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An examination of the efficiency of Australian crop variety evaluation programmes

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Abstract

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We develop methods for determining the relative accuracy of CVEP based on selection of newly promoted entries. The accuracy of the current testing regimes for the Australian CVEP under study is determined. The accuracy of alternative schemes, with different numbers of years of testing, numbers of locations per year and numbers of replicates per trial is also examined. Cost effective methods for improving the accuracy of CVEP are discussed.

Keywords

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An examination of the efficiency of Australian crop variety evaluation programmes

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SUMMARY

In this paper we present the analysis of yield data from a broad cross-section of crop variety evaluation programmes (CVEP) conducted in Australia. The main sources of variety by environment interaction are 'non-static' interactions, namely those linked to seasonal influences. These contributed an average of 41·3% of the total variance. In contrast the static component accounts for only 5·3% of the total.

We develop methods for determining the relative accuracy of CVEP based on selection of newly promoted entries. The accuracy of the current testing regimes for the Australian CVEP under study is determined. The accuracy of alternative schemes, with different numbers of years of testing, numbers of locations per year and numbers of replicates per trial is also examined. Cost effective methods for improving the accuracy of CVEP are discussed.

INTRODUCTION

Resource allocation in crop variety evaluation programmes (CVEP) is an important issue for the plant breeding industry in Australia. There is increasing pressure from governments and funding bodies to reduce the cost of obtaining information regarding the comparative performance of elite lines and commercial varieties. A cost reduction may, however, affect the reliability of the information to an extent that would decrease the response to selection. The economic impact of such outcomes has been examined in detail by Brennan *et al*. (1998) for the wheat variety evaluation programme conducted by NSW Agriculture. This type of study requires estimates of the relative magnitude of the sources of variation in data arising from CVEP. Brennan *et al*. (1998) used variance components from Cullis *et al*. (1996), who examined yield data for 1982–1991 for the NSW wheat programme.

The Australian Crop Accreditation System (ACAS) funded by the Grains Research and Development Corporation stipulates minimal specifications for the release of accredited data on a range of traits for most of the commercially significant crops grown in Australia. In particular, for yield, specific details concerning the numbers of locations, years and replications are given. The statistical and economic bases for these criteria have not been rigorously developed.

Thus the primary objective of this paper is to enumerate the relative magnitude of sources of variation (variance components) in current Australian CVEP. A secondary aim is to develop a mechanism for evaluating the efficiency of these programmes based on the estimated variance components.

The traditional approach for determining the relative efficiency of CVEP is based on acceptance probabilities (Patterson *et al*. 1977). These were developed in the context of statistical analyses in which variety effects are considered as fixed. Cullis *et al*. (1996) assumed random variety effects. The validity of this assumption is discussed in detail by Smith & Cullis (2000) and supported by Patterson & Silvey (1980) who imply that the assumption of random variety effects is more appropriate. The aim of our paper is to develop a method for measuring the efficiency of CVEP when variety effects are assumed random. We focus on the two major selection issues in late stage variety testing. The first concerns the retention of entries from one year to the next. Due to the cost of variety evaluation there is a strict limit on the total number of entries tested each year (in most programmes this is about 30). Promising new breeding lines can therefore only be added if existing material

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is discarded. The other key selection issue concerns the commercial release of varieties. When selecting entries to be retained for further testing or to be recommended for commercial release it is important to maintain a large response to selection. We develop methods for the evaluation of CVEP based on response to selection. They require derivation of the posterior distribution of the true and estimated genetic effects.

This paper is arranged in two main sections. In the first section we present estimates of variance components for a range of Australian CVEP. The data-sets and statistical methods are described. In the second section we consider the relative efficiency of these CVEP based on the criterion of response to selection. The paper concludes with a discussion of the implication of the accuracy of the current CVEP and ways to improve their efficiency.

DESCRIPTION OF DATA

Yield data from final stage testing trials (often known as S4 trials) conducted from 1989 to 1997 have been used for this investigation. Table 1 presents the crops and the state-based programmes under consideration. In most cases 6 years of data is used, with a minimum of 4 years. Trials had either 3 (NSW, WA) or 4 replicates (SA, VIC). Trial designs included incomplete block designs (SA and VIC) and neighbour balanced row-column designs (NSW and WA). Individual trial data were analysed using the methods of Gilmour *et al.* (1997) and variety trial means and weights were saved for subsequent analysis (Smith & Cullis 2000).

Trial site locations in SA and VIC are almost invariant across years, but this is not the case in NSW and WA. For example, the trial at Ardlethan (NSW) may be moved up to 50 km from year to year. Trials in SA and VIC have been classified according to year, region and location within region, while trials in NSW and WA are classified by year and region alone. Regions relate either to geographical or rainfall classifications. In NSW, wheat and barley are evaluated in either early (E) or main (M) season trials. Varieties are classified according to maturity and are generally grown in the appropriate trial series. This information is summarized in Table 1.

Varieties were retained in the data-sets if they appeared in at least six trials. Variety covariates were

Table 1. *Description of the data-sets used*

Crop	Years	Regions	Region type	Locations	Trials
New South Wales (NSW)					
Barley (E)	92–97	6	Geog	—	124
Barley (M)	92–97	6	Geog	—	335
Wheat (E)	90–97	4	Geog	—	218
Wheat (M)	90–97	4	Geog	—	402
Lupins	90–97	2	Rain	33	113
Peas	90–97	2	Geog	—	86
South Australia (SA)					
Wheat	92–97	6	Geog	26	147
Barley	92–97	6	Geog	21	115
Oats	92–97	6	Geog	16	82
Lentils	92–97	4	Geog	8	36
Peas	92–97	4	Rain	13	62
Canola	94–97	6	Geog	19	54
Lupins	92–97	5	Geog	19	81
Victoria (VIC)					
Wheat	89–97	7	Geog	40	260
Barley	92–97	4	Geog	25	112
Lentils	92–97	2	Geog	14	40
Peas	92–97	5	Geog	22	79
Western Australia (WA)					
Wheat	91–97	19	Geog	—	495
Barley	91–97	20	Geog	—	338
Oats	91–97	18	Geog	—	456
Lupins	92–97	21	Geog	—	310
Peas	92–97	21	Geog	—	208

Table 2. *Description of variety covariates*

Crop	Variety Covariate
NSW	
Lupins	Type: 1 = Angustifolius; 2 = Albus
SA	
Wheat	Type: 1 = Durum; 2 = Other
Oats	Type: 1 = Hulless; 2 = Dwarf; 3 = Tall
Lentils	Maturity: 1 = Early maturing; 2 = Mid; 3 = Late
WA	
Oats	Type: 1 = Dwarf; 2 = Tall

recorded where appropriate (see Table 2). For example, for lupins in NSW, the two species are grown in the same trials, though variety recommendation and release is only relevant within species.

Table 3 presents a range of summary statistics for each data-set. Several of the crops of lesser commercial value have limited coverage of locations and varieties, however the size of the data-sets for wheat and barley for all states is significant. The range of yields for each data-set reflects the fluctuations in growing season rainfall experienced in the Australian cropping belt. There is a high turn-over of varieties. In particular WA and VIC discard over 50% of varieties after one year of testing.

Statistical models

The total variation in the data is divided into components based on variety main effects, variety by environment interaction and error arising from the fact that the data are estimated means. Environments are partitioned into regions (R), locations within regions (R.L) and years (Y). The actual subdivision depends on the state and crop programme. The major differences are due to the use of invariant trial sites (SA and VIC) and the inclusion of variety covariates. The main effects of the variety covariates are included as fixed effects; interactions of the covariates with environments are included as random effects. Table 4 presents the ANOVA decomposition which was adopted for the analysis of these data. Terms involving

Table 3. *Summary statistics for data-sets*

Crop	Number of means	Yield (t/ha) mean	Yield (t/ha) range	Number of varieties	% varieties tested 1 year	2 years	⩾ 3 years
NSW							
Barley (E)	1851	3·36	(1·03, 7·48)	109	39	30	31
Barley (M)	10211	3·31	(0·42, 6·55)	400	43	28	29
Wheat (E)	2985	3·74	(0·37, 8·70)	70	37	19	44
Wheat (M)	7289	3·50	(0·32, 8·13)	151	46	13	41
Lupins	1889	1·69	(0·18, 3·99)	124	62	19	19
Peas	2330	2·03	(0·25, 4·43)	177	22	27	51
SA							
Wheat	5389	2·25	(0·24, 5·83)	97	45	21	34
Barley	2458	2·66	(0·28, 5·91)	47	28	30	43
Oats	2065	2·80	(0·36, 6·25)	66	52	20	29
Lentils	325	1·62	(0·31, 3·39)	14	7	21	71
Peas	1205	2·06	(0·28, 3·61)	41	34	12	54
Canola	1223	1·73	(0·41, 3·35)	112	64	23	13
Lupins	950	1·64	(0·16, 4·19)	34	18	26	56
VIC							
Wheat	7942	3·10	(0·27, 8·26)	174	57	17	26
Barley	3309	2·96	(0·40, 6·29)	107	64	21	15
Lentils	401	1·30	(0·09, 3·27)	33	48	21	30
Peas	2381	2·19	(0·24, 4·69)	145	41	17	42
WA							
Wheat	12955	2·29	(0·31, 5·69)	197	52	20	28
Barley	6376	2·52	(0·27, 5·76)	167	69	15	17
Oats	6743	2·49	(0·69, 5·57)	150	51	25	23
Lupins	4765	1·47	(0·17, 2·97)	130	68	15	18
Peas	2915	1·42	(0·21, 3·37)	98	52	24	23

Table 4. *ANOVA decomposition*

Term	Decomposition	Type
Variety		
	variety	R
Environment		
	year†	F
	region†	F
	region.loc*†	F
	year.region†	F
	year.region.loc*†	F
Variety.Environment		
	variety.year	R
	variety.region	R
	variety.region.loc*	R
	variety.year.region	R
	variety.environment‡	R
Error		
	error	R

* These decompositions were included for SA and VIC data-sets.
† For computational efficiency these effects were not fitted but were replaced by a single factor indexing environments. This produces equivalent estimates of variance components.
‡ This term represents the remaining variety by environment interactions.

variety covariates are excluded for brevity. Note that the term 'variety.environment' (V.E) denotes residual variety by environment interaction. It usually reflects the highest order interaction, for example, V.Y.R.L.

All analyses were conducted in ASREML (Gilmour *et al.* 1999), a programme for estimation of variance components using REML (Patterson & Thompson 1971). It uses the average information algorithm (Gilmour *et al.* 1995) and sparse matrix methods. This enables very large data-sets to be analysed. For example the mixed model for the WA wheat data involved 45452 equations. Trial mean yields are weighted to account for error variance heterogeneity between trials, unequal replication and spatial adjustments within trials (see Smith & Cullis 2000).

VARIANCE COMPONENTS: RESULTS AND DISCUSSION

REML estimates of the variance components are presented in Table 5 as percentages of total variance. The major source of variation is within-trial error, ranging from 25% of total variance up to 61%. The next largest source of variation was attributable to the high order variety by environment interactions, V.E. This ranged from 16% to 60%. Variance components associated with V and V.R were small by comparison, ranging from 5% to 33% for V and 0% to 8% for V.R. The impact of these results is significant for the reporting of results. Variety effects for variety by region summaries are reported as the sum of the Best Linear Unbiased Predictors (BLUPs) of the variety and variety by region effects (Smith & Cullis 2000). These effects are often very small as a result of the size of the V and V.R components relative to the total of the other components.

CVEP have traditionally focused on the importance of regionally based variety recommendations. This implies that a significant amount of the variety by environment interaction can be explained by the V.R or the V.R.L terms. The results from this study do not support this argument. To illustrate this more clearly consider the classification of variety by environment components as 'static' (sources which remain constant from year to year, namely V.R+V.R.L) or 'non-static' (sources linked to seasonal variation, V.Y+V.Y.R+V.E). The mean static variety by environment variance is 5·3% compared with 41·3% for the non-static component.

These results are consistent with the findings of Cullis *et al.* (1996) and Frensham *et al.* (1997) who demonstrate that more complex reporting of varietal performance is required. This would include the use of both environmental and varietal covariates to better explain the non-static component. Current work is focused on the derivation of data-dependent environmental covariates which explain large proportions of the variety by environment variance (Piepho 1997; Smith *et al.* 1998). This is discussed in greater detail in the final discussion of results.

ACCURACY OF CROP VARIETY EVALUATION PROGRAMMES

In this section we evaluate the relative accuracy of a range of testing schemes (including current practice) for all of the CVEP examined in the section on variance components. The effect of altering the number of years of testing, the number of trials per year and the number of replicates per trial is investigated. Schemes are compared on the basis of the yield response associated with the selection of entries to be retained for further testing or recommended for commercial release.

Varietal selection and recommendation is based on yield estimates from the analysis of data from all relevant CVEP trials. Smith & Cullis (2000) describe the mixed model analysis currently used in most Australian CVEP. The analysis provides BLUPs of variety and variety by region effects. Broad-based selection decisions are based on the former whereas selections on a regional basis involve the sum of the two.

A key determinant of the accuracy of a CVEP is the correlation between the true variety effects and those predicted from the mixed model analysis. The

Table 5. *REML estimates of variance components as a percentage of total variance for all CVEP; variety by environment components classified as static or non-static*

	Static			Non-static				
Crop	V	V.R	V.R.L	V.Y	V.Y.R	V.E	Error	Total $(t/ha)^2$
NSW								
Barley (E)	15	0	—	12	12	36	25	0·571
Barley (M)	19	3	—	5	4	34	36	0·443
Wheat (E)	12	3	—	9	5	37	34	0·416
Wheat (M)	12	1	—	6	4	38	39	0·343
Lupins	5	0	4	5	0	25	60	0·094
Peas	15	2	—	14	5	28	35	0·344
SA								
Wheat	15	6	3	9	9	23	35	0·155
Barley	13	3	4	15	4	30	31	0·243
Oats	13	1	6	5	2	30	44	0·335
Lentils	5	0	5	5	5	26	54	0·206
Peas	9	4	4	6	1	34	42	0·246
Canola	33	0	5	1	4	11	45	0·176
Lupins	5	2	4	8	3	17	61	0·145
VIC								
Wheat	8	7	2	10	4	25	43	0·240
Barley	14	2	5	13	3	26	37	0·318
Lentils	22	0	0	36	0	15	27	0·338
Peas	17	0	6	8	5	20	45	0·340
WA								
Wheat	18	8	—	5	8	27	34	0·135
Barley	19	7	—	5	3	35	31	0·193
Oats	16	6	—	5	4	39	31	0·189
Lupins	11	8	—	3	6	29	42	0·080
Peas	7	5	—	4	8	34	43	0·108

stronger is the correlation the higher is the response to selection. In order to calculate the correlation we must derive the joint distribution of the true and predicted effects. In the following we present results regarding the joint distribution of true and predicted genetic effects in a balanced multi-environment trial (MET) data-set. Results for a general linear mixed model are given in the appendix. For simplicity, proofs are omitted but can be found in Hunt & Cullis (1999).

Theoretical results

Consider a balanced MET data-set in which n_1 varieties have been tested for n_2 years. Each year a total of $n_3 n_4$ trials are conducted, where n_3 is the number of regions and n_4 the number of fixed locations within regions. Each trial has n_5 replicates. This setting reflects the CVEP in SA and VIC.

The corresponding linear mixed model for the data vector, y, is

$$y = X\tau + Z_1 u_1 + Z_{12} u_{12} + Z_{13} u_{13} + Z_{123} u_{123} + Z_{134} u_{134} + Z_{1234} u_{1234} + e \quad (1)$$

where X is the design matrix for the fixed effects of environment, a factor representing the factorial combination of year (Y), region (R) and location (L). The random effects design matrices, $Z_{(i)}$, are the design matrices for variety (V), V.Y, V.R, V.Y.R, V.R.L and V.Y.R.L. The vectors τ and $u_{(i)}$ are the corresponding fixed and random effects and e is the vector of errors (or u_{12345}). The mixed model analysis provides Best Linear Unbiased Estimates (BLUEs) of the fixed effects, denoted $\hat{\tau}$, and BLUPs of the random effects, denoted $\tilde{u}_{(i)}$ (see appendix). The decomposition of the total variance is presented in ANOVA form in Table 6. The associated degrees of freedom involve $\nu_i = n_i - 1$.

Each pair of vectors of random effects in equation 1 is assumed to be independent. Further we assume that the elements of each vector are identically and independently distributed Gaussian deviates with mean zero and variance $\sigma^2_{(i)}$, viz (σ^2_1, σ^2_{12}, σ^2_{13}, σ^2_{123}, σ^2_{134}, σ^2_{1234}, $\sigma^2_{12345} = \sigma^2$). Table 6 presents the stratum variances, θ_i (see Nelder 1964; Hunt & Cullis 1999).

Simplified expressions for the variance matrix of the true and predicted variety effects as functions of

Table 6. *ANOVA decomposition for random terms in the balanced MET*

Strata	D.F.		Stratum variance ($\sigma^2 = \sigma^2_{12345}$)
Variety			
variety (V)	ν_1	θ_1	$n_2n_3n_4n_5\sigma^2_1+n_3n_4n_5\sigma^2_{12}+n_2n_4n_5\sigma^2_{13}+n_4n_5\sigma^2_{123}+n_2n_5\sigma^2_{134}+n_5\sigma^2_{1234}+\sigma^2$
Variety.Environment			
V.year (V.Y)	$n_1\nu_2$	θ_2	$n_3n_4n_5\sigma^2_{12}+n_4n_5\sigma^2_{123}+n_5\sigma^2_{1234}+\sigma^2$
V.region (V.R)	$n_1\nu_3$	θ_3	$n_2n_4n_5\sigma^2_{13}+n_4n_5\sigma^2_{123}+n_2n_5\sigma^2_{134}+n_5\sigma^2_{1234}+\sigma^2$
V.Y.R	$n_1\nu_2\nu_3$	θ_4	$n_4n_5\sigma^2_{123}+n_5\sigma^2_{1234}+\sigma^2$
V.R.loc (V.R.L)	$n_1n_3\nu_4$	θ_5	$n_2n_5\sigma^2_{134}+n_5\sigma^2_{1234}+\sigma^2$
V.Y.R.L	$n_1n_3\nu_2\nu_4$	θ_6	$n_5\sigma^2_{1234}+\sigma^2$
Error			
V.Y.R.L.rep	$n_1n_2n_3n_4\nu_5$	θ_7	σ^2

Table 7. *Number of trials within region per year*

Crop	Min	Max	Mean
NSW			
Barley (E)	1	12	4
Barley (M)	3	21	10
Wheat (E)	1	17	7
Wheat (M)	4	29	13
Lupins	1	20	7
Peas	5	10	7
SA			
Wheat	1	8	4
Barley	1	5	3
Oats	1	4	2
Lentils	1	3	2
Peas	1	3	3
Canola	1	6	3
Lupins	2	4	3
VIC			
Wheat	1	10	5
Barley	1	8	5
Lentils	1	7	4
Peas	1	6	3
WA			
Wheat	1	14	4
Barley	1	6	3
Oats	1	11	4
Lupins	1	7	3
Peas	1	6	2

the stratum variances can be obtained. These are presented in the following two theorems (Hunt & Cullis 1999).

Theorem 1 *The variance matrix of* $(u_1, \tilde{u}_1)$ *for the balanced MET above is*

$$\begin{bmatrix} \sigma^2_1 I_{n_1} & \sigma^2_1 h^2_1 K_1 \\ symm & \sigma^2_1 h^2_1 K_1 \end{bmatrix}$$

where $K_1 = I_{n_1} - J_{n_1}/n_1$, $h^2_1 = \sigma^2_1 n_2n_3n_4n_5/\theta_1$ *and* J_{n_1} *is an* $n_1 \times n_1$ *matrix of ones.*

Theorem 2 *The vector of true and predicted variety effects within a region for the balanced MET above is given by* $(u_1 + A_{13}u_{13}, \tilde{u}_1 + A_{13}\tilde{u}_{13})$, *for a suitably chosen matrix* A_{13}. *The associated variance matrix is*

$$\begin{bmatrix} (\sigma^2_1+\sigma^2_{13}) I_{n_1} & b^2_{13} K_1 \\ symm & b^2_{13} K_1 \end{bmatrix}$$

where

$$b^2_{13} = \sigma^2_1 h^2_1 + \sigma^2_{13} h^2_{13} + \frac{\sigma^2_{13} h^2_1}{n_3}\left(\frac{\sigma^2_{13}}{n_3\sigma^2_1} + 2 - \frac{h^2_{13}}{h^2_1}\right)$$

$$h^2_{13} = \sigma^2_{13} n_2n_4n_5/\theta_3$$

Response to selection for balanced METs

The yield response associated with selection of entries to be retained for further testing or recommended for commercial release is presented in Table 8. We have assumed that 30 entries have been tested in a balanced MET and that the 5 entries with the highest BLUPs have been selected. The number of regions is as given in Table 1 for each crop. The number of locations per region was set to the mean number for each crop (see Table 7). The number of replicates was set to 3 in all cases. Varying the number of replicates from 2 to 4 had little effect on the responses. Responses are presented for both overall and regional selection and for 1, 2 and 3 years of testing. They are expressed relative to the maximum achievable response for the given configuration, that is, when the heritability is unity. By definition, this relative response to selection is equivalent to the correlation between the observed and predicted variety effects.

The responses in Table 8 for 1 and 2 years of testing correspond to the current testing regimes. Alternative schemes involving larger numbers of years and locations per region were investigated. The response to selection for a range of numbers of years and

Table 8. *Response to selection (proportion of maximum) for each CVEP for one, two and three years of testing, three replicates and the current number of regions and locations per region*

	Overall				Regional			
Crop	1 year	2 years	3 years	max (t/ha)	1 year	2 years	3 years	max (t/ha)
NSW								
Barley (E)	0·72	0·82	0·86	0·300	0·72	0·82	0·86	0·300
Barley (M)	0·86	0·92	0·94	0·293	0·85	0·91	0·91	0·314
Wheat (E)	0·71	0·81	0·85	0·227	0·69	0·80	0·85	0·251
Wheat (M)	0·79	0·88	0·90	0·208	0·78	0·86	0·90	0·214
Lupins	0·57	0·70	0·77	0·070	0·57	0·70	0·77	0·070
Peas	0·67	0·77	0·81	0·231	0·67	0·78	0·83	0·248
SA								
Wheat	0·73	0·82	0·86	0·154	0·71	0·80	0·85	0·181
Barley	0·64	0·76	0·81	0·180	0·61	0·72	0·79	0·202
Oats	0·75	0·84	0·89	0·212	0·73	0·82	0·87	0·221
Lentils	0·52	0·64	0·70	0·099	0·52	0·64	0·70	0·099
Peas	0·66	0·76	0·81	0·154	0·62	0·74	0·80	0·185
Canola	0·95	0·98	0·98	0·247	0·95	0·97	0·97	0·248
Lupins	0·53	0·65	0·72	0·083	0·50	0·62	0·70	0·103
VIC								
Wheat	0·63	0·74	0·79	0·145	0·66	0·77	0·81	0·199
Barley	0·67	0·78	0·84	0·218	0·66	0·77	0·83	0·234
Lentils	0·60	0·73	0·79	0·278	0·60	0·73	0·79	0·278
Peas	0·77	0·86	0·90	0·244	0·77	0·86	0·90	0·244
WA								
Wheat	0·86	0·92	0·94	0·159	0·81	0·87	0·90	0·193
Barley	0·87	0·92	0·94	0·194	0·80	0·87	0·89	0·229
Oats	0·85	0·91	0·94	0·176	0·79	0·86	0·89	0·206
Lupins	0·86	0·91	0·93	0·098	0·76	0·84	0·87	0·128
Peas	0·75	0·84	0·87	0·088	0·63	0·72	0·77	0·114

locations per regions for the wheat and barley CVEP are displayed in Figs 1 and 2. Response to selection for all other CVEP are available on request.

When there is no measurable variety by region interaction, selection is simply based on the overall performance. However, when there is variety by region interaction, selection may either be based on overall or regional performance. This decision rests with the crop variety evaluators and breeders. We present response to selection for both scenarios. When the variety by region interaction variance component is zero, the two sets are identical.

The responses to selection based on a single year of data are poor (Table 8). There are substantial gains in using data from 2 years of testing, but the response is still unacceptably low for many crops (only 6 out of the 22 have a response which is at least 90% of the maximum attainable for overall recommendations).

Discussion of results

It is relatively easy to obtain 2 years of data for promotion decisions, since most entries have had a single year of testing in S3 trials prior to testing in S4 trials. S3 trials generally involve a much larger number of varieties and are usually conducted at a subset of the S4 locations within each region. It is difficult to extend the length of testing at the S4 stage beyond a single year before making promotion decisions so that alternative methods for increasing response to selection must be sought. Increasing the number of locations per region does not provide the answer. Figs 1 and 2 show that the effect of increasing the number of locations is much less than that of increasing the number of years. In fact, for barley, there is very little effect at all. Additionally there is a significant cost associated with increasing the number of locations per region. There has been a reduction in the scale of testing for most CVEP in Australia over the past 5 to 10 years, and this trend is unlikely to change with current funding.

We believe that the greatest and most cost effective gains can be obtained through the use of a composite S3 and S4 trial data-set and a more rigorous and appropriate statistical analysis. Conducting an analysis based on combined S3 and S4 data can introduce

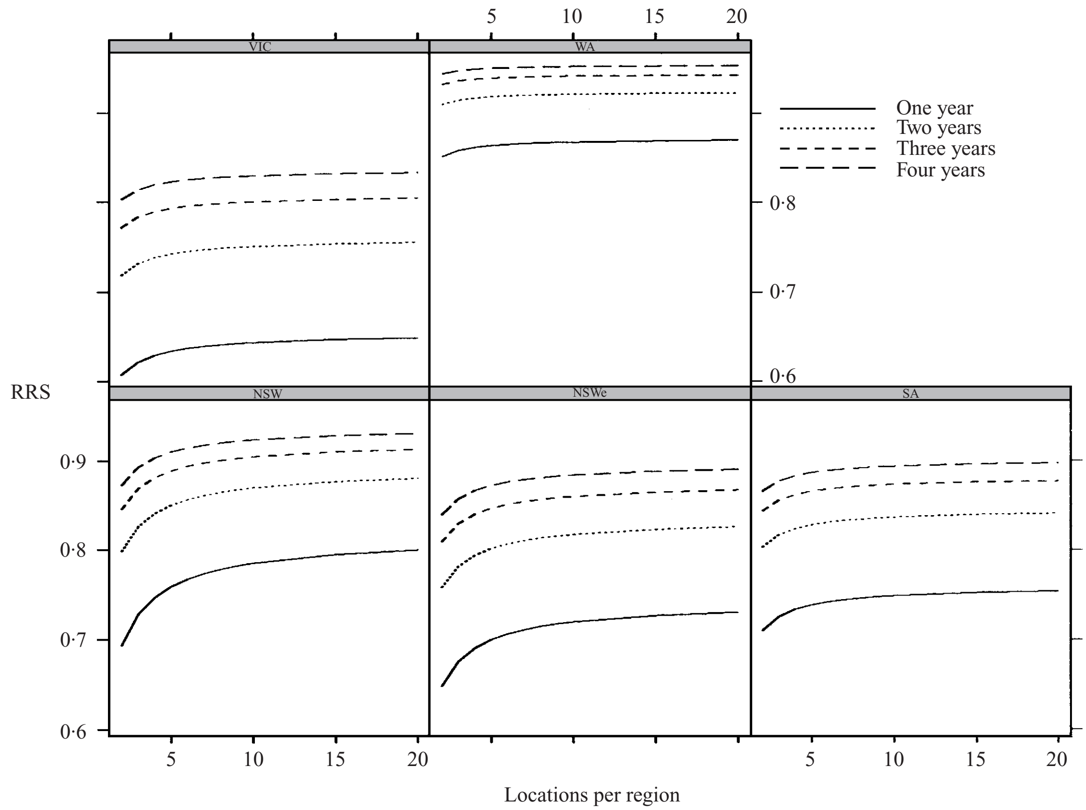

Fig. 1. The effect of the number of years and locations on the relative response to selection (RRS) for wheat CVEP (three replicates and the current number of regions).

bias in the estimation of variance components as there has been selection at the S3 stage (Thompson 1977). This can be avoided by appropriately modelling the genetic variance and covariance structure both between and within S3 and S4 trials. Smith *et al.* (1998) present an analysis for MET data in which the genetic effects are described by a multiplicative model and the plot errors by a separable spatial model for each trial. They also included important varietal covariates, such as maturity scores to assist with the interpretation of variety by environment interactions. The gains over the more traditional 2-stage variance component approach are numerous.

The multiplicative model approach advocated by Smith *et al.* (1998) is being used for the analysis of early generation variety trials (Cullis *et al.* 1998) throughout most public plant breeding programmes in Australia. Data from these METs include only a few environments, but a much larger number of entries than in CVEP trials. There are two main impediments to the adoption of the Smith *et al.* (1998) approach for the analysis of late stage variety trial data from CVEP. The analysis requires access to original plot data. These data are largely unavailable in electronic form for many CVEP in Australia and therefore the implementation of well designed and efficient database systems for the storage, interrogation and retrieval of CVEP data is a priority. Secondly, the computational burden for large numbers of environments with the current numerical algorithm implemented in ASREML (Gilmour *et al.* 1999) is prohibitive. This problem is being addressed and we are confident of being able to analyse data-sets with over 100 trials in a one-stage analysis in the near future.

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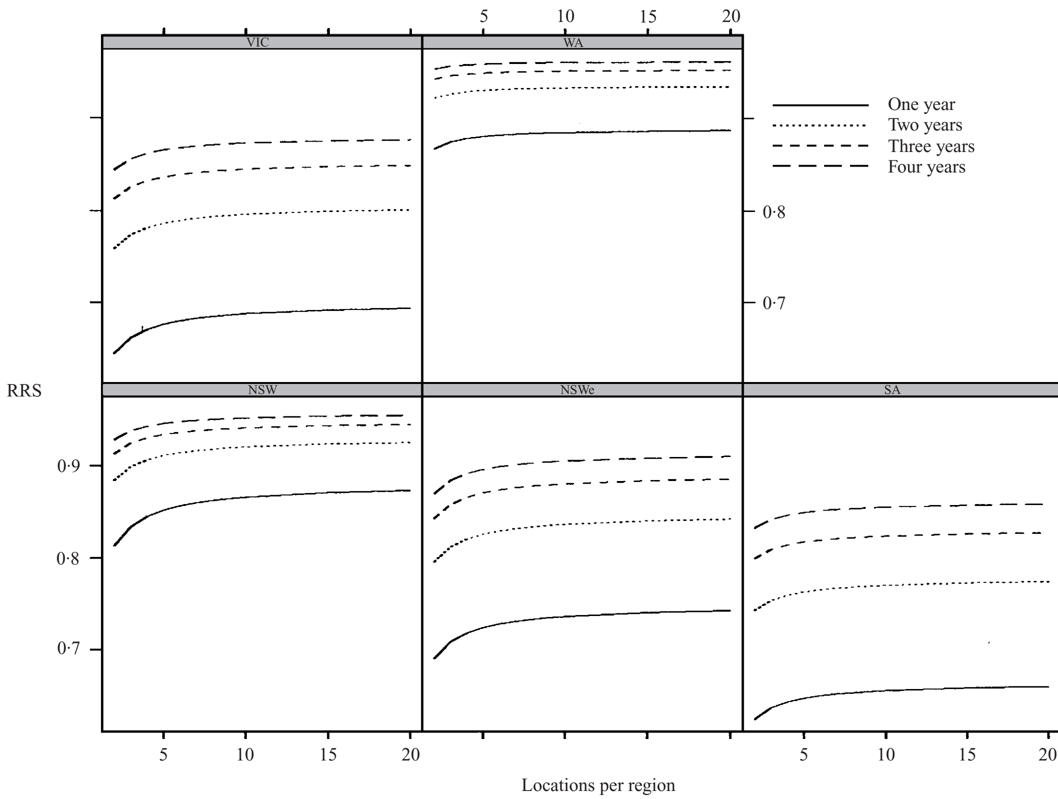

Fig. 2. The effect of the number of years and locations on the relative response to selection (RRS) for barley CVEP (three replicates and the current number of regions).

APPENDIX

Here we derive the joint distribution of true and predicted random effects in a general linear mixed model. Consider the linear mixed model for the data vector, y

$$y = X\tau + Zu + e \qquad (2)$$

where e is the vector of errors, $\tau^{(t\times 1)}$ is the vector of fixed effects with design matrix $X^{(n\times t)}$ (assumed to have full column rank), $u^{(b\times 1)}$ is the vector of random effects with design matrix $Z^{(n\times b)}$.

We assume that the joint distribution of the random components in equation 2, (u, e) is Gaussian, with mean zero and variance matrix

$$\begin{bmatrix} G & 0 \\ 0 & R \end{bmatrix}$$

The marginal distribution of y is then

$$y \sim \mathrm{N}(X\tau, (ZGZ' + R))$$

The BLUE of τ and BLUP of u are obtained by solving the mixed model equations, given by

$$\begin{bmatrix} X'R^{-1}X & X'R^{-1}Z \\ Z'R^{-1}X & (Z'R^{-1}Z + G^{-1}) \end{bmatrix} \begin{bmatrix} \hat{\tau} \\ \tilde{u} \end{bmatrix} = \begin{bmatrix} X'R^{-1}y \\ Z'R^{-1}y \end{bmatrix} \qquad (3)$$

The matrix on the left hand side of equation 3 is known as the coefficient matrix and is denoted by C. Various forms are available for the solutions. For example,

$$\hat{\tau} = (X'V^{-1}X)^{-1}X'V^{-1}y$$
$$\tilde{u} = GZ'Py$$

where $V = ZGZ' + R$ and
$P = R^{-1} - R^{-1}WC^{-1}W'R^{-1}$, $W = [X\ Z]$.

Theorem 3 *The joint distribution of* $(u, \tilde{u})$ *is Gaussian, with mean zero and variance matrix*

$$\begin{bmatrix} G & GZ'PZG \\ symm & GZ'PZG \end{bmatrix}$$

where $GZ'PZG = G - C^{22}$ *and* C^{22} *is the portion of* C^{-1} *corresponding to* u.

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