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AN ANALYSIS OF THE ECONOMIC POTENTIAL OF SOME INNOVATIONS IN A WHEAT BREEDING PROGRAMME

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Considerable resources are employed in agricultural research, and the allocation of these resources has become an important topic in agricultural economics literature (for example, see Fishel 1971; Arndt, Dalrymple and Ruttan 1977). Two main questions are addressed in this literature. How many resources should be allocated to agricultural research? How should these resources be allocated between different research projects? A third question is addressed less often. How should resources be allocated within a particular research project? The question is interdependent with the first two, as it cannot be determined without consideration of the amount of resources available, while the amount allocated should depend on the needs and structure of the project itself.

Plant breeding, or the improvement of crop plants through genetic manipulation and selection, is a major area of agricultural research. By its nature, plant breeding is a time-consuming procedure. It normally takes approximately 10 years of selection and evaluation from the time of crossing to the selection of the superior breeding line. In addition, a successful commercial cultivar is not produced from each year's crossing, so that usually a number of years' crossing (followed by a 10-year testing period) is necessary for each commercial cultivar.

There has been some limited application of economics to plant breeding objectives and operations (Englander and Evenson 1979; Evenson, O'Toole, Herdt, Coffman and Kauffman 1979; Simmonds 1979; Bollard 1980; Binswanger and Barah 1980; Barah, Binswanger, Rana and Rao 1981; Sanders and Lynam 1982; Eskridge 1987). However, there appear to have been few attempts to use economic principles to evaluate and compare the gains from different plant breeding programmes or differently structured programmes. The aim in this paper is to use a discounted cash flow analysis to compare different wheat breeding methods and approaches, in order to determine the changes in costs and benefits from some selected innovations that could reduce the period of time taken to produce a commercial wheat cultivar.

Market Framework for Australian Wheat

The representation of research-induced innovations as shifts in supply curves is widespread (Norton and Davis 1981; Edwards and Freebairn 1984; Davis, Oram and Ryan 1987). In the analysis of a new wheat variety in this paper, yield-increasing effects of the new variety lead to a rightwards

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shift in the supply curve (Lindner and Jarrett 1978), while the quality-improving effects lead to an upward shift in the demand curve (Unnevehr 1986). For simplicity, the change in the value of production is used in this analysis as an approximation of the estimated change in social welfare. This simplified approach is equivalent to assuming a perfectly elastic demand curve and a perfectly inelastic supply curve.

There are several implications of this approach. First, changes in wheat production from any new wheat cultivar are assumed to be sufficiently small that there will be no fall in the world wheat price. While this is unlikely to apply to the Australian wheat breeding industry as a whole (and it would almost certainly not apply to international wheat breeding centres), it seems to be a reasonable assumption in the case where an individual programme is analysed. Second, a given proportional yield advantage shifts the supply curve to the right by the same proportion. Given that the new variety is assumed to lead to higher output with no increase in inputs, and that weather is the dominant factor affecting regional production, these simplifications lead to an acceptably small loss of accuracy in a study such as this in which uncertainty about many features and parameters is so pervasive. Third, following Freebairn, Davis and Edwards (1982), the relevant price for estimating producer surplus is the farm-gate price. In this analysis, the supply of marketing services is assumed to be perfectly elastic at a fixed unit cost (that is, the difference between the f.o.b. export prices and the farm-gate price does not vary with the level of production). Under these assumptions, total social welfare gains equal producer gains. Finally, possible increases in production that can take place because wheat becomes more competitive with other alternative enterprises are ignored. However, this supply response effect is likely to be small compared to the change in the value of production (Norton and Davis 1981).

Discounted Cash Flow Analysis of a Wheat Breeding Programme

The choice of breeding strategy and selection method in a public wheat breeding programme is a public investment decision (Sanders and Lynam 1982), and can be evaluated by investment criteria such as the expected net present value, the benefit-cost ratio and the internal rate of return.

Returns from breeding programme

The total returns from a new cultivar comprise the value of the additional production resulting from the cultivar and the increase in value through improved quality of all the production of that cultivar. The returns from a breeding programme in a given year, R_t, can be defined as

$$R_t = P_tQ_t - P_{0t}Q_{0t} \tag{1}$$

where P_t and Q_t are price and quantity, respectively, in year t, and P_{0t} and Q_{0t} are price and quantity, respectively, that would have prevailed in year t if the cultivar had not been produced.

Assuming that there are no important interactions between selection characters, and ignoring annual fluctuations in the value of unit gains in selection characters, equation (1) can be transformed (Brennan 1989) to

$$R_t = YAS_t[G_yW_y + G_qW_q(1 + G_y/100)] \tag{2}$$

where y is the mean yield (t/ha) of existing cultivars in the target region,

A is the total wheat area (ha) in the target region, S_t is the share of that area sown to the cultivar in year t, W_y and W_q are the average unit value of 1 per cent gains in yield and quality, respectively, and G_y and G_q are the percentage gain from selection in characters affecting yield and quality, respectively.

The representative programme used in this analysis is based on breeding operations carried out at the Agricultural Research Institute, Wagga Wagga and at the Victorian Crops Research Institute, Horsham. In this programme, a complete cycle from crossing to completion of selection and evaluation takes 10 years (Brennan 1988). On average, one cultivar is released from the programme for commercial production every four cycles of breeding, so that the average period from initial crossing to commercial release is 13 years.

For the purposes of the empirical analyses used in this study, the target region for the wheat breeding programme was based on southern NSW, where the area of the target region for the breeding programme (A) and the mean yield of the target region (Y) were taken as 1 million ha and 1.7 t/ha, respectively (Brennan 1988).

The rate of expected genetic improvement in each selection character (Simmonds 1979) is estimated as

$$G_i = K_i D_i h_i^2 \tag{3}$$

where G_i is the proportional genetic advance through selection for character i over the initial breeding population, K_i is the selection differential for character i, D_i is the standard deviation for character i and h_i^2 is the heritability for character i. There is a given rate of expected yield and quality improvement once the breeding population and method of selection are determined. In the representative breeding programme, the expected genetic gains from the original breeding population as a result of one cycle of selection are 8.3 per cent for yield and 6.1 per cent for quality, respectively. This represents an expected gain over currently grown cultivars of 2.3 per cent for yield and 1.1 per cent for quality (Brennan 1988). In the analysis in this paper, the gains over the existing cultivars are assumed constant throughout the useful life of the new cultivar. In its turn, the new cultivar is replaced by superior cultivars. Unless the cultivar is used as a parent for other new cultivars, its contribution to yield and quality gains ceases when it is no longer grown. The method of estimation used in this paper assumes that the cultivar is not used as a parent for future cultivars.

In valuing the selection characters, a representative price, based on the 5-year mean for southern NSW, of \$111/t at the farm-gate was used, equivalent to \$174/t f.o.b. (Brennan and Benson 1986). At a price of \$111/t, a 1 per cent increase in yield is worth \$1.11/t, provided the demand for wheat is perfectly elastic. The value of a 1 per cent increase in the quality index (\$0.81/t) is derived as the mean of the values of increases in four quality characteristics: flour extraction rate (\$2.19/t), protein content (\$0.39/t), test weight (\$0.61/t) and amylase activity (\$0.03/t) (Brennan 1988). The values are assumed constant throughout the analysis, implying constant real prices over the period of analysis. However, it is unlikely that long-run trends in wheat prices and research costs will be similar, which is a possible source of bias in the results. By relating the prices used to a period of historically low world prices, the risk of overstating gains is likely to be small. There is also likely to be less effect on the comparisons of different breeding options, which are expressed in terms of differences from the representative programme, than on the underlying profitability of the representative programme itself.

The level of use of the cultivar in year t can be explained, *inter alia*, by the yield advantage over current cultivars at the time of its release, the number of years since its release, and the maturity group and wheat type (bread or biscuit). From a regression of adoption pattern over time on these variables (Brennan 1988), the derived formula for the pattern of adoption through time of a mid-season bread wheat cultivar with a 2.3 per cent yield increase is

$$S_t = t/(0.8159 - 0.16360t + 0.015677t^2) \qquad (4)$$

where t is the number of years since the release of the cultivar, and S_t is the proportion of the target area sown to the cultivar in year t. On this basis, the cultivar reaches its maximum adoption of 16 per cent of the wheat area in the target region in the seventh year after its release, and is assumed to be no longer grown after 20 years.

For the cultivar expected from the representative breeding programme, the nominal annual returns range up to $922 000 at the time of maximum adoption in the seventh year after release (Brennan 1989). The returns are discounted to the year in which the original cross was made (that is, 13 years before release, given the four cycles of breeding before a successful cultivar is produced). At a 5 per cent real discount rate, total discounted returns are $3 816 000.

Costs of breeding programme

The nominal costs of each operation in the representative breeding programme, including labour, operating capital and overhead costs, were estimated. The costs of each generation were calculated once the operations being carried out and the numbers involved in the representative programme were determined. Nominal annual costs rise from a low level in the first year to a maximum of $116 000 in the sixth year (Brennan 1989). The costs are highest in the fifth to ninth years of the programme. The discounted total costs of one complete cycle were estimated as $148 000. On the basis that one cultivar was released every 4 years, the discounted average cost of producing each cultivar for commercial release is $550 000.

Evaluation of representative programme

The discounted costs and returns for a cultivar produced by the representative or base programme are given in Table 1. The three investment criteria indicate that the investment of the resources in this wheat breeding

TABLE 1

Analysis of Costs and Returns for Base Programme

	Discount rate (per cent per annum)				
	0.0	2.5	5.0	7.5	10.0
Discounted[a] total costs	708	622	550	490	438
Discounted[a] total returns	10 921	6373	3816	2339	1465
Net present value[a]	10 213	5751	3266	1849	1026
Benefit-cost ratio	15.4	10.2	6.9	4.8	3.3
Internal rate of return	19.2	19.2	19.2	19.2	19.2

[a] Discounted to year of initial crossing of parental lines.

programme is profitable. The importance of the discount rate used is evident from the wide range of results obtained for different discount rates (Table 1). However, even at the higher discount rate, the investment of resources in the wheat breeding programme is profitable for society.

In the analysis in the following section, the results are presented for a discount rate of 5 per cent. For comparison, the results are also shown in the tables for a discount rate of 10 per cent, although they are not discussed.

Analysis of Effect of Reducing Breeding Time

As Mayo (1980) has noted, plant breeding is a slow process; hence, it is important that breeders will be ready to take advantage of methods that allow more rapid production of commercially useful material. The question of reducing the time from the initial crossing to the release of a cultivar for commercial production is addressed in the analytical model. Three options are analysed: (a) earlier release of cultivars, (b) off-season nurseries, and (c) tissue culture.

Earlier release of cultivars

The approach of releasing cultivars a year earlier (after F_9 generation), so that returns are brought forward by a year, is analysed. The assumption is that the F_{10} generation testing is still carried out, to provide the same information to growers, but it is carried out after the release of the cultivar, without affecting the rate of adoption. Thus, costs remain the same, but returns are brought forward a year. Bringing forward returns leads to an increase in discounted returns (Table 2), so that the earlier release of cultivars leads to increased profitability.

Many cultivars are held up from release for an extra year in order to obtain more information about their quality or their suitability for certain environments. The results of this analysis indicate that the final year's information on a cultivar is obtained at considerable potential cost to the industry. The estimated 1.5 per cent of growers who adopt the new culti-

TABLE 2

Analysis of Effect of Reducing Breeding Time

Base programme	Discount rate	Discounted costs	Discounted returns	Net present value	Benefit-cost ratio	IRR[a]
	(per cent)	($000)	($000)	($000)		(per cent)
Base programme	5.0	550	3816	3266	6.9	19.2
	10.0	438	1465	1026	3.3	
Release after F_9	5.0	550	4007	3456	7.3	20.8
	10.0	438	1611	1173	3.7	
Off-season nurseries	5.0	588	4207	3619	7.2	20.5
	10.0	496	1772	1276	3.6	
Tissue culture	5.0	489	4418	3929	9.0	23.6
	10.0	420	1950	1529	4.6	

[a] Internal rate of return.

var in the first year after its release are assumed to be unlikely to be deterred by the unavailability of the results of the final year's testing.

Analysis of off-season nurseries

In the representative or base programme, the F_1 seed increase already takes place in the glasshouse over summer. Off-season nurseries are used in many Australian wheat breeding programmes, often for F_3 generation over summer. Their use is generally dependent on weather conditions to enable early harvest and rapid re-sowing. Such a summer nursery is used mainly for seed increase, but can also provide useful selection opportunity for disease reactions and for development habit. There is some scope for further use of off-season nurseries, possibly international nurseries or in an artificial environment in Australia.

While off-season nurseries have been used successfully for selection in breeding programmes such as those in Mexico conducted by CIMMYT, and British programmes using New Zealand as a nursery, the scope for the wider use of off-season nurseries in wheat breeding programmes in Australia is limited by the relatively narrow climatic range within Australia. At present, quarantine regulations would be likely to prevent an overseas off-season nursery, since imported wheat seed is required to be grown out in a quarantined glasshouse before being cleared for import (M. Mackay, Australian Wheat Collection, personal communication, June 1988). However, the aim in this analysis is to identify potential gains if off-season nurseries were permitted under quarantine regulations.

In the analysis of the use of off-season nurseries, the initial assumption is that all costs are the same as the base programme, but that two of the early generations (F_3 and F_5), are carried out in off-season nurseries. Hence, 2 years are cut from the time needed to produce a commercial cultivar. The effect of this reduction in breeding time (Table 2) is to increase both discounted costs and discounted returns, thus leading to an increase in profitability.

Tissue culture

Longworth (1987) has noted the potential for tissue culture to increase the efficiency of selection in plant breeding by speeding up the breeding process. There are many forms of tissue culture that could be of assistance to the practising breeder. One form is doubled haploid culture, where the process of developing fixed lines from parental material is carried out *in vitro* in the laboratory rather than over several generations in the field.

The effect of the use of doubled haploid culture in a wheat breeding programme is assumed to be a reduction in the number of years to produce lines for advanced testing. The effect is seen as compressing the generations from F_1 to F_5 into 2 years of tissue culture (D. Luckett, personal communication, January 1988). Therefore, the time saved to produce material for advanced testing is 3 years. Using doubled haploid methods, De Buyser, Henry and Taleb (1985) found that the time saved over a conventional breeding system was 3 to 5 years; thus, this analysis is a conservative one.

There is some discussion in the literature as to the relative performance of lines produced in a tissue culture programme compared to a conventional programme (De Buyser *et al.* 1985; Winzeler, Schmid and Fried 1987). For the purposes of this analysis, it is assumed that the material produced in each approach is equivalent in terms of yield, quality and disease reaction.

While the cost of this operation is uncertain, for the purposes of this analysis it is assumed to be $50 000 per year. This estimate is made on the basis that the tissue culture programme could be carried out by a Technical Officer (at a labour cost of approximately $30 000 per year; Brennan 1988), with operating and capital costs of approximately $20 000 per year.

The results of the incorporation of tissue culture into the breeding programme in this manner are shown in Table 2. Discounted total costs are lower than in the base programme, while bringing forward returns leads to an increase in discounted returns. As a result, the profitability increases substantially with tissue culture.

Discussion

The analysis described in this paper indicates that there is scope for wheat breeders to increase the expected net benefits from their programmes by adopting techniques and technologies that reduce the time that normally elapses between the initial crossing of parental lines and the release of a commercial cultivar from the programme. There are gains of $191 000 for each cultivar through the earlier release of cultivars from the programme, before the final year of extensive yield and quality testing has been completed, provided the adoption pattern is the same.

The potential gains from a system of off-season nurseries for two early generations, where no extra costs are incurred, are shown to be $353 000 for each cultivar. This result suggests that, if some co-operative scheme for off-season nurseries could be established for several breeding programmes (whether overseas or in an artificial environment in Australia), the benefits could be substantial.

Since quarantine restrictions would be likely to prevent the free and rapid exchange of material that would be essential for an overseas off-season nursery to be effective, the gains identified in this analysis are opportunity costs for the current quarantine regulations. A complete economic analysis of the role of the quarantine restrictions, and an examination of ways in which they could be modified to allow a free exchange of this material, would be necessary before any conclusions could be drawn on whether the regulations should be changed.

The third option of using tissue culture to generate the variable breeding population in place of several early generations in a conventional programme has markedly higher potential economic gains: some $663 000 for each cultivar. Therefore, research to investigate and develop tissue culture methods to operate in this way has a high potential payoff, and should have a relatively high priority for wheat breeding resources.

In assessing the relative merits of the three innovations, the investment criteria used provide some differences in ranking. By each criterion, the base programme is less profitable than each of the innovations and tissue culture has the highest economic potential. However, on the basis of net present value, off-season nurseries are rated as more profitable than earlier release of varieties, while these rankings are reversed on the basis of benefit-cost ratios and internal rates of returns. Resource allocation decisions will therefore depend on the criteria considered most appropriate to the decision maker.

In conclusion, the analysis presented indicates that positive economic gains can be obtained from innovations that reduce the length of time between the initial crossing and the release of a commercial cultivar to growers. While technology still has to be developed to enable off-season nurseries to be employed in Australian wheat breeding, and the technology for incorporating tissue culture into wheat breeding programmes is still being developed, the expected economic gains indicate that research into these aspects could have a high payoff for the industry.

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