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Optimal strategies for regional cultivar testing

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In undertaking cultivar trials, the variability of the response of the cultivars to the different environments in which they are grown introduces the possibility of release errors and non-release errors in the decisions made on the basis of the trial results. In this article a model is developed that accounts for the economic costs of those errors as well as the costs of operating the trials, and enables the features of the optimal cultivar testing program to be identified. The model is illustrated by application to wheat cultivar trials in central and southern NSW.

1. Introduction

In plant breeding programs, assessment of potential new cultivars involves comparing their characteristics (for example, yield and disease resistance) to those of standard cultivars in the field. Cultivar comparisons usually involve a series of field trials replicated over sites and years. The usual aim of these trials is to identify repeatable differences between cultivars in a given environment, and thus determine which potential new cultivars are genuinely superior to the standard or commonly grown cultivars. However, the very nature of both the cultivars and the environments in which field testing occurs commonly introduces risks in selecting or identifying truly superior cultivars.

Cultivars rarely perform uniformly across locations and years, because they interact with the unique environmental conditions under which they are grown in each trial. Consequently, the ranking of cultivars is seldom the same at each location in the same year or in each year at the same location. The interaction of cultivars with their test environment (genotype by environment interaction — $G \times E$) means that it is unlikely for superior cultivars to be identified on the basis of a single year's testing at a single site.

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Various spatial and statistical analyses have been applied to further our understanding of $G \times E$ interaction and its impact on the selection of superior cultivars (Fox and Rosielle 1982a, b; Shorter and Norman 1983; Brennan *et al.* 1981; Byth, Eismann and DeLacy 1976; Gleeson and Cullis 1987; Cullis and Gleeson 1991). The study of $G \times E$ interaction has facilitated the design of field testing programs.

The management of field testing programs must address the issue of how many years, locations and plot replications to use in field testing cultivars so that the researcher is reasonably sure that a *truly* superior cultivar has been identified. This issue has almost solely concerned biologists and statisticians (Sprague and Federer 1951; Finney 1964; Hamblin, Fisher and Ridings 1980; Brennan *et al.* 1981; Patterson *et al.* 1977; Talbot 1984), rather than economists. The work in this area, perhaps to be expected, has generally involved analyses that either fail to consider explicitly financial costs[1] (Finney 1964; Hamblin *et al.* 1980; Brennan *et al.* 1981; Patterson *et al.* 1977; Talbot 1984), or that capture only some of the costs of field testing (Sprague and Federer 1951). Prior to Kingwell (1987), no study explicitly accounted for the opportunity costs and actual costs of foregone cultivar superiority through errors in the testing program.

Two examples of such costs can be identified (Kingwell 1987). First, field tests may falsely indicate that a new cultivar is higher yielding than standard or commonly grown cultivars. Hence, when the new cultivar is adopted on farms, farmers forego some yield as well as incurring costs of adopting the new cultivar. Second, field test results may falsely indicate a new cultivar yields no more than the standard or commonly grown cultivars. Failure to identify this superior cultivar for adoption involves an opportunity cost of foregone yield during the period when the cultivar would have been grown.

The more trials that are conducted in a given environment, the greater the accuracy of determining the value of new cultivars. The greater accuracy obtained from an increased number of trials provides benefits through reducing the likelihood of errors arising from cultivar decisions made with fewer data.

In this article, field testing for the purpose of identifying superior cultivars is examined. First, a decision model that builds on Cullis *et al.* (1996a, b) and Kingwell (1987) is developed, in which all costs (including opportunity costs) associated with field testing and the acceptance probabilities derived from field trials are incorporated. Second, the model is applied to a wheat growing region in central and southern NSW. Finally, the results are

[1] Patterson *et al.* (1977) and Talbot (1984) implicitly recognise the importance of such costs in their concepts of critical difference and acceptance regions.

discussed and conclusions are drawn for field testing within the region, and implications for the field testing of other crops in other regions are also highlighted.

2. Model of field testing of cultivars: field trials

For simplicity, consider the situation where farmers in a given region are currently growing one cultivar, V_0. The objective of the field testing program is to evaluate a set of n advanced breeding lines ($V_1, \ldots, V_n$) to determine which one is best in that region's environment, and whether it is superior to V_0. The tests are carried out over m sites each year for k years.

The model described here focuses on field testing for merit. The analysis assumes that the sole purpose of field testing is to identify whether a new cultivar, when grown at sites representative of some region, does in fact on average provide a superior outcome to the standard cultivar(s). While in practice the merit of a cultivar is generally measured by yield per hectare, conceptually the merit could be a weighted index of all inherent cultivar characteristics such as yield and quality traits. For convenience, in this article the term yield is used to describe the merit of a cultivar.

From the testing, the best cultivar is found to be V_i, which implies that

$$\overline{Y}_i > \overline{Y}_j, \text{ for all } j \neq i \ (1 \leq j \leq n), \tag{1}$$

where $\overline{Y}_i$ is the average yield per hectare of cultivar V_i over all trials.

2.1 Costs of cultivar testing

In cultivar testing, replicated trials are conducted on a number of sites over a number of years, and include standard or check cultivars as well as the lines being evaluated. The total trial costs, D, incurred by the agency conducting the field trials are:

$$D = \sum_{t=1}^{k} [M_t + mF_t + mr(n+s)G_t], \tag{2}$$

where:

k = the number of years of testing;
m = the number of sites each year;
n = the number of lines tested;
r = the number of replications in the trials;
s = the number of check cultivars in each trial;
M_t = the overhead (administrative) agency costs associated with the trials in year t;

F_t = the variable costs per site in year t;
G_t = the variable costs per plot in year t.

There may be further costs (L) incurred when a new cultivar is released. L can be defined as:

$$L = S + H + J, \tag{3}$$

where:

L = the cost of releasing a new cultivar;
S = the cost of producing farmer seed for a new cultivar;
H = the cultivar registration costs;
J = the publicity costs associated with the release of a new cultivar.

The cost of seed of the new cultivar to the farmer is not a net cost to the system, as it is a transfer payment from the farmer to the breeding agency in the case for publicly bred cultivars. For privately developed cultivars, the firm's profits can be included in the cost of producing seed of the new cultivar. The model would need to be extended if the differences in seed costs were a significant factor in the farmer's decision to adopt new cultivars.

2.2 Benefits of cultivar testing

The benefits of the cultivar testing are the total (farmer) benefits from growing V_i rather than V_0. That is,

$$B_t = A_{it}[(P_{it}Y_i - P_{0t}Y_0) - (C_{it} - C_{0t})], \tag{4}$$

where:

B_t = the total benefits in year t;
A_{it} = the total area sown (in hectares) to cultivar i in year t;
P_{it} = the price obtained for cultivar i in year t;
Y_i = the true yield of cultivar i;
C_i = the cost of growing cultivar i in year t.

We make two assumptions so that equation 4 can be simplified. First, we assume that there is no change in production costs per hectare with the new cultivar (i.e., $C_{it} = C_{0t}$). Second, there is no real change in price over time (i.e., $P_{it} = P_i$). In addition, the true yield is not known at the time of cultivar adoption; only the trial results are known. Trial results may not represent the true yield because the environments (years and sites) in which the testing was carried out may not be representative of the environments in which the crops will be grown commercially.

The estimated total benefits of cultivar V_i based on trial results, where the mean yield of V_i is $\overline{Y}_i$, are:

$$B_t = A_{it}(P_i\overline{Y}_i - P_0\overline{Y}_0) - A_{it}E_t, \tag{5}$$

where E_t is the total error costs per hectare in year t.

Since the benefits only arise subsequent to the cultivar testing, there is a lag of at least k years (where there are k years of testing) between the beginning of testing and the beginning of cultivar adoption. The life of a successful cultivar is taken as x years from its initial adoption. The pattern of adoption and replacement of a cultivar during its productive life is discussed in further detail below.

2.3 Optimising the model

The purpose of the model is to identify the optimal testing strategy, based on an assessment of all costs and benefits of the testing regime used.[2] The objective function of the model is to maximise the net returns from cultivar testing.

The model is couched in terms of a non-linear programming problem. Algebraically, the objective function is:

$$Max[N] = B - D - L, \tag{6}$$

where:

N = the net benefits arising from the testing program;
B = the total gross benefits arising from the testing program;
D = the total agency cost associated with field testing.
L = the cost of releasing a new cultivar.

By incorporating equations 2, 3 and 5, equation 6 can be expanded to:

$$\begin{aligned} Max[N] = &\sum_{t=y+1}^{y+x}[A_{it}(P_iY_i - P_0Y_0) - A_{it}E_t] \\ &- \sum_{t=1}^{k}[M_t + mF_t + mr(n+s)G_t] - (S + H + J) \end{aligned} \tag{7}$$

Maximising equation 7 reveals the optimal field test strategies, in terms of the necessary number of years, sites and plot replications, for providing the maximum benefit to the industry, subject to various preconditions such

[2] An alternative suggested by Lindgren (1976, p. 281), but not explored in this article, is to set the critical values used in the statistical analysis in such a way as to minimise the costs of the errors.

as discount rate and price. It now remains to consider the composition and estimation of the error costs arising from the testing program.

3. Decision errors: types of errors

The decision whether to release a cultivar is made after comparing the yield of a new cultivar against the yield of a standard cultivar, using a *t*-test. In this decision-making process, two forms of errors are defined:

1. A 'release error' (R) is the error made when a new cultivar is released whose true yield is less than that of the standard cultivar.
2. A 'non-release error' (NR) is made when a cultivar is not released, even though its (unknown) true yield is superior to that of the standard cultivar.

3.1 Probabilities of errors

The probability of committing these types of errors depends on the critical percentage difference (CPD) used in the test. CPD is defined as the value that must be exceeded by the observed difference in yields between the new cultivar (Y_i) and the standard cultivar (Y_0). In this article, we base the test on a CPD of zero; that is, a new cultivar will be released if its observed yield is equal to or greater than the standard cultivar.

Following Patterson *et al.* (1977) and Cullis *et al.* (1996b), we now define 'acceptance probabilities' as the probability of accepting for release a new cultivar whose true (unknown) yield is greater than that of the standard cultivar by a stated percentage. Therefore, the probability of committing a non-release error is calculated as (1 – the acceptance probability) for the same stated percentage difference in yield.

The probability of committing a release error can be calculated as the probability that a new cultivar is released even though its true yield is less than that of the standard cultivar by a given stated percentage. The probability of committing a release error with a stated yield difference is also calculated as (1 – the acceptance probability) for that yield difference. Since the CPD is set at zero, the probability of committing a release error is the same as the probability of committing a non-release error with the same absolute percentage difference. That is, when the CPD is zero, the probability of committing a non-release error for a cultivar with a true yield of 5 per cent higher than the standard is the same as the probability of a release error for a cultivar with a true yield 5 per cent less than the standard.

The acceptance probabilities are a function of several factors, some of which are related. Each acceptance probability calculated is a value uniquely associated with a particular set of preconditions. These are:

1. the magnitude of the difference between the CPD and the higher true yield of the new cultivar — the greater the magnitude, the lower the chance of committing a non-release error;
2. the variance of the cultivar means: this variance is affected by the mix of sites, years and replications and by the size of the sample — the smaller the variance, the lower the probability of committing release and non-release errors;
3. the size of the CPD chosen — the higher the CPD, the lower the acceptance probabilities;
4. the size of the test used in making the decision — the lower the level of significance, the higher the chance of making non-release errors and the lower the chance of making release errors.

Estimates of the acceptance probabilities can be readily developed, as outlined in Cullis *et al.* (1996b), for various mixes of replications, years and sites. Hence, the probabilities of committing release and non-release errors are readily obtained and applied to the model described in equation 7.

Different market conditions also need to be considered. For example, the price obtained for the product and discount rates used can affect the estimates of the costs of decision errors for a given production region, as is discussed in the following section.

3.2 Costs of errors

Transforming the probabilities of decision errors into cost estimates requires considering the adoption response of farmers, as described in Brennan and Cullis (1987). The cost of non-release errors is then estimated by contrasting the adoption response estimated to have occurred if field trials truly indicated yield relativities versus the adoption response based on the presence of non-release error. The differences in adoption response then need to be discounted to present values, so that the costs of the different types of errors can be estimated.

The cost of release errors is estimated by contrasting the adoption response based on true indications of yield relativities against that based on the presence of release error (the latter involves the release of an inferior cultivar). Again, differences in adoption response would need to be discounted to present values, include any real change in the profitability of production and include the cost of purchasing seed of a superior cultivar.

In the case of a release error, it is unlikely that farmers would continue to grow an inferior cultivar in the same way as they would a superior cultivar. In practice, farmers through their own trial sowings and from those on neighbouring farms, test the claims of yield superiority and often quickly establish whether those claims merit their support or not (Brennan and Cullis 1987). Hence, in the case of a wrongly released cultivar, farmers would relatively quickly realise its yield inferiority, causing release error costs to be relatively small. For non-release error, however, farmers have no access to the rejected cultivar, and so may unknowingly forego a yield advantage over many years (Kingwell 1987). Hence, non-release errors are potentially more costly, and the regression estimates of adoption response are more applicable in their case due to the truly higher-yielding nature of these cultivars wrongly rejected.

The error costs arising from a release decision are a function of the number of years since the decision was made. Release error costs depend on the area sown to the new cultivar, while the non-release error costs depend on the area that would have been sown to the cultivar in a given year. The cost of the non-release errors in the t^{th} year after the release decision can be expressed as follows:

$$E_{NRt} = A_{it}(e_{NRt}|d)(W_{NR}|d), \tag{8}$$

where:

E_{NRt} = the non-release error cost in the t^{th} year after release;
A_{it} = the area (in hectares) that would have been sown to cultivar i in the t^{th} year after release;
$e_{NRt}|d$ = the cost per hectare of non-release error the t^{th} year after release, given that the true yield difference between the unreleased and the standard cultivar is d;
$W_{NR}|d$ = the probability of non-release error, given that the true yield difference between the unreleased and the standard cultivar is d.

Similarly, the cost of release errors the t^{th} year after release can be expressed as follows:

$$E_{Rt} = A_{it}(e_{Rt}|d)(W_R|d) \tag{9}$$

where:

E_{Rt} = the release error cost the t^{th} year after release;
A_{it} = the area (in hectares) sown to cultivar i the t^{th} year after release;
$e_{Rt}|d$ = the cost per hectare of release error the t^{th} year after release, given that the true yield difference between the new and the standard cultivar is d;
$W_R|d$ = the probability of release error, given that the true yield difference between the new and the standard cultivar is d.

Over time, the costs of non-release errors arising from a particular release decision are:

$$E_{NR} = \sum_{t=k+1}^{k+x} [A_{it}(P_i Y_i - P_0 Y_0)](W_{NR}|d), \tag{10}$$

where x is the number of years of the life of a successful cultivar.

In the case of release error, where an inferior cultivar is mistakenly released as a superior one, farmers will continue to grow the new cultivar for z years before they become aware of its true (inferior) yielding ability. Therefore, the costs over time of the release error, where L is the cost of releasing a new cultivar, are:

$$E_R = \left[L + \sum_{t=k+1}^{k+z} \{A_{it}(P_0 Y_0 - P_i Y_i)\} \right](W_R|d), \tag{11}$$

for the first z years of cultivar adoption.

Therefore, the total error costs associated with a release decision can be calculated as the sum of the non-release and release errors:

$$E = \sum_{t=k+1}^{k+x} [A_{it}(P_i Y_i - P_0 Y_0)]W_{NR} + \sum_{t=k+1}^{k+z} [A_{it}(P_0 Y_0 - P_i Y_i)]W_R + L W_R. \tag{12}$$

4. Application of model to wheat in New South Wales: costs of field testing

The model was applied to yield testing of wheat cultivars in central and southern NSW. First, values for M, F and G in equation 2 were obtained

Table 1 Data for model for Central and Southern NSW

Parameter	Symbol	Value
True difference between standard and new cultivar	d	5%
Overhead costs of trials	M	\$35 000
Average variable costs per site	F	\$211.18
Average variable costs per plot	G	\$2.18
Number of lines tested per trial	n	25
Number of check cultivars per trial	s	5
Extra cost of producing seed of new cultivar	S	\$35 000
Cultivar registration costs	H	\$5 000
Publicity costs associated with new cultivar	J	\$20 000
Wheat price (\$/t FOB)	P	\$200
Area of wheat (ha)	A	1 200 000
Average yield (t/ha)	Y	1.82
Discount rate (per cent)		8.0

from staff administering the cultivar field trials. These values are shown in table 1 and, together with various values of k, m, r, n and s, provide values for D in equation 2.

A simplifying assumption made to enable the model to be applied readily to wheat in NSW was that there is no price differential between the new cultivar and the one it replaces (that is, $P_i = P_0 = P$).

4.1 Estimating error costs of field testing for wheat in NSW

Brennan and Cullis (1987) studied the factors that determine the rate at which different cultivars are adopted and then replaced. They found that there was a link between the adoption response of farmers and results from cultivar field trials. Applying inverse polynomials to adoption patterns for cultivars to the regional adoption and disadoption of wheat cultivars in Australia, Brennan and Cullis (1987) found that relative yield advantage, as recorded in field trials, significantly explained adoption response. Brennan (1988) reported that the following equation indicated the adoption and disadoption phase of a new cultivar in southern NSW, given that one new cultivar was released approximately each year:

$$Q_t = 1/[(0.432 - 0.609/Y') + (-0.0209 + 0.0374/Y')t + (-2.568 + 3.46/Y')(1/t)] \tag{13}$$

where:

Q_t = the percentage of the area sown to the cultivar in year t;
Y' = the relative yield of the cultivar over currently-grown cultivars in field trials;
t = the number of years after release.

On that basis, a new cultivar with a yield advantage of 5 per cent (i.e., $Y' = 1.05$) would have an adoption pattern as shown in table 2. In the first year, it would be grown on 1.7 per cent of the area and 4.1 per cent in the second year. The adoption reaches a peak of 17 per cent of the total area in year seven, and continues to be grown until twenty years after release.

By allowing field trial yield results to be incorporated in the prediction of adoption and disadoption response, this approach enables the costs of the different types of errors to be estimated. On the basis that farmers would grow a cultivar for two years before they concluded that it was genuinely inferior in their environment (i.e., $z = 2$), the production losses from a

Table 2 Adoption pattern of cultivar with 5 % yield advantage

Years after release	% of area sown
1	1.7
2	4.1
3	7.2
4	10.8
5	14.1
6	16.3
7	17.0
8	16.5
9	15.3
10	13.9
11	12.5
12	11.2
13	10.1
14	9.1
15	8.2
16	7.5
17	6.9
18	6.4
19	5.9
20	5.5

Source: Brennan (1988).

release error would be a 5 per cent production losses from the area sown in years one and two. On the other hand, the production losses from a non-release error would be a 5 per cent loss on the area specified in table 2 throughout the whole of the potentially productive life of the cultivar not released. Of course, each of these income streams need to be discounted to enable them to be compared.

On the basis of the above data, the costs of registering and releasing a new cultivar and producing seed for farmers are estimated at A$60 000. From equation 9, the present value (in the first year of testing, discounted at 8 per cent per year) of the cost of a release error is estimated at A$0.93 million (A$0.78 per hectare), while the present value of the cost of a non-release error (equation 10) was A$17.04 million (A$14.20 per hectare).

4.2 Estimating probabilities of errors

A data set describing the yield performance of advanced wheat lines grown in the region over ten years (Cullis *et al.* 1996a) was used to determine the error probabilities for different testing regimes, using the approach outlined above. The error probabilities for various sizes of a testing regime are shown in figure 1. It is apparent that increasing the number of years, sites or replications leads to a reduction in probability of errors.

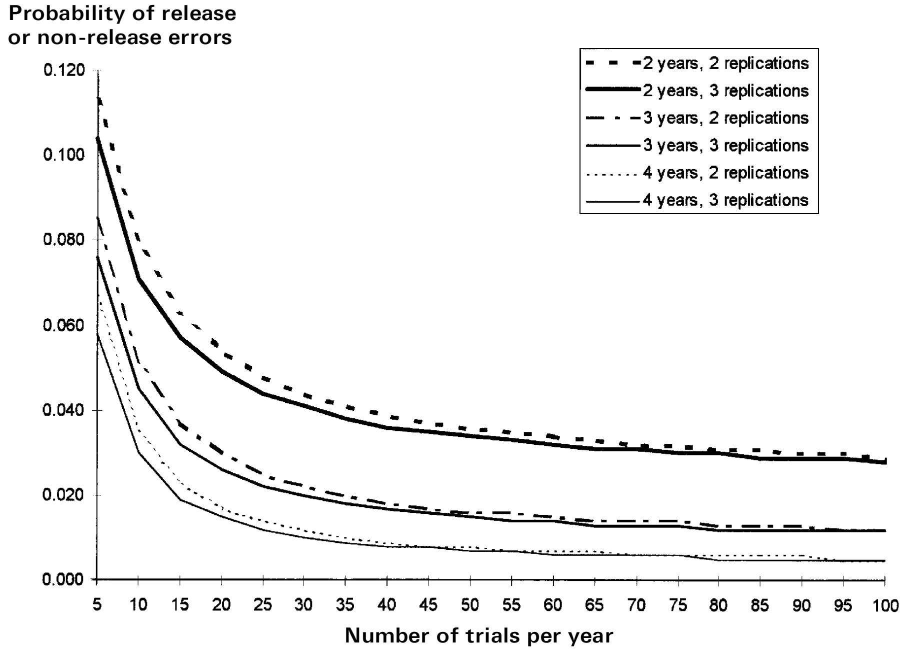

Figure 1 Error probabilities for wheat in Southern NSW

4.3 Optimal field testing for wheat in NSW

The data and estimates in tables 1 and 2 can be used to determine the optimum number of trials for wheat in southern NSW. Given that the values for area (A), price (P) and yield difference (d), which determine the benefits from the yield gains, are fixed, the maximising problem defined in equation 7 can be simplified to a cost-minimising problem. Thus, the objective function can be modified to:

$$Min[X] = D + E, \tag{14}$$

where X is the total costs of errors and testing, D is defined in equation 2 and E is defined in equation 12. This equation will define the cost and characteristics of the field trial program which is optimal for the region.

An illustration of the costs associated with different testing regimes is shown in table 3, where the changes in trial and error costs as the number of trials is varied (with three replications over three years) are shown. As the number of trials increases, the costs of trials increase, but the error costs fall. With three years of testing and three replications, the total costs are at a minimum with 25 trials per year.

Table 3 Illustration of results of analysis of wheat trials in Southern NSW[a]

Number of:			Discounted costs[b] ($'000)				
				Error costs			
Years	Sites	Replications	Trial costs	Non-release	Release	Total	Total costs
3	5	3	210	1295	71	1366	1576
3	10	3	259	767	42	809	1067
3	15	3	306	545	30	575	881
3	20	3	353	443	24	467	820
3	25	3	399	375	21	395	795
3	30	3	446	341	19	359	805
3	35	3	492	307	17	323	815
3	40	3	538	290	16	305	843
3	45	3	583	273	15	288	871
3	50	3	629	256	14	270	898
3	55	3	675	238	13	252	926
3	60	3	720	238	13	252	972
3	65	3	765	221	12	234	999
3	70	3	811	221	12	234	1044
3	75	3	856	221	12	234	1090
3	80	3	901	204	11	216	1117
3	85	3	947	204	11	216	1162
3	90	3	992	204	11	216	1207
3	95	3	1037	204	11	216	1253
3	100	3	1082	204	11	216	1298

Notes: [a] With three years of testing and three replications.
[b] Discounted to first year of testing at 8 per cent per year.

Table 4 Summary of results of Southern and Central NSW wheat analysis

	2 replications		3 replications	
Years	Optimum no. of trials/year	Total cost ($'000)	Optimum no. of trials/year	Total cost ($'000)
2	45	1084	40	1074
3	30	801	25	795
4	20	707	20	707

There is a range of possible combinations of years, replications and number of trials that can be considered. A comparison of the costs of alternative testing regimes is shown in table 4. For each combination of years and replications, the optimum number of trials is shown along with the associated costs. For example, with two years of testing and two replications per trial, the optimum number of trials is 45, which has a total cost (including trial and error costs) of A$1.084 million per year. Overall, the lowest cost options are four years of testing with either two or three replications, when the optimum number of trials is twenty (at a total cost of A$707 000 per year). Note, however, that with these data, the difference in total costs between the optimum number of trials with two replications and the optimum with three replications is negligible.

4.4 Discussion of results

It should be noted that this analysis only addresses the issue of costs associated with variety trials. For each additional year of testing over and above the minimum possible number, the benefits from the release of the flow of new successful varieties is also delayed. There are significant costs of delaying the release of new varieties (Brennan 1989). For example, if over a twenty-year period a cumulative increase in yields from varietal improvement of 0.5 per cent per year is delayed by one year for central and southern NSW, the total costs per year of the delay is A$0.95 million. Therefore, any cost saving in trials by adding an extra year is likely to be more than offset by a reduction in the benefits from delaying successful varieties.

Therefore, this analysis is most appropriately used for comparing the costs associated with a varying number of trials and replications which have the number of years of testing predetermined. The benefits from changing the number of years of testing can be identified, but the determination of the appropriate number is best carried out using information from the context of the whole crop improvement program.

5. Precision of estimates and sensitivity analysis

As with any analytical model, the results obtained depend on the values used for the parameters in the analysis. To test the sensitivity of the results to the values chosen for a number of parameters, sensitivity analysis was carried out. The sensitivity of the results to the values of a number of key parameters (regional production, wheat price, number of lines in each trial, and the discount rate) was tested by comparing the results obtained with parameter values 20 per cent greater and 20 per cent less than the value chosen in the base run. In addition, the sensitivity of the results to the value of z, the number of years before farmers reject an inferior cultivar, was tested for values of 1 and 3 years.

In table 5, the effect on the optimum number of trials and the total economic cost of changes to a number of key parameters is shown. Interestingly, where there are three replications and three years of testing, there is no change to the optimum number of trials as the value of some key

Table 5 Sensitivity of results to parameter change[a]

	Base run assumption	Optimum no. of trials	Total cost ($'000)
Base results		25	795
Production in region	2.18 m.t.		
+20%		25	873
−20%		25	716
Price	$200/t fob		
+20%		25	873
−20%		25	716
Number of lines in trial	25		
+20%		25	811
−20%		25	778
Discount rate	8% pa.		
+20%		25	736
−10%		25	872
Years of release error	2		
1		25	780
3		25	819

Note: [a] With three years testing, with three replications

parameters are increased or decreased by 20 per cent of their base values. However, the total costs are sensitive to the production in the region and the price of the grain produced, as well as to the discount rate used, while there are only small changes in total costs as a result of changes in the number of lines tested in each trial or in the geographical size of the region.

A key issue for trial administrators is the extent to which the broad region is disaggregated into smaller sub-regions for the purpose of evaluation and recommendations. This can be assessed in more detail, using the data provided in table 6. If the region to which the trials relate is assumed to have only 600 000 hectares, rather than 1.2 million hectares as assumed for the

Table 6 Analysis of size of region/sub-region in optimum number of trials[a]

No. of sub-regions in region	Optimum no. of trials per sub-region	Total no. of trials in region
1	25	25
2	20	40
3	15	45
4	15	60

Note: [a] For three years testing, with three replications, 1.2 million hectares in region.

Table 7 Optimum number of trials for different-sized production environments[a]

Production in region ('000 tonnes)	Gross value of production ($m)	Optimum number of trials
400	80	10
800	160	15
1200	240	20
1600	320	25
2000	400	25
2400	480	25
2800	560	25
3200	640	35

Note: [a] For three years testing, with three replications.

analysis above, the optimum number of trials in a region does not halve as the size of the region is halved. Therefore, disaggregating a larger region into two or more smaller sub-regions will result in an increase in the total number of trials that would minimise the total trial costs (see table 6). The cost of the additional trials would reduce the benefits from targeting specific smaller environments with the breeding program. The number of sub-regions required should be determined prior to this analysis being undertaken. This analysis highlights the possible gains that can be achieved if State or other administrative boundaries are ignored in determining the number of trials. Any artificially defined sub-regions can lead to a greater number of trials being needed in the production region than if it is all considered one unit from the trialling point of view.

The impact of changes in the size of the production environment is illustrated further in table 7, where the optimum number of trials (over three

Table 8 Estimates of variance components used to calculate acceptance probabilities[a]

Variance component	Measure	Estimate	Standard error
Genotype × location	σ^2_{gl}	0.005366	0.000529
Genotype × year	σ^2_{gy}	0.006646	0.000761
Genotype × year × location	σ^2_{gyl}	0.033759	0.000803
Error	σ^2_{e}	0.087150	na[b]
Genotype	σ^2_{g}	0.022187	0.003663

Notes: [a] Estimated using restricted maximum likelihood from analysis of a variety trialling database with ten years' data involving 1 071 trials with approximately 16 000 individual trial means (see Cullis *et al.* 1996a, b).
[b] na = not applicable, since plot error is a mean of all plot errors from trials (Cullis *et al.* 1996a, b).

years with three replications) is shown for varying sizes of production environment (measured in tonnes of wheat produced). As the total production increases, the number of trials needed increases, but less than proportionally. The implication of this is that smaller crops or production environments will need to be more intensively trialled than larger environments.

The other key component of the precision of the results obtained is the stochastic nature of some elements of the model. The acceptance probabilities used in the model have been calculated from variance components estimated from the analysis of variety trials results involving 1 071 trials and approximately 16 000 trials means (see Cullis *et al.* 1996a, b). The standard errors of these components are shown in table 8.

6. Conclusions

In this article, economic principles are applied to determining the economic costs and benefits of variety evaluation trials to cropping industries. A model identifying the least-cost characteristics of a field trial program for yield testing wheat cultivars is described. The model is applied to wheat variety trials in central and southern NSW. The model identifies the importance of non-release decision errors in yield testing and suggests that a least-cost field trial program should include 25 sites, with three replications per trial, if the advanced lines are to be tested over three years.

Various sensitivity analyses revealed that the results are sensitive to some parameters, particularly the size of the production region for which the testing is being carried out. Nevertheless, for wheat in central and southern NSW, the optimum number of trials is encouragingly robust over a range of parameter values.

The analysis shows that there can be a reduction in the number of wheat trials in the region from the average of around 100 over the past fifteen years to about 25 per year, without reducing the economic value of the testing to farmers significantly. More data sets need to be evaluated using this analysis to enable broader conclusions to be drawn about the number of trials needed for smaller crops, especially non-cereal crops, since it is possible that there will be marked differences in the error probabilities between wheat and other non-cereal crops.

References

Brennan, J.P. 1988, *An Economic Investigation of Wheat Breeding Programs*, Agricultural Economics Bulletin no. 35, Department of Agricultural Economics and Business Management, University of New England, Armidale.

Brennan, J.P. 1989, 'An analytical model of a wheat breeding program', *Agricultural Systems*, vol. 31, no. 4, pp. 349–66.

Brennan, J.P. and Cullis, B.R. 1987, 'Estimating the adoption and disadoption of wheat cultivars', paper presented to the 31st annual conference of the Australian Agricultural Economics Society, Adelaide, February.

Brennan, P.S., Byth, D.E., Drake, D.W., DeLacy, I.H. and Butler, D.G. 1981, 'Determination of the location and number of test environments for a wheat cultivar evaluation program', *Australian Journal of Agricultural Research*, vol. 30, no. 2, pp. 221–32.

Byth, D.E., Eismann, R.L. and DeLacy, I.H. 1976, 'Two-way pattern analysis of a large data set to evaluate genotypic adaptation', *Heredity*, vol. 37, no. 2, pp. 215–30.

Cullis, B.R. and Gleeson, A.C. 1991, 'Spatial analysis of field experiments – an extension to two dimensions', *Biometrics*, vol. 47, no. 4, pp. 1449–60.

Cullis, B.R., Thomson, F.M., Fisher, J.A., Gilmour, A.R., Thompson, R. 1996a, 'The analysis of the NSW wheat variety database. I: Modelling trial error variance', *Theoretical and Applied Genetics*, vol. 92, no. 1, pp. 21–7.

Cullis, B.R., Thomson, F.M., Fisher, J.A., Gilmour, A.R., Thompson, R. 1996b, 'The analysis of the NSW wheat variety database. II: Variance component estimation', *Theoretical and Applied Genetics*, vol. 92, no. 1, pp. 28–39.

Finney, D.J. 1964, 'The replication of variety trials', *Biometrics*, vol. 20, no.1, pp. 1–15.

Fox, P.N. and Rosielle, A.A. 1982a, 'Reference sets of genotypes and selection for yield in unpredictable environments', *Crop Science*, vol. 22, no. 6, pp. 1171–5.

Fox, P.N. and Rosielle, A.A. 1982b, 'Reducing the influence of environmental main-effects on pattern analysis of plant breeding environments', *Euphytica*, vol. 31, no. 2, pp. 645–56.

Gleeson, A.C. and Cullis, B.R. 1987, 'REML estimation of a neighbour model', *Biometrics*, vol. 43, no. 2, pp. 277–88.

Hamblin, J., Fisher, H.M. and Ridings, H.I. 1980, 'The choice of locality for plant breeding when selecting for high yield and general adaptation', *Euphytica*, vol. 29, no. 1, pp. 161–8.

Kingwell, R.S. 1987, 'Economically optimal strategies for regional yield tests of cultivars', unpublished thesis for Master of Science in Agriculture, University of Western Australia, Nedlands, WA.

Lindgren, B.W. 1976, *Statistical Theory*, 3rd edition, Macmillan Publishing Co., New York.

Patterson, H.D., Silvey, V., Talbot, M. and Weatherup, S.T.C. 1977, 'Variability of yields of cereal varieties in UK trials', *Journal of Agricultural Science*, vol. 89, no. 1, pp. 239–45.

Shorter, R. and Norman, R.J. 1983, 'Cultivar × environment interactions for kernel yield in Virginia type peanuts in Queensland', *Australian Journal of Agricultural Research*, vol. 34, no. 4, pp. 415–26.

Sprague, G.F. and Federer, W.T. 1951, 'A comparison of variance components in corn yield trials: II. Error, year × variety, location × variety, and variety components', *Agronomy Journal*, vol. 43, no. 12, pp. 535–41.

Talbot, M. 1984, 'Yield variability of crop varieties in the U.K.', *Journal of Agricultural Science*, vol. 102, no. 2, pp. 315–21.