OPTIMAL STRATEGIES FOR REGIONAL CULTIVAR TESTING FOR VARIOUS CROPS

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1. Introduction

This paper follows closely the analytical framework of Kingwell (1987) and Brennan et al. (1998) in determining optimal strategies for regional cultivar testing. However, this paper does contain important differences. Firstly, this paper widens the review of crop cultivars from wheat to include barley, oats and lupins. Secondly, a new estimation method is presented to describe cultivar adoption and disadoption. Lastly, the determination of optimal strategies relies on a new analysis of cultivar trial data by Cullis and Hunt (pers.comm.) that in turn draws on earlier work of Yeo and David (1984).

The first section of the paper is an overview of cultivar testing. A second section describes a decision model for determining the optimal field testing of a crop. This model is essentially the one developed by Kingwell (1987) and Brennan et al. (1998). A third section of the paper applies this model to the fielding testing of a range of crops in Western Australia. A final section discusses the results in light of earlier findings of Kingwell (1987) and Brennan et al. (1998) and provides concluding comments. The structure of this paper closely follows that of the Brennan et al. paper.

2. An Overview of Field Testing of Cultivars

In plant breeding programmes, field assessment of potential new cultivars involves comparing their characteristics (for example, yield, straw height, time to anthesis) to those of one or more standard cultivars. Cultivar comparisons involve a series of field trials replicated over sites and years. The aim of these trials is to identify 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 introduces risks in identifying *truly* superior cultivars.

Cultivars rarely perform uniformly across spatially diverse locations and years. Consequently, the ranking of cultivars is seldom the same across locations or years. The interaction of cultivars with their test environment (genotype *x* environment interaction) means that it is unlikely for superior cultivars to be identified on the basis of a single year's testing at a single site. Various spatial and statistical analyses have been applied to further our understanding of genotype *x* environment interaction and its impact on selection of superior cultivars (Byth et al., 1976; Brennan et al., 1981; Fox and Rossielle, 1982a, b; Shorter and Norman, 1983; Gleeson and Cullis, 1987; Cullis and Gleeson, 1991). Improved understanding of genotype *x* environment interaction has facilitated the design of field testing programs.

To design a field testing program requires addressing the key question of how many locations, years of testing and plot replications are needed before one is reasonably sure that a *truly* superior cultivar has been identified; and how *reasonably* sure does the identification need to be? As pointed out by Kingwell (1987) and Brennan et al.(1998) this issue has concerned many biologists and statisticians (Sprague and Federer, 1951; Finney, 1964; Hamblin et al., 1980; Brennan et al., 1981; Patterson et al., 1977; Talbot, 1984), yet economists have rarely been involved. Hence, it is not unexpected that design of field testing programs often has ignored financial costs[1] (Finney, 1964; Hamblin et al., 1980; Brennan et al., 1981; Patterson et al., 1977; Talbot, 1984), or considered only some costs of field testing (Sprague and Federer, 1951). Apart from Kingwell (1987) and Brennan et al.(1998) studies usually do not explicitly account for the opportunity costs and actual costs of foregone cultivar superiority due to decision errors associated with a testing program.

As noted by Brennan et al. (1998) two examples of such costs occur. Firstly, field test results falsely may indicate a new cultivar is superior to standard or commonly grown cultivars. If the new cultivar is recommended to and adopted by farmers then they will forego some varietal advantage (for example, yield) and incur varietal changeover costs. Secondly, field test results falsely may indicate a new cultivar performs no better than the standard or commonly grown cultivars. Failure to recommend and adopt this superior cultivar involves an opportunity cost of foregone benefit (for example, yield or price premium for quality) over the period when farmers would have benefited from its adoption.

3. A Decision Model for Field Testing

Many plant breeding programs remain focused on yield improvement. Accordingly, field testing of advanced breeding lines in a region often involves evaluating these lines against a standard or commonly grown variety (V_s). A set of breeding lines ($V_1, \ldots, V_n$) is compared to V_s over a range of locations and years to gauge which line most outyields V_s. The usual selection decision resulting from this testing is choose line V_i where

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

and $\overline{Y}_i$ is the average yield per hectare of breeding line Vi over all trials involving n lines.

The model described here focuses solely on field testing for yield and is formulated as a non-linear programming problem. The model assumes the sole purpose of field testing is to identify if a potential new cultivar, when grown at sites representative of some region, does in fact on average outyield some standard cultivar(s). In the model other cultivar characteristics (for example, grain quality) are ignored or it is assumed that their expression is perfectly correlated with yield.

The purpose of the model is to identify which testing strategy is optimal, given that test costs and costs of incorrect decisions based on test results should be minimized, and that certain technical restrictions may also apply to field testing. The objective function of the model is to maximize the net returns from cultivar testing while acknowledging the costs of yield testing and wrong inferences about cultivar yields. Algebraically, the objective function is to:

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[1] Patterson et al and Talbot implicitly recognize the importance of such costs in their concepts of critical difference and acceptance regions.

$$Max[N] = B - D - L \tag{1}$$

where:
N = the net benefits arising from the testing program,
B = the total gross benefits arising from the testing program,
D = the total provider costs associated with field testing,
L = the cost of releasing a new variety.

As shown by Brennan et al. (1998) *B*, *D* and *L* in equation (1) are in turn dependent on a range of factors. Equation (1) can be expanded to include those factors and the expanded form used in this paper differs slightly from that of Brennan et al. and is:

$$Max[N] = \sum_{t=y+1}^{y+x} [A_{it}[(\mathrm{P}_{\mathrm{it}}\mathrm{Y}_{\mathrm{i}} - \mathrm{P}_{\mathrm{ct}}\mathrm{Y}_{\mathrm{c}}) - (\mathrm{C}_{\mathrm{it}} - \mathrm{C}_{\mathrm{ct}}) - E_t](1+i)^{-t} -$$
$$\sum_{t=1}^{k}[F_t + lM_t + lr(n+c)G_t](1+i)^{-t} - \sum_{t=1}^{y+1}(S_t + H_t + J_t)(1+i)^{-t} \tag{2}$$

where
A_{it} = the total area sown (in hectares) to cultivar *i* in year *t*,
P_{it}, P_{st} = the prices obtained for cultivars *i* and *c* in year *t*,
Y_i,Y_s = the true yield of cultivars i and s respectively when grown on area A_i in year *t*,
C_{it},C_{ct} = the cost per hectare of growing cultivars *i* and *c* respectively on area A_i in year *t*,
E_t = the per hectare decision error costs associated with the field testing strategy,
F_t = overhead or fixed costs associated with field testing,
M_t = variable costs per location,
G_t = variable costs per plot,
S_t = cost of producing farmer seed for a new cultivar in year *t* (usually only for one or two years during the period $t = 1,..,y,y+1$ will these costs be incurred)
H_t = cultivar registration costs which are only incurred in year *y*,
J_t = publicity costs associated with release of a new cultivar (usually only incurred during one or two years of the period $t = 1,..,y,y+1$,
l = number of locations used in field testing,
r = number of replicates in field trials,
n = number of new lines being assessed,
c = number of check or standard cultivars used in field testing,
x = the number of years since registration which represents the adoptive life of the new cultivar,
k = the number of years of testing,
y = the interval in years between the commencement of field testing of a new cultivar and its registration and
i = the discount rate.

The first summation term in equation (2) is equivalent to the *B* term in equation (1). It represents the additional net revenue generated by farmers' adoption of the new cultivar. It accounts for changes in the area sown to new cultivar plus any cost-reducing or price-enhancing advantages of the new cultivar. Because to-date most new cultivars released as higher-yielding cultivars do not offer these additional cost or price advantages Brennan et al.

ignore these other advantages in their analysis. However, the more prevalent application of genetic engineering techniques in crop breeding could see more frequent releases of cultivars with cost-reducing (e.g. herbicide-resistance) or price-enhancing (e.g. high protein) characteristics.

The term E_t in equation (2) refers to the decision error costs associated with field testing. These costs reduce the net benefits of field testing. Section 3.1 of this paper explores further the nature of these decision errors.

The second summation term in equation (2) is equivalent to the D term in equation (1). It represents the costs of provision of field testing services. Usually testing of cultivars occurs over a number of years, locations and trial replicates. The provision of such broadscale testing necessarily incurs many costs including travel, accommodation, machinery and equipment maintenance and replacement, fertiliser, herbicide, fuel and monitoring costs along with the salaries of the many staff involved in all stages of trial design, management, implementation, data analysis and reporting.

The last summation term in equation (2) is equivalent to the L term in equation (1). It describes the cost of seed bulk-up prior to release of a new variety, plus administrative and promotional costs associated with the release and advertising of a new variety.

3.1 Decision errors associated with field testing cultivars

As identified by Kingwell (1987) and Brennan et al. (1998) there are two types of decision errors (E_t in equation (2)) associated with field yield assessments of cultivars. Firstly there is a release error. This error is the release of a new cultivar whose yield has been falsely identified by field testing as being superior to that of check cultivars. In this case the cultivar that is actually inferior or no better than the existing cultivars grown by farmers will be recommended to them as a superior cultivar. The economic cost of this release error tends to not be great because the new cultivar either yields similarly to commonly grown cultivars or its yield inferiority becomes quickly known due to further on-farm testing by early adopters of the new cultivar.

The second error which is of greater economic significance is a non-release error. This error involves field testing falsely indicating a superior cultivar is inferior. Acting on the results of field testing, the superior cultivar is removed from further testing thereby farmers are denied access to a truly superior cultivar.

These errors arise because decisions about cultivars are based on test statistics that are sample dependent. Decisions based on such statistics are not guaranteed to be correct. In agricultural experiments the probability of a release error is usually set in advance at some low level and in crop performance trials is traditionally set at P=0.05 (Carmer, 1976). The convention to set this probability at P=0.05 assumes that the release error is more serious than the non-release error (Chou, 1975). By contrast, non-release error is not set advance but rather is conditional on several factors as outlined by Kingwell (1987) and Brennan et al. (1998).

Probabilities of Decision Errors

Decision errors arise because field trials are not perfect indicators of how cultivars will perform across different field conditions with varying management. As outlined by Yeo and David (1984) the assessment of cultivars in field trials involves selecting the best k cultivars from a group of n ($k \leq n$) when measurements of genotypic superiority y_i $(i=1,\ldots,n)$ are not available. Instead selection must be based on associated measures x_i (e.g. phenotypic yield).

Yeo and David assume that cultivar testing can be represented as drawing n independent pairs (x_i,y_i) from distributions (X_i,Y_i) with probability and cumulative density functions $f(x,y)$ and $F(x,y)$ respectively. They further assume that high Y-values (i.e. large y_i) are desired and that X and Y are positively correlated. This leads to their decision rule that:

> From the original n cultivars choose the s $(k \leq s \leq n)$ cultivars with the largest X-values, where s is the smallest integer such that the k best cultivars are included among the s with a probability δ at least equal to a preassigned value P^* $(0<P^*<1)$.

They apply their general model to cultivar field trials by first stating the yield X_{ij} of cultivar i on plot j as:

$$X_{ij} = \mu + T_i + X_{ij} \,, \tag{3}$$

for $i=1,\ldots,n$ and $j=1,\ldots,r$ where

μ is an unknown constant and the cultivar effects T_i and residuals Z_{ij} are mutually independent normal variates with zero means and respective variances σ_T^2 and σ_Z^2; there being n cultivars and r replicates. The aim is to choose the k best cultivars (i.e. the cultivars with the k highest T-values). T_i corresponds to Y_i in the general formulation. Also $\overline{X}_{i.}$, the ith cultivar mean, corresponds to X_i in the general formulation. Hence, from equation (3) the decision problem involves selection from a bivariate normal distribution with correlation coefficient; $\rho = [1+ (r\zeta)^{-1}]^{-½}$, where $\zeta = \sigma_T^2 / \sigma_Z^2$. For this distribution Yeo and David calculate the probability that a sub-set of s cultivars containing the s largest of n X-values will also include the k cultivars $(1 \leq k \leq s \leq n)$ with the largest Y-values. They denote this probability as ${}_n\delta_{s:k}$ with its calculation being:

$${}_n\delta_{s:k} = \frac{n!}{(n-s-1)!(s-k)!(k-1)!} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \theta_1^{n-s-1}(x,y)$$

$$.\theta_3^{s-k}(x,y).\theta_4^{k-1}(x,y).g(x,y).h(x,y)dxdy \tag{4}$$

where, with the usual notation for the standard normal probability and cumulative density functions,

$g(x,y) = \phi(y)\Phi[(\rho y-x)/(1-\rho^2)^{½}]$,
$h(x,y) = \phi(x)\Phi[(y-\rho x)/(1-\rho^2)^{½}]$,
and θ_j can be expressed as a single integral, for example,

$$\theta_4(x,y) = \int_x^\infty \phi(u)\Phi[\frac{\rho u - y}{(1-\rho^2)^{1/2}}]du.$$

This methodology of Yeo and David which generates $_n\delta_{s:k}$ probabilities as outlined in equation (4) can be applied to cultivar field trials. These probabilities of selecting (and not selecting) the truly superior cultivars can be calculated for various numbers of *k*, *s* and trial regime characteristics (replications, years of testing and numbers of locations). A subsequent section of this paper lists $_n\delta_{s:k}$ probabilities calculated by Cullis and Hunt (pers. comm.) for various testing regimes of the main field crops grown in Western Australia.

Costs of Decision Errors

To transform the probabilities of decision errors into estimates of the costs of decision errors requires knowledge of the adoption response of farmers. As outlined by Brennan et al. (1998) the cost of the decision errors can be 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 the decision error. The cost of a release error depends on the area sown to the newly-released yet inferior cultivar while the cost of a non-release error depends on the area that *would* have been sown to the superior cultivar if testing had not incorrectly identified the cultivar as inferior.

As shown by Brennan et al. the cost of a non-release and release error in year *t* after release is:

$$E_{NRt} = A_{it}(e_{NRt}|d)(W_{NR}|d) \tag{5}$$

$$E_{Rt} = A_{it}(e_{Rt}|d)(W_R|d) \tag{6}$$

where:

E_{NRt} , E_{NRt} = the cost of a non-release and release error in year t after release of the cultivar,

A_{it} = the area sown or the area that would have been sown to cultivar *i* in year *t*,

e_{NRt}/d , e_{Rt}/d = the cost per hectare of non-release and release error in year *t* after release, given the true yield difference between the unreleased or released and check cultivar is *d*,

W_{NR}/d , W_{NR}/d = the probability of non-release and release error, given the true yield difference between the unreleased or released and check cultivar is *d*,

Equation (5) that specifies costs of non-release errors in year *t* can be generalised to show the costs of non-release errors over the life of a cultivar to be:

$$E_{NR} = \sum_{t=k+1}^{k+x}[A_{it}(P_iY_i - P_oY_o)](W_{NR}|d) \tag{7}$$

where x is the duration of adoption of the superior cultivar, assuming it was released.

Similarly, costs of release errors will occur over *z* years after which farmers will no longer grow the inferior cultivar as by then it will be common knowledge that the cultivar is inferior. Release error costs will include *L*, the cost of releasing the new cultivar.

$$E_R = \left[L + \sum_{t=k+1}^{k+z} \{ A_{it} (P_o Y_o - P_i Y_i) \} \right] . W_R \big| d \qquad (8)$$

The sum of equations (7) and (8) is the total cost of decision errors associated with field testing of cultivars.

4. An Application of the Decision Model for Cultivar Testing: Field Crops in Western Australia

The model outlined in the preceding section was applied to cultivar testing of the main field crops grown in Western Australia — wheat, lupins, barley and oats. The parameters of the model are listed in table 1. Staff engaged in cultivar testing provided data on F_t, overhead or fixed costs associated with field testing, M_t, variable costs per location and G_t, variable costs per plot.

The costs listed in table 1 are in constant 1998 dollar terms. These values in table 1, together with various values of l (the number of locations used in field testing), r (the number of replicates in field trials), n (the number of new lines being assessed), c = number of check or standard cultivars used in field testing, x (the number of years since registration which represents the adoptive life of the new cultivar) and k (the number of years of testing) provide values of D in equation (1) or the second term in equation (2).

The data in table 1 show that field testing costs for each crop are similar and that the main parameter differences relate to the price, area sown and yields of each field crop.
As in Brennan et al., a simplifying assumption is made that $P_{it} = P_{ct}$ and $C_{it} = C_{ct}$. This infers that a new cultivar offers no price premium or cost-reducing advantages over existing check or standard cultivars. Traditionally, this has often been the case with new field crop cultivars offering yield advantages rather than quality or input-saving characteristics.

The inclusion in table 1 of smaller crops such as oats and the inclusion of lupins follows an observation of Brennan et al. that their analysis needed to be widened to include other crops in order to assess how broadly applicable their findings might be.

Table 1: Data for field crop testing in Western Australia

Parameter	Symbol	Value
Wheat		
Overhead cost of trial system ($'000)	F	272
Average variable costs per site ($'000)	M	1.7
Average variable costs per plot[a] ($)	G	25
Number of lines tested per trial[b]	n	15
Number of check cultivars per trial	c	3
Extra cost of producing seed of new cultivar ($'000)	S	38
Cultivar registration costs ($'000)	H	5
Publicity costs associated with new cultivar ($'000)	J	29
True difference between new and standard cultivar (%)	d	5
Real Discount rate (%)	i	5
Real price ($/t FOB)	P	200
Average yield (t/ha)	Y	1.8
Area ('000 ha)	A	4400
Lupin		
Real price ($/t FOB)	P	210
Average yield (t/ha)	Y	1.2
Area ('000 ha)	A	1000
Barley		
Real price ($/t FOB)	P	175
Average yield (t/ha)	Y	1.7
Area ('000 ha)	A	800
Oat		
Real price ($/t FOB)	P	150
Average yield (t/ha)	Y	1.8
Area ('000 ha)	A	350

[a] The average variable plot cost for all cereals is $25. However, for lupins the plot cost is $30.

4.1 Estimating costs of decision errors associated with field testing

As outlined in an earlier section estimates of the costs of decision errors requires knowledge of the adoption response of farmers in order to transform the probabilities of decision errors into cost estimates. For southern New South Wales Brennan and Cullis (1987) examined regional adoption and disadoption of wheat cultivars and found that relative yield advantage, as recorded in field trials, was a significant explanator of adoption response. Their approach firstly involved fitting inverse polynomials (Nelder, 1966) to adoption and disadoption responses for many cultivars. Another simpler approach by Brennan (1988) involved estimation of the equation $A_t = f(Y^{-1}, t, t^{-1})$ where A_t is the proportion of wheat area sown to cultivar *i* in year *t*, *Y* is the relative yield of the cultivar over currently grown varieties in field trials and t is the number of years since release of cultivar *i*. Estimation of the equation for southern New South Wales produced the following equation (9):

$$A_t = 1/[(0.0432-0.609)/Y)+(-0.0209 + 0.0374/Y)t + (-2.568 + 3.46/Y)(1/t)] \qquad (9)$$

Cultivar adoption and disadoption in Western Australia can be estimated as outlined below. The percentage of area sown to a particular variety (A_t) is a function of that cultivar's yield superiority (when the cultivar was first released, Y) and t years since release of the cultivar.

Algebraically,

$$A_t = S_t K_t \tag{10}$$

where
A_t is the percentage of the crop area sown to the cultivar in year t,
S_t is a scaling function such that:

$$S_t = at + bt^2 + ctY + dt^2 Y \tag{11}$$

with Y being the cultivar superiority (in yield equivalents) at the time of release and

$$K_t = \frac{1}{t\sqrt{2\pi V}} e^{\frac{-[\ln(t) - U]^2}{2V}} \tag{12}$$

In equation (12)

$$U = \ln\left[\frac{f_1(Y)^2}{\sqrt{f_1(Y)^2 + f_2(Y)}}\right]$$

and

$$V = \ln\left[\frac{f_1(Y)^2 + f_2(Y)}{f_1(Y)^2}\right]$$

Cultivar adoption data for Western Australia was the source of observations on A_t, Y and t and using this data estimates of $f_1(Y)$ and $f_2(Y)$ were generated. Estimates of equation (10) for wheat, lupins, barley and oats are given in table 2 along with test statistics.

To give an indication of how adoption patterns can differ, the estimated adoption patterns for cultivars displaying yield improvements of 3 and 8 per cent, at the time of release, are given in figure 1. As shown in figure 1 the higher the degree of yield improvement the greater the market share of the cultivar and especially for wheat, the more years pass until maximum adoption. Improved lupin cultivars tend to generate very large market shares quickly whereas improved wheat cultivars are less quickly adopted, and often their peak adoption is less. The adoption patterns for the new wheat cultivars are influenced by more frequent later releases of further improved cultivars. For example, since 1990 Agriculture Western Australia[2] has released 17 cultivars of wheat compared to 8 cultivars of lupins. Further, since 1990 several wheat cultivars from other States have been released for use in Western Australia.

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[2] This is the publicly-funded agency that is the main provider of crop varieties in the south-west of Australia.

Table 2: Estimates of equation A_t for each crop

Crop	**Estimated equation for A_t**
Wheat	$A_t = 1.399 - 323.852\ K_tt + 4.285\ K_tt^2 + 324.897K_ttY - 4.593K_tt^2Y$ (44.54) (4.02) (41.94) (3.58) $R^2_{adj} = 0.63$
Lupin	$A_t = 10.499 + 114.257\ K_tt - 36.519\ K_tt^2 + 4.721K_ttY + 24.412K_tt^2Y$ (273.74) (29.13) (254.23) (27.04) $R^2_{adj} = 0.59$
Oats	$A_t = 6.038 - 377.621\ K_tt + 46.804\ K_tt^2 + 373.154K_ttY - 44.682K_tt^2Y$ (267.60) (30.55) (252.37) (28.77) $R^2_{adj} = 0.13$
Barley	$A_t = 7.326 - 1679.178\ K_tt - 14.509\ K_tt^2 + 1672.377K_ttY + 8.853K_tt^2Y$ (a)

Source: Based on data and information in the AgWA Crop Variety Sowing Guide (various issues) and the Farm Budget Guide (various issues)

(a) The barley cultivar Stirling has dominated barley sowings for much of the last 15 years. There are too few observations of other varieties of relative merit to allow estimation of the adoption equation. Accordingly the equation here is an estimate based mainly on Stirling, that describes a possible adoption pattern for an improved barley cultivar. Numbers in parentheses are standard errors of coefficient estimates.

As illustrated in figure 1, adoption of a new cultivar is sensitive to its yield superiority. Peak adoption is greater when yield advantage is greater and, for wheat, the interval from release to peak adoption also is greater when yield advantage is greater. By contrast, the specification of adoption used by Brennan (1988) suggests that peak adoption and the interval to peak adoption are insensitive to cultivar yield superiority. For example, Brennan’s specification suggests that peak adoption always occurs after 7 years and that wheat cultivars with 8 and 3 per cent yield superiority have peak adoption of 18.2 and 16.2 per cent respectively.

Brennan et al. (1998) used the assumption that field testing should be designed to reliably detect yield differences of 5 per cent and that therefore adoption patterns of 5 per cent higher-yielding cultivars should be used in calculating the costs of release and non-release errors. Adopting the same set of assumptions leads to estimates of these errors, set out in table 3, for each crop in Western Australia. Cost estimates are also provided for field testing regimes based on detection of 3 and 7 percent yield differences.

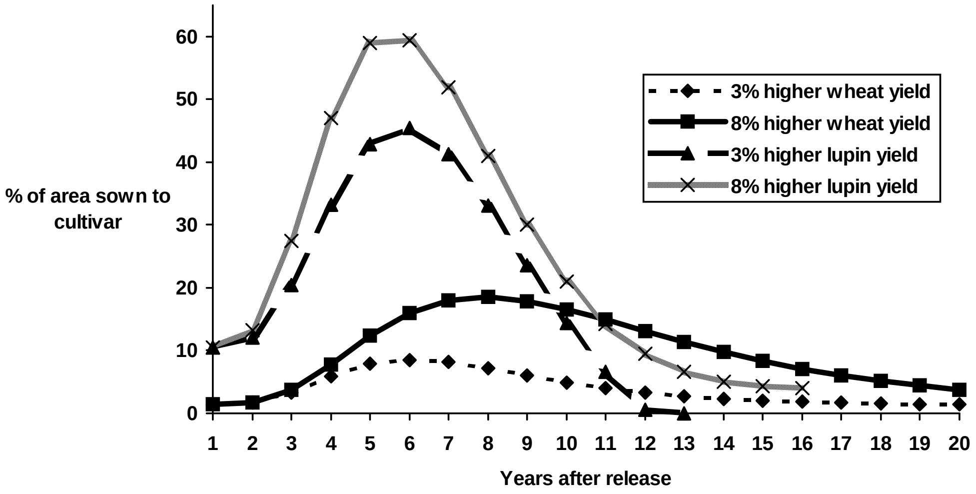

Figure 1: Estimated adoption patterns for two wheat cultivars and two lupin cultivars

Table 3: Estimates of costs of non-release and release errors associated with testing for different yield differences

Crop	Cost unit	Yield difference					
		3%		5%		7%	
		Non-release cost	Release cost	Non-release cost	Release cost	Non-release cost	Release cost
Wheat	$m	23.0	1.4	62.1	2.3	120.8	3.3
	$/ha	5.2	0.3	14.1	0.5	27.4	0.7
Lupin	$m	16.1	1.6	31.7	2.7	50.0	3.9
	$/ha	16.1	1.6	31.7	2.7	50.0	3.9
Barley	$m	6.0	1.0	26.6	1.7	67.8	2.3
	$/ha	7.5	1.3	33.3	2.1	84.7	2.9
Oat	$m	4.0	0.3	6.7	0.5	9.1	0.7
	$/ha	11.4	0.9	19.2	1.6	25.9	2.2

4.2 Estimating probabilities of decision errors associated with field testing

The probabilities of decision errors were determined by Cullis, Hunt and Braysher (pers. comm.) using the method of Yeo and David (1984). In their analysis for equation (4) the following values were assumed: $n = 15$, $k = 2$ and $s = 4$. In words, the trial system for each crop was assumed to consider 15 cultivars, with the decision error being that the truly best 2 cultivars would not be included among the top 4 cultivars as ranked by the trial data. Typically, the implicit selection decision would be to discard all but these top four lines. The implication of discarding truly-top ranked potential cultivars is that farmers would not have access to these lines resulting in their farm-level rate of yield improvement being less. Probabilities of non-release errors for wheat and lupins are shown in figures 2a and 2b. The data for barley and oats are not shown as calculated probabilities are very similar to those of wheat. Further, only the case of two replicates per site is shown as there are only slight reductions in error probabilities when the number of replicates increases beyond two.

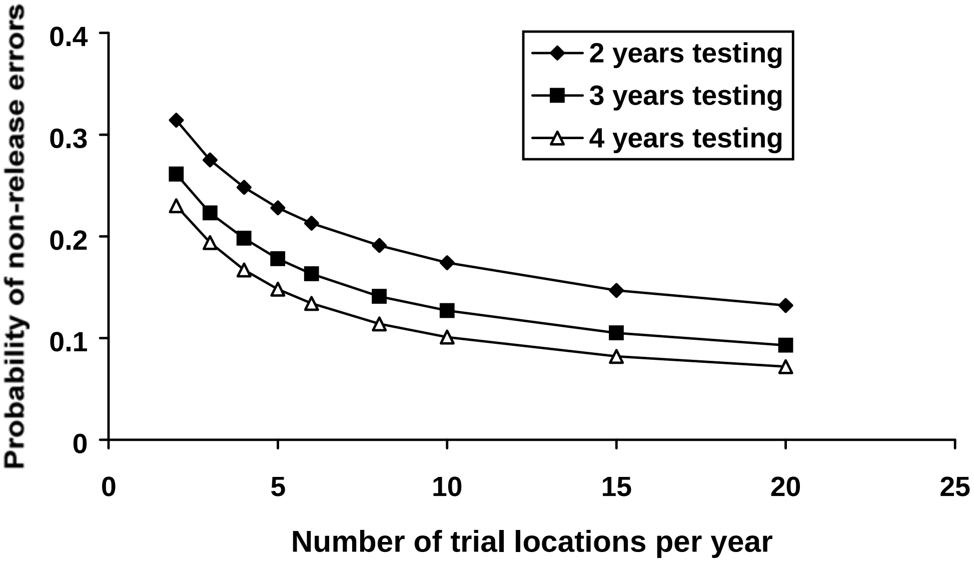

Figure 2a: Error probabilities for wheat (2 replicates per trial at each location)

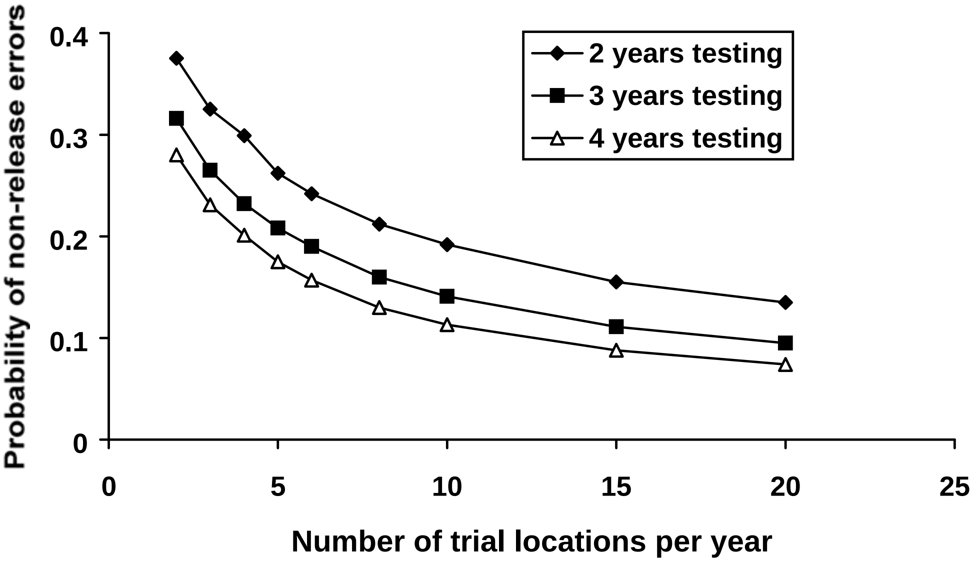

Figure 2b: Error probabilities for lupins (2 replicates per trial at each location)

Results in figures 2a and 2b show that the number of trials per year and the number of years of testing are the main influence on error probabilities. However, beyond 15 trials (locations) per year there is little further reduction in the probability of non-release errors. Other results[3] not shown in figures 2a and 2b indicate that increasing the number of replicates beyond two in each trial only slightly reduces error probabilities.

Estimates of the probabilities of release errors are not yet available. These estimates when available will be based on the same values of $n = 15$, $k^{\#} = 2$ and $s = 4$. In words, the trial system for each crop will consider 15 cultivars, with the decision error being that the truly worst two 2 cultivars will included among the top 4 cultivars as ranked by the trial data. Typically, retention decisions based on trial data would lead to these inferior cultivars being released. Farmers adopting these cultivars would experience little yield advantage and, more likely, some yield loss. It is likely that probabilities of release errors will be much less than non-release errors.

Brennan et al. assumed the non-release and release error probabilities were equal. To facilitate comparison with their findings in this paper the same assumption is adopted. However, a future analysis will incorporate, when available, estimates of the probabilities of release errors based on an appraisal of crop trial data in Western Australia. Adopting the assumption that non-release and release error probabilities are equal will slightly inflate the economic costs associated with decision errors. However, because the economic significance of release errors is much less than non-release errors (Carmer 1976; Kingwell 1987; Brennan et al. 1998) the impact of these inflated costs on the selection of the optimal field testing regime ion of cost is likely not to be large.

4.3 Optimal field testing for field crops in Western Australia

The data and estimates in tables 1 and 3, together with the estimates of probabilities of decision errors, can be used to determine the nature of the optimum field testing regime for each crop in the main agro-ecological cropping zones of Western Australia. As pointed out by Brennan et al., due to the simplifying assumptions that $P_{it} = P_{ct}$, $C_{it} = C_{ct}$ and the fixed yield difference equation (2) can in turn be simplified to a cost-minimization problem with the objective function:

$$Min[C] = E + D \qquad (13)$$

where:
C = the present value of total costs of testing and decision errors,
D = the total provider costs associated with field testing as described in the second term of equation (2) and,
E = the cost of decision errors as described in equation (8).

The optimization problem specified in equation (13) can also be augmented with various logistic or financial constraints. For example, breeders may be encouraged for various

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[3] These are estimates based on 3 and 4 replicates. These results are available from the author.

reasons to limit the duration of field testing to no more than 3 years or the provider of field testing services may be financially constrained. Such constraints would be represented by:

$$y \leq 3 \quad \text{and}$$

$$F_t + lM_t + lr(n+c)G_t \leq \Omega_t \qquad \text{for t = 1,…,n and where}$$

Ω is the limited funds available in each year *t* for field testing.

Limited finances for cultivar testing is increasingly a reality in Western Australia and the Grains Research and Development Corporation is keen to rationalise and make more effective its support for cultivar testing in Australia (Lazenby et al., 1994).

Table 4 lists the optimum testing regime for each crop in each agro-ecological zone in Western Australia and also presents constrained optimal regimes.

Table 4: Optimum field testing regimes for wheat, lupins, barley and oats in each agro-ecological zone of Western Australia

Crop	Optimum (sites per region, no. of years, no. of reps)	Constrained optimum ($y \leq 3$)	Constrained optimum ($\Omega \leq$ \$1.25m)
Yield diff. (d = 0.05)			
Wheat	15,4,2	20,3,2	8,2,2
Lupin	15,4,2	15,3,2	6,2,3
Barley	10,4,2	15,3,2	4,2,3($\Omega \leq$ \$1m)
Oat	8,2,2	8,2,2	2,2,3($\Omega \leq$ \$0.85m)
Yield diff. (d = 0.03)			
Wheat	10,4,2	10,3,2	8,2,2
Lupin	10,3,2	10,3,2	6,2,3
Barley	8,2,2	8,2,2	4,2,2($\Omega \leq$ \$1m)
Oat	5,2,2	5,2,2	2,2,3($\Omega \leq$ \$0.85m)

The findings in table 1 suggest that optimal field testing for each crop requires testing over at least two years, with two replicates. For oats only two years of testing at two replicates is required. For the other crops the years of testing range from two to four years, but always with 2 replicates. For wheat, the main crop grown in Western Australia, optimal testing involves four years of field trials when time or financial constraints do not apply.

The results for wheat are consistent with those obtained for southern New South Wales by Brennan et al who also found that four years of testing was optimal, with either two or three replicates. However, there are differences in the number of trial sites per region. Brennan et al. found that 20 trials per year over four years was optimal for testing in the 1.2 million hectare region of southern New South Wales. By contrast this study has found that at least 150 trials per year over four years is required for the 4.4 million hectare region of wheat-growing in Western Australia. The requirement for additional trials in Western Australia arises firstly from the higher decision error probabilities generated by the new analysis of trial data (Cullis, Hunt and Braysher, pers.comm.). Secondly their analysis was based on 15 agro-ecological zones in Western Australia. Yet as Brennan et al. point out "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." (p.223). They go on to show that if a region is sub-divided then, although fewer trials per region may be required, the total number of trials increases. The situation for southern New South Wales was that the optimal total number of trials increased from 25 to 60 if the region was treated as 4 sub-regions. Whether the 15 regions used in Western Australia are actually clearly different agro-ecological zones is under examination.

Results in table 4 show that optimal testing involves fewer trial sites and years of testing as the crop diminishes in regional importance. For example, in most cases only two years of testing are required for oats and barley and, even when time or financial constraints do not apply, the optimal number of sites per sub-region is as few as 8 for barley and 5 for oats.

Interestingly, the optimal number of sites per sub-region identified in table 4 are very consistent with the recommendations of Lazenby et al. (1994). They comment that there should be "a maximum of 15 trial sites for major crops in each agro-ecological zone." (p. xvii). When time or financial constraints do not apply, the optimal number of sites per sub-region identified in table 4 ranges from 5 to 15.

5. Discussion

The analysis in this paper identifies the importance of non-release errors. These errors are the discarding of potentially high-yielding cultivars due to a failure of the testing program to identify them correctly. However, the method of estimating the cost of these errors may over-estimate these errors. For example, in Brennan et al. and in this paper the estimation method assumes that no other variety would substitute for the cultivar lost through being wrongly discarded. In fact, it could be argued that although say a 7% higher-yielding cultivar is lost due to a non-release error, in the same year in which that cultivar is lost another say 4% higher-yielding cultivar is identified correctly and is released. That is, the yield foregone by a farmer is not 7% but rather is only 3%. The 7% yield loss is in fact an upper-bound estimate of the cost of non-release.

The impact of this over-estimation of the non-release cost is illustrated indirectly by results in table 4. In the case where the yield difference being tested for is 5% versus 3% then the costs of non-release are much higher, justifying a larger testing program. However, where the costs of non-release are less (3% versus 5%) then a smaller testing program is optimal.

The analysis used here and by Brennan et al. could easily be extended to show the incidence of costs of the optimal testing regimes. The cost-minimization problem takes no account of the distribution of cost components among the key stakeholders of cultivar testing. The costs of non-release and release errors principally are borne by farmers while the testing program costs are borne mainly by tax-payers, although growers contribute in part through their taxes and by levy payments to the Grains Research and Development Corporation that in part funds cultivar testing and cultivar promotion. Because current analyses show non-release errors are a main component of the economic cost of cultivar testing, the cost-minimisation model often suggests a lowering of these errors through provision of field testing programs currently paid for mainly by governments. By contrast, invoking financial constraints to reduce the size of field testing programs increases the likelihood of additional costs of release and non-release errors that are borne by farmers.

Another important issue not addressed in this paper is the impact on optimal testing regimes when information is required from trials about cultivar characteristics other than yield. Protein content, response to various herbicides, processing qualities and ease of harvest are but some of the many characteristics of cultivars about which information is also required. If comparative judgements about cultivars need to include these characteristics other than yield then testing regimes will need modification.

A related issue is that the analyses in this paper assume no differentiation among cultivars of a crop species other than according to yield. However, there are different types or grades within crop species. There are noodle, biscuit and bread wheats. There are feed and malting barleys. There are oats for hay-making or grain production. The agro-ecological zones for testing cultivars in each category may differ and simply testing and selecting cultivars on the basis of their yield is likely to be inadequate. Such complexity is overlooked in this paper.

Currently, in Western Australia there are around 60 sites used each year for wheat cultivar testing, plus 30 sites for lupins, 34 sites for barley and 34 sites for oats. The results presented in table 4 suggest that the optimal number of sites, assuming retention of the 15 sub-regions, is more likely to be around 150, 150, 120 and 75. The inference is that there is under-investment in cultivar testing in Western Australia. By contrast, Brennan et al. point out that in southern New South Wales the number of wheat trials averaged around 100 over the last 15 years. They concluded that the number of trials in that region could be reduced. Even if that region was divided into 4 sub-regions the optimal total number of trials was still only 60.

6. Conclusions

This paper follows closely the analytical framework of Kingwell (1987) and Brennan et al. (1998) in determining optimal strategies for regional cultivar testing. However, this paper does contain important differences. Firstly, this paper widens the review of crop cultivars from wheat to include barley, oats and lupins. Secondly, a new estimation method is presented to describe cultivar adoption and disadoption. Lastly, the determination of optimal strategies relies on a new analysis of cultivar trial data by Cullis and Hunt (pers.comm.) that in turn draws on earlier work of Yeo and David (1984).

A decision model for determining the optimal field testing of cultivars is presented and applied to major crops grown in Western Australia. Results show that optimal field testing for each crop requires testing over at least two years, with two replicates. For oats only two years of testing with two replicates per trial site is required. For wheat, barley and lupins optimal testing involves two to four years of trials, but always with 2 replicates per trial. For wheat, the main crop grown in Western Australia, optimal testing involves four years of field trials when time or financial constraints do not apply.

In discussing findings the method of estimating non-release errors associated with field testing is questioned and the need to determine appropriate agro-ecological regions for field testing is highlighted. Several important qualifications on the study’s findings are raised. However, given the current set of sub-regions in Western Australia, findings suggest there is currently under-investment in cultivar testing in the State. This finding is contrary to that of Brennan et al for southern New South Wales where over-investment in field testing was identified.

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