	
1985	24.i						15.i					6.iii		30.vii		
1986	16.i	16.i				11.ii	14.i							18.vii		
1987	2.ii	2.ii	24.i			18.ii	9.i	19.ii		12.i	12.iii	10.ii		13.vii		
1988	27.i	27.i					9.ii		4.ii	10.ii	14.iii	11.ii		15.vii		
1989	26.i	26.i					18.i		24.i			12.ii	9.iv		10.i	13.ii
Climate from sowing to harvest																
Row spacing (cm)	71	17	71	71	71	71	90	17	90	90	90	71	45	45	90	90
Water regime	Rainfed	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Rainfed	Rainfed	Irrigated	Rainfed	Irrigated	Irrigated	Irrigated	Irrigated	Rainfed	Irrigated
Rainfall/irrigation (mm)[A]																
1983	421		446	450	87/150											
1984	219		346	327			250					103/90	34/300		247	
1985	182						265					203/60		40/373		
1986	181	181				250/120	313							233/90		
1987	183	183	307			396/70	203	203		169	358/50	101/90		104/88		
1988	423	423					310		273	273	523	204/50		101/50		
1989	287	287					483		223			292/40	289/200		338	290/50
Min. temp. range (°C)																
1983	11–16		3–16	11–16	15–19											
1984	6–16		0–14	16–16			12–18					9–18	11–18		5–21	
1985	9–17						12–17					6–20		10–18		
1986	11–16	11–16					12–17							13–19		
1987	9–17	9–17	3–16			14–19	13–20	13–20		13–20	12–22	12–20		10–19		
1988	8–15	8–15				14–20	8–16		5–21	8–16	12–22	5–16		13–17		
1989	2–21	2–21					12–17		12–17			12–17	14–21		12–17	12–17
Max. temp. range (°C)																
1983	20–28		24–41	20–28	26–33											
1984	20–27		24–34	20–27			25–29					24–32	22–26		19–32	
1985	20–29						26–31					21–33		20–29		
1986	27–30	27–30				25–31	29–31							23–29		
1987	21–29	21–29	29–39			24–31	26–32	26–32		26–32	22–30	24–33		21–30		
1988	21–27	21–27					22–29		22–29	22–29	22–30	25–34		21–29		
1989	21–27	21–27					22–28		22–28			26–34	24–30		22–28	26–34
Location																
Latitude (S)	28°12′	28°6′	28°25′	27°06′	27°33′	27°31′	26°33′	26°33′	26°33′	26°33′	25°05′	24°24′	17°0′	17°12′	26°33′	24°24′
Longitude (E)	152°6′	152°6′	151°05′	151°54′	152°20′	152°59′	151°30′	151°30′	151°30′	151°30′	152°0′	150°30′	145°25′	145°34′	151°30′	145°25′
Elevation (m)	480	480	284	438	90	25	430	430	430	460	40	173	335	715	430	715

[A] Rainfall (mm) and irrigation (mm) applied.

Table 2. Row spacing, water regime, and years in which trials were grown for the 13 locations used two or more times for the Queensland navy bean trials from 1983 to 1989

Location	Water regime	Row spacing (cm)	1983	1984	1985	1986	1987	1988	1989	Total
Wa	Irrigated	90					✓	✓		2
Bi	Irrigated	71		✓	✓		✓	✓	✓	5
Mw	Rainfed	90					✓	✓		2
Rv	Rainfed	90		✓	✓	✓	✓	✓	✓	6
He	Rainfed	71	✓	✓	✓	✓	✓	✓	✓	7
Hn	Rainfed	17				✓	✓	✓	✓	4
Ka	Irrigated	45			✓	✓	✓	✓		4
Rl	Rainfed	71				✓	✓			2
In	Irrigated	71	✓	✓			✓			3
Cl	Rainfed	71	✓	✓						2
Ma	Irrigated	45		✓					✓	2
Ki	Irrigated	90						✓	✓	2
Ku	Rainfed	90		✓					✓	2
Total			3	7	4	5	9	8	7	43

Table 3. Origin, maturity classification, susceptibility to bacterial blight, and number of locations in which the 17 navy bean lines appeared in the Queensland navy bean regional yield trials from 1983 to 1989

Line	Origin[A]	Maturity[B]	Bacterial blight[C]	Frequency						
				1983	1984	1985	1986	1987	1988	1989
2ga	Qld	3	2	3	7	4				
Actolac	Qld	1	3	3	7	4	5	9	8	7
Actosan	Qld	1	2	3	7	4				
Bac 125	USA	1	2				5	9	8	7
Bac 134	USA	2	2				5	9		
Banker	USA	2	1	3	7	4	5	9		
Campbell 11	USA	3	3	3	7	4		9	8	7
Campbell 16	USA	3	3	3	7	4				
CH14-28d	Sel.	3	1					9	8	7
CH14-8d	Sel.	3	1					9	8	
CH9-4d	Sel.	3	2					9	8	7
Gallaroy	Qld	1	3	3	7	4	5	9	8	7
Kerman	Qld	2	3	3	7	4	5	8	8	7
Nep 2	USA	2	2				5	9		
Revenue	Qld	2	1	3	7	4	5	9	8	7
Selection 46	Qld	2	1	3	7					
W1401	Qld	2	2	3	7	4			8	7

[A] Qld, original QPDI lines; USA, introductions from USA; Sel., derived crosses.
[B] 1, early. [C] 1, less susceptible.

Components of variance

As individual plot data were not available for this series of trials, the analysis was effectively conducted in 2 stages (Patterson *et al.* 1977; Williams *et al.* 1992) using trial summaries from the original randomised block analysis (stage 1) of each experiment. These summaries included mean yield, $\overline{y}_{ij}$, for line *j*, error mean square (s_i^2), and error degrees of freedom (df_i) for each trial, *i*. REML estimates of variance components (Patterson and Thompson 1971; Patterson *et al.* 1977) for grain yield were estimated from trial means using the algorithm of Gilmour *et al.* (1996). Locations that only occurred in single years were excluded from the analysis.

The weight for trial *i* used in the analysis was calculated as $w_i = r_i(\overline{s}^2/\hat{s}_i^2)$, where r_i is the number of replications in the trial ($r_i = 3$ in all cases), $\overline{s}^2$ is the pooled error variance over all trials, and $\hat{s}_i^2$ is the predicted error variance for each trial from the above linear model (Cullis *et al.* 1996*a*). The effect of this weighting policy is to include each experiment in the analysis as though it had a residual variance of $\overline{s}^2$.

The basic statistical model (*GLY*) for yield includes (assumed normally distributed) random effects for line, line × location, line × year, and line × location × year with corresponding variance components σ_g^2, σ_{gl}^2, σ_{gy}^2, and σ_{gly}^2, respectively. An estimate of the residual variance (σ_e^2) was available from $\overline{s}^2$. Experiment was fitted as a fixed effect, thereby accounting for the main effects and interactions of location, year, irrigation, and row spacing. The random components were further partitioned by considering extended models (GLY^+) with additional terms for (line) origin, maturity, and bacterial blight resistance and their interactions with environment effects. With only a small number of lines and locations there was a low level of sampling within

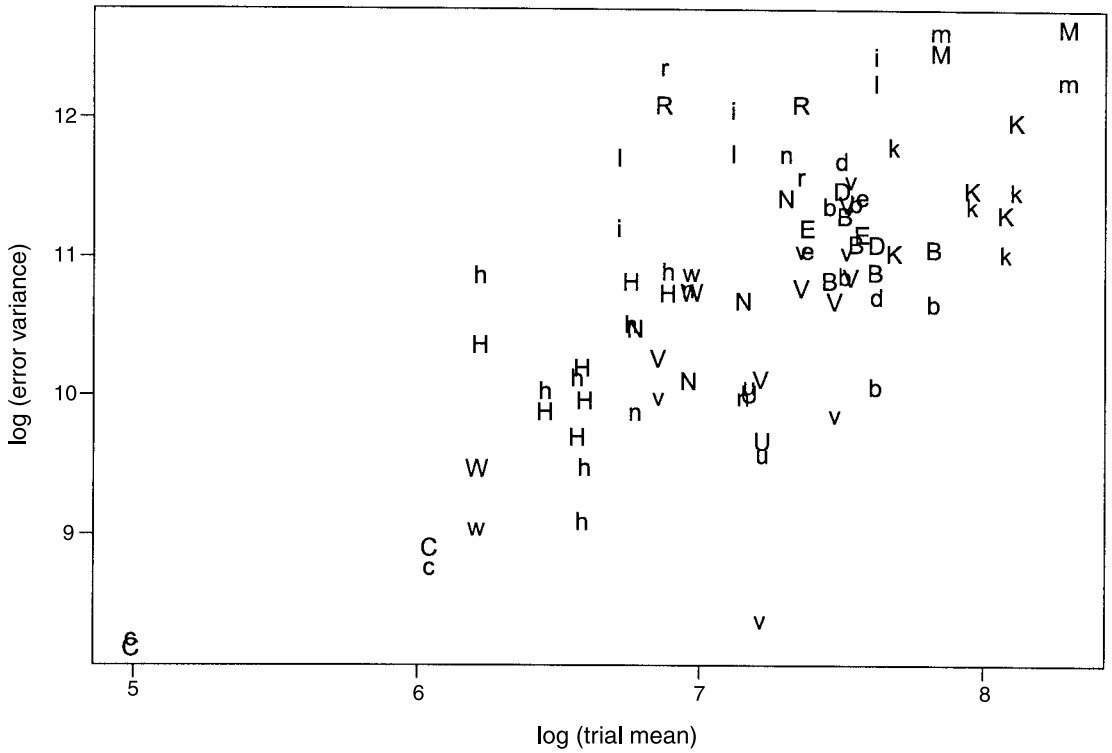

Fig. 2. The relationship between log of trial error variance and log of trial mean for 43 experiments from the Queensland navy bean multi-environment trials. Observed values for locations (see Table 1) are identified as: b = bi, c = cl, g = ga, h = he, n = hn, i= in, k = ka, d = ki, u = ku, m = ma, w = mw, r = rl, v = rv, e = wa. Fitted values from the generalised linear model relating trial error variance to log of mean yield, year, and location effects are identified by upper case characters.

many cross-classified categories and a good deal of confounding of effects. For this reason, the effect of subsets of these covariates on G×E interactions was examined in a series of simpler models. An extended model (GLY^{+}) which includes the maturity factor was finally selected.

Trialing system efficiency

The consequences of changes to the trialing system on the risk of rejecting superior lines was assessed in terms of acceptance probabilities (Patterson *et al.* 1977). The acceptance probability is the probability of accepting a new line when the true difference between it and 1 or more standard lines, expressed as a percentage of the general mean, is set at a predetermined value called the critical percentage difference. The acceptance probabilities depend on (1) the relative size of σ^2_g, σ^2_{gl}, σ^2_{gy}, σ^2_{gly}, and σ^2_e; (2) the number of replications, locations, and years used in the METs; and (3) the critical percentage difference.

For this study the critical percentage difference was set at zero; that is, a new line is accepted if the observed difference between it and a standard is equal to or greater than zero. Trialing efficiency for navy bean METs was investigated for a range of replications, locations, and years.

Results

Modelling trial error variance

There was a strong positive association between error variance and trial mean yield (Fig. 2, Table 4), with a regression coefficient for $\log(\bar{y})$ from the fitted model of 1.288, higher than the 0.891 reported by B. Cullis (pers. comm.) for the wheat trials discussed in Cullis *et al.* (1996*a*). There is also evidence of consistent location and year effects after adjusting for the effect of experiment mean (Table 4); that is, some locations appear inherently more variable than others (Table 5) and the effect of adverse (or favourable) seasons was evident across locations. Predicted error variances for years ranged from 32 766 to 127 038 $(kg/ha)^2$ in 1985 and 1983, respectively. Of the management regimes only row spacing showed an effect approaching significance, with predicted main effects of 52 536, 52 914, 82 706, and 39 465 $(kg/ha)^2$ for spacings of 17, 45, 71, and 90 cm, respectively. However, because of the limited sampling within some row

Table 4. Analysis of deviance for the generalised linear model relating trial error variance to mean yield, year, and location effects for the 43 Queensland navy bean regional trials

Each term in the table is adjusted for those above it

Term	d.f.	Deviance	Mean deviance	Deviance ratio
$\log(\bar{y})$	1	199.9	199.9	39.4
Year	6	74.9	12.5	2.5
Location	12	142.7	11.9	2.4
Residual	23	116.6	5.1	
Total	42	534.2	12.7	

Table 5. Predicted error variance for each location (adjusted for trial mean) from the generalised linear model relating trial error variance to mean yield, year, and location effects for the Queensland navy bean regional trials

Site	Predicted variance $(kg/ha)^2$	s.e. $(kg/ha)^2$	Water regime	Row spacing (cm)
wa	48 359	22 948	Irrigated	90
bi	36 330	12 946	Irrigated	71
mw	51 527	26 141	Rain	90
rv	36 338	9570	Rain	90
he	62 679	26 239	Rain	71
hn	52 536	15 030	Rain	17
ka	34 310	18 002	Irrigated	45
rl	198 224	99 329	Rain	71
in	155 055	53 674	Irrigated	71
cl	44 695	46 099	Rain	71
ma	90 121	53 197	Irrigated	45
ki	49 123	20 668	Irrigated	90
ku	18 228	7829	Rain	90

spacing levels, no reliable conclusion can be drawn of any effect of row spacing on trial error variance and the term was dropped from the analysis. Predicted error variances for locations, adjusted for mean yield, are given in Table 5. Fig. 2 also shows the fitted values from the linear model, highlighting the smoothing effect of the modelling.

In general, the consistent effects of location and season on trial error variance shown in Table 5 are in agreement with observed prevailing conditions. For example, 1983 was an unusual year with severe drought conditions over the 1982–83 summer and late planting at some locations, followed by above average rain through the growing period with some locations waterlogged prior to harvest. In contrast, 1985 was considered a relatively good growing season. The Rocklea location was consistently more variable, being subject to periodic animal grazing, while Inglewood suffered from severe weed infestation.

Cullis *et al.* (1996*a*) found a significant effect of time of planting on error variance in their study of wheat in southern New South Wales. In this study there is a relatively narrow planting window across years and a strong relationship between planting time and latitude. In view of this, the addition of any time of planting factor to the model in Table 3 would not be expected to be effective. Trial locations were partitioned into 2 groups (regions) representing the far northern locations (Kairi, Mareeba) and the remaining southern locations, and a term for the linear effect of planting time within region was added to the model. The addition of this term had no significant effect on the residual deviance.

Variance components

For the standard model (*GLY*) the dominant variance component (Table 6) is plot error (σ^2_e), followed by unexplained σ^2_{gly}, contributing 57.5% and 26.1% of the phenotypic variance, respectively. The σ^2_{gy} component was non significant (effectively zero) and was dropped from the model.

The components involving origin, bacterial blight, irrigation, and row spacing were small relative to their standard errors and were omitted from the extended model (Table 6). The inclusion of maturity, a likely source of G×E interaction, had little effect on the σ^2_g and σ^2_{gl} components but a considerable effect on σ^2_{gly}. The σ^2_{gly} component was reduced from 26.1% to 18.5% of the phenotypic variance when maturity was added to the model. There was a small effect of maturity on grain yield with effects of 112.1 and 7.6 kg/ha relative to maturity class 1 for classes 2 and 3 (later maturing), respectively (Table 7).

The (relative) yielding abilities of individual lines (Table 7) are best linear unbiased predictors (BLUP, for example Henderson 1975; Searle *et al.* 1992) from the *GLY* and GLY^+ models. For model GLY^+, these data represent the intrinsic yielding value (IYV), that is, the BLUP of the line effect adjusted for maturity. The total estimated line effect (Table 7)

Table 6. Estimated components of variance from two linear models fitted to yield (kg/ha) data for the Queensland regional navy bean trial series from 1983 to 1989

Loc, location; Mat, maturity; *z* = (component)/(standard error of component)

Source of variance	Model GLY			Model GLY^+		
	Component $(kg/ha)^2$	*z*	% Total phenotypic variance	Component $(kg/ha)^2$	*z*	% Total phenotypic variance
Line	10 809	2.12	8.6	9219	1.92	7.1
Line.loc	9882	2.40	7.8	10 101	2.59	7.8
Mat.loc				0		0.0
Line.year	0		0.0	0		0.0
Mat.year				0		0.0
Line.loc.year	32 898	7.18	26.1	23 870	5.78	18.5
Mat.loc.year				13 514	2.78	10.5
Plot error	72 362		57.5	72 362		56.1
Total phenotypic variance	125 951			129 066		

Table 7. Best linear unbiased predictors (BLUP) and rank order from the two linear models (*GLY* and *GLY*⁺) fitted to the Queensland regional navy bean trial series

The BLUPs for *GLY*⁺ are adjusted for maturity and represent the intrinsic yielding value (IYV) of each line. Also shown for *GLY*⁺ is the estimated maturity value (EMV) relative to maturity class 1 (early) and the total estimated line effect (IYV+EMV) for each line

Line	BLUP (kg/ha)				Maturity effect	Total line effect	Maturity class
	GLY	Rank	*GLY*⁺	Rank			
Gallaroy	–179.3	(17)	–139.0	(17)		–139.0	1
Kerman	–104.0	(16)	–69.83	(15)		–69.83	1
Actolac	–49.22	(12)	–12.57	(10)		–12.57	1
Banker	52.25	(5)	10.88	(7)	112.1	123.0	2
Cam11	73.94	(3)	21.34	(5)	112.1	133.4	2
Revenue	–45.97	(11)	–94.96	(16)	112.1	17.14	2
2ga	–25.14	(10)	3.568	(8)	7.6	11.17	3
W1401	30.63	(8)	–19.69	(11)	112.1	92.41	2
Cam16	–70.91	(14)	–41.86	(14)	7.6	–34.26	3
Actosan	27.60	(9)	44.30	(4)		44.30	1
Sel46	44.75	(6)	20.24	(6)	112.1	132.3	2
Bac125	–67.73	(13)	–28.33	(12)		–28.33	1
Bac134	184.9	(1)	205.4	(1)		205.4	1
Nep2	32.66	(7)	–3.741	(9)	112.1	108.4	2
Ch14–8d	–79.49	(15)	–41.68	(13)	7.6	–34.08	3
Ch14–28d	53.01	(4)	79.97	(2)	7.6	87.57	3
Ch9–4d	122.0	(2)	65.93	(3)	112.1	178.0	2

is the sum of the estimated maturity value (EMV, following Hammond *et al*. 1992). Yield trials designed for the *medium* maturing class may disadvantage both the early- and late-maturing entries. For example, the line Actosan was ranked 9th from the *GLY* model but 4th in terms of IYV using *GLY*⁺, that is, after adjusting for maturity.

The BLUPs for maturity × location × year (from *GLY*⁺) summarise the performance of the groups of lines within maturity classes across environments, identifying those environments that are advantageous or otherwise to different maturity types. In the biplot (Gabriel 1971) of the maturity × location × year BLUPs each original location × year combination is represented by an arrow that indicates the relative loadings on the first (*x*-axis) and second (*y*-axis) principal components (Fig. 3). The modelled observation for maturity class is indicated by a point. The size of the maturity × location × year BLUP for a maturity class in a location × year environment is estimated from the biplot by dropping a perpendicular from the position of the class to the vector representing the environment. Component 1 is a contrast between earlier and later maturing lines, with maturity class 1 performing well in particular environments (for example Biloela in 1987; Redvale in 1984; Wallaville in 1987) and class 2 and 3 performing better in others [e.g. Hermitage with narrow rows (hn) in 1989 and Redvale in 1988]. Component 2 represents a (less important) differentiation between the later maturity classes. The slight yield advantage indicated by the effect of maturity class 2 could be related to stability, that is, a slightly more consistent response across environments than class 1 lines and outperforming class 3 lines in select environments.

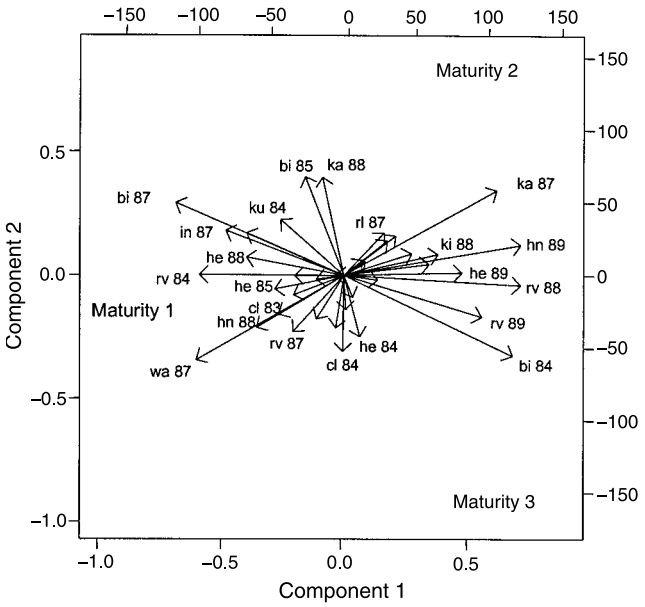

Fig. 3. Biplot of maturity × location × year BLUPs from the model including maturity effects fitted to the Queensland navy bean multi-environment trial data. For clarity, not all environments are labelled. (Maturity 1 = early.)

Trialing system efficiency

Changing the number of replications had the least (though not negligible) effect on the acceptance probability (Fig. 4), noting that in all instances 5 replicates (for example) is always more accurate than 3. The effect of year is lower (and location higher) than what might be expected because of the

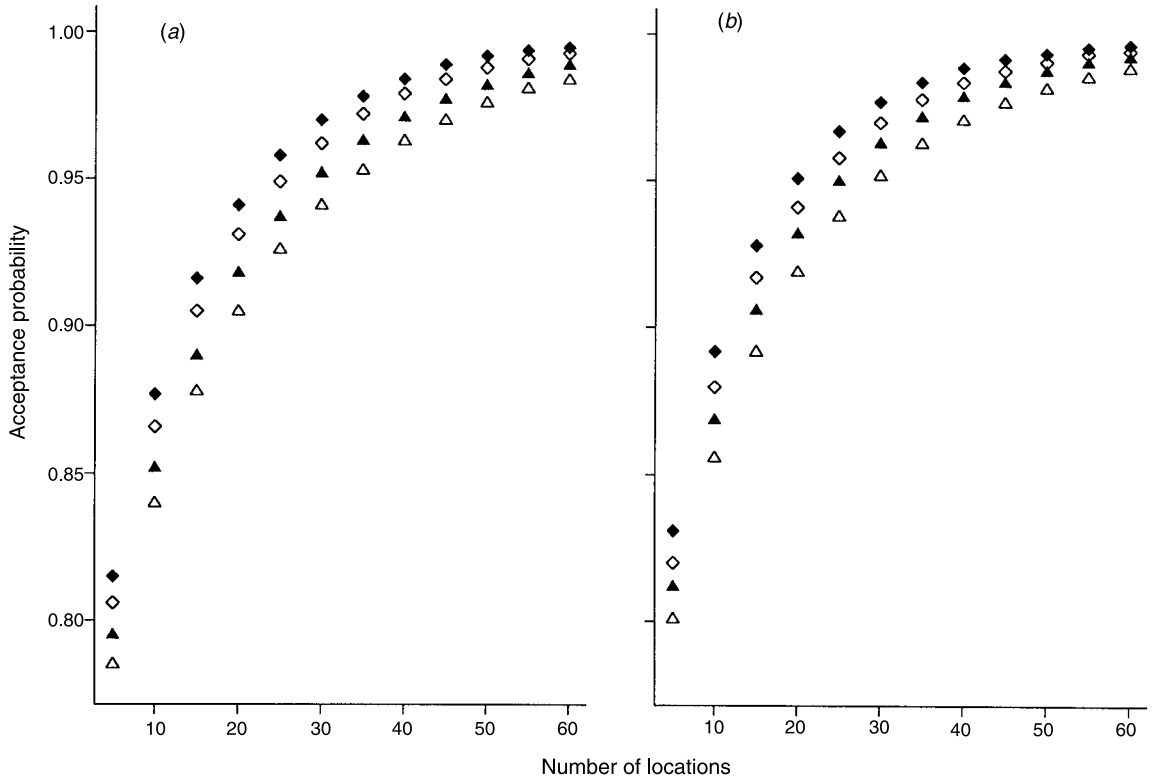

Fig. 4. Acceptance probabilities for a critical difference of 0 and true (unobserved) difference of 5% for combinations of the numbers of replicates (r ={3,5}), locations (m={5–60}), and years (n={2,3}). (*a*) Standard model (*GLY*), (*b*) extended model (GLY^+) with maturity covariate. Δ r = 3, n = 2; ▲ r = 5, n = 2; ◇ r = 3; n = 3; ◆ r = 5, n = 3.

absence of the σ^2_{gy} component (Table 6). The dominating effect of plot error implies that all effects contribute to the acceptance probabilities in a similar fashion. The effect of maturity on σ^2_{gly} is evidenced by the slightly higher displacement of the points for the extended model.

In the current trialing system the average number of locations per year is less than 10 and the number of replications is 3. In this system for a critical difference of zero when the true difference between the lines is 5.0%, the acceptance probability is approximately 0.8 with 2 years of testing (Fig. 4). That is, if the true (but unobservable) advantage of a new line is 5% then the probability of accepting that line is approximately 0.8 if the observed advantage is zero or greater.

Discussion

The modelling of the error variances has provided some insight and a useful summary of the factors influencing plot error variance over this series of experiments. Of the 2 imposed management practices, there was no evidence that irrigation was related to residual variance. However, there was a suggestion that row spacing could be a factor that warrants further investigation.

A notable feature of the variance components in Table 6 is the absence of the σ^2_{gy} component and the dominance of plot error. Advances in experimental design such as latinised row-column layouts (John and Williams 1995) and spatial analysis techniques (Cullis 1991) have since been introduced into the navy bean breeding program. Although at the time of writing there is not sufficient data for a direct comparison, these factors are likely to have a marked effect on residual variance, particularly at those locations identified in the error variance model as having persistent local effects.

Another feature of the extended model is that the line predictors (BLUPs) are estimators adjusted for maturity effect. If maturity is not included in the model the rankings of line performance include any systematic effect (either positive or negative) due to this factor. In the trials reported here, early and late lines were disadvantaged compared with average (mid) maturity lines. This was illustrated in these data by the movement of the early line Actosan from 9th in the standard model to 4th ranking in the extended model. This is interpreted as implying that the evaluation of the intrinsic worth of this line as a parent for transmitting yielding genes to its offspring was underestimated by the standard model which included in the predictor the systematic disadvantage of early maturity in these trials. Hence, intrinsic worth of the line as a parent is an estimator adjusted for any systematic factors affecting performance in METs. The BLUPs adjusted for systematic effects are defined here as intrinsic yielding

values (IYVs). Actosan has since been included as a parent in the breeding program.

The relative importance of σ^2_{gly} (after plot error) is not really surprising considering the geographical range of locations (latitude 28°25′ to 17°0′S) and highlights the difficulty of breeding for wide adaptation across Queensland. Of all the genetically determined traits thought likely to influence G×E interactions, maturity was the only one of any (statistical) significance, itself exhibiting a complex maturity×location×year interaction with negligible consistency shown in lower order interaction terms. The biplot of the maturity × environment BLUPs (Fig. 3) highlights key environments that discriminate between early and later maturing lines, suggesting that selecting for maturity could be advantageous. The importance of genotype maturity in reducing G×E is apparent, and since this study the navy bean breeding program has moved towards a stratified selection regime based on maturity.

The variance components and hence acceptance probabilities are estimated from a relatively small sample and as such are likely to be affected by the sampling errors of the components. Likewise, the estimates could well change with the addition of further populations of years, locations, and lines and the introduction of more efficient statistical design and analysis. The acceptance probabilities have been calculated by simply varying sample size and assuming that the variance components remain constant and are estimated from a representative sample of environments. Heterogeneity of components as seen with plot error, for example, suggests that the acceptance probabilities should be used with care. The estimated variance components and acceptance probabilities indicate that there is no redundancy in the sampling of test environments and an increase in trial locations sampled each year could be justified on the basis of efficiency gains; even when taking some account of maturity, an identifiable source of G×E interaction. This would need to be balanced against the cost effectiveness of such an increase for a small breeding program, the experimenter's risk policy (currently a probability of 0.8), and emerging evidence from more efficient statistical methods.

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