Developing Cost Functions for a Wheat Breeding Program

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Abstract
To assist in the management of plant breeding programs, and particularly in managing change, the detailed cost structure and the nature of the cost function facing plant breeders need to be known. In this paper, an attempt is made to define a cost function for a representative wheat breeding program. The improved understanding of the cost function enables the implications for the potential uses of new breeding technologies such as genetic markers or physiological measurements to be explored to increase the efficiency of breeding programs. It also provides a basis for assessing the extent to which costs vary with the size of a breeding program.

Key words:
crop improvement; breeding; economics; marginal cost; average cost

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1. Introduction

Until recently, scientific wheat breeding in Australia was largely carried out in the public sector. Each State Department of Agriculture or Primary Industries established its own breeding program, with other programs operated by the University of Sydney and the Commonwealth Scientific and Industrial Research Organization (CSIRO). Wheat breeding has long been supported by the levies placed on growers, and the matching Commonwealth Government payments, through the Grains Research and Development Corporation (GRDC) and it predecessors. Thus, farmers were collectively able to fund the public-sector wheat breeding programs.

The introduction of Plant Breeders' Rights in the 1980s meant that breeders were able to obtain financial returns from the use of their varieties through seed royalties. With the recent introduction of "end-point royalties" on all wheat sold or delivered for sale, the incentives for private breeding programs have changed significantly (Lindner 2004). Private-sector breeding programs are now more readily able to obtain returns from the production of their varieties, and hence to take up breeding on a commercial basis. At the same time, public wheat breeding programs have become more commercially oriented and are acting increasingly like private sector breeders. As a result, Australian wheat breeding is now a largely commercially-focused activity, and is taking place increasingly in the private sector.

Within both the public and private sectors, plant breeders inevitably face demands that are beyond their current resources. As a result, they need to be able to assess the most efficient way to manage the resources at their disposal. In particular, as new technologies such as molecular markers and new physiological measurements are incorporated into the breeding programs, breeders and their administrators face important decisions about how to structure and operate their programs.

A key piece of information in that decision-making is the detailed cost structure and the key components of the costs of trials at different stages of wheat breeding programs. That information will assist in the management of the breeding program, and particularly in managing change. As changes are considered for the program, the consequences in terms of costs can be determined.

In an earlier study, Brennan and Khan (1989) developed detailed costing of a wheat breeding program. The structure of the programs and the nature of some of the operations have changed since that time, as well as the technologies used and the costs involved. The objective of this study is to develop detailed and relevant costing of the different operations and stages of breeding programs, to enable the cost consequences of changes in the program to be identified. In this paper, the costs of breeding operations in a wheat breeding program using modified pedigree selection have been estimated.

Lindner (2004) highlights the importance of different cost structures among plant breeders in the utilisation of modern essential plant breeding infrastructure such as molecular markers. Those important differences in average and marginal costs between breeders can be determined by the framework developed in this paper.

2. Wheat Breeding Operations

2.1 Plant breeding activities

In a wheat breeding program, parent genotypes are crossed to produce a population of progeny lines that have variability in a number of characteristics. The task of the breeder is to select the line or lines from that variable population that possess the best combination of desirable characteristics. In that process, breeders use "phenotypic" selection (based on observed measurements) and genotypic marker selection to search large populations for progeny with the desired genetic traits. That phenotypic measurement can take place in the field, glasshouse or the laboratory, in conjunction with statistical analysis. Genotypic selection is conducted in the laboratory using DNA marker techniques.

Initially, there are only small quantities of seed, which increases with each subsequent generation grown. Once a large variable population is established, the breeder progressively discards breeding lines by selecting for different criteria or in different environments, until a small number of "elite" breeding lines remain. Because of seasonal variability and the high level of genotype-by-environment interaction, this process is a slow and uncertain one. As the number of selected lines reduces progressively through successive generations, the level and intensity of evaluation increases, as well as the range of environments in which the breeding lines are tested. In a typical conventional wheat breeding program based on modified pedigree selection methods, at the end of approximately ten years of selection the best breeding line from the cross is ready for release as a new variety for farmers. Each year a new crossing cycle is commenced, so that at any one time there will be up to ten separate generations in a breeding program going through different stages of evaluation and selection.

Costs will vary with the evaluation that is carried out and the number of breeding lines at each stage of the program. In the early stages where seed is limiting, only one small plot or row of each line can be sown for evaluation, or populations of lines are "bulked" together for later selection of superior individual plants. At this stage, the breeding lines are still segregating, which means that their progeny are not yet fixed genetically, so that selection is somewhat limited. Approximately after F5 generation, breeding lines become fixed and their progeny are the same each generation, and selection becomes more precise.

As seed becomes more plentiful and the number of breeding lines reduced, and once lines become fixed, accurate testing for yield and other characteristics requires multiple (replicated) plots of each breeding line. This increase in replication increases the costs of evaluating lines in those generations. In addition, the performance of the breeding lines is always evaluated in relation to current varieties ("check" varieties or "controls"). In evaluating a breeding line, then, the replications and controls, as well as the buffer plots sown around a trial to ensure uniformity and often to generate disease in the trial, also need to be costed. As a result, there are always more plots sown in a trial than breeding lines evaluated, because of check varieties, replications, etc. Accordingly, both average and marginal costs per breeding line tested will be greater than they are per plot sown.

Statistical analysis is used to design experiments to obtain the maximum possible level of genetic discrimination between breeding lines, so that traits for selection can be readily distinguished from the environmental and random variation. In addition, advanced breeding lines are evaluated in a range of production environments, and multi-location trials involve additional activities such as travel to sites.

The different stages of breeding operations are outlined in Table 1 for a breeding cycle in a hypothetical breeding program. Each year, the number of crosses and breeding lines in each stage varies, depending on the genetic material being used, the immediate aims, strategic objectives, seasonal conditions, resources available and the development of new or changed selection priorities (such as changed disease conditions). Therefore, the numbers provided in the table are only indicative.

(Table 1 about here)

Breeding lines are progressed to the next stage if they appear superior in one or more traits. The decision to progress to the next level of detailed evaluation is made considering budgetary constraints as well as the perceived probability of the line being ultimately released as a variety for farmers.

2.2 Early generation operations

In the early generations (up to the stage at which multi-location trials are conducted), the structure of the operations is as illustrated in Figure 1. For each generation, there are breeding plots or rows and accompanying evaluation nurseries. The plots or rows are the main set of breeding lines evaluated in the field in that generation, and the source of seed for the next generation. The nurseries are used to screen the population of breeding lines (or sub-sets of them) to be screened for a range of desirable traits. Given that the nurseries often only require seedling tests, or perhaps tests on the seeds themselves, there can be a sequential series of nurseries during a season, where only breeding lines selected after one nursery are included in the following nursery. However, other nurseries are concurrent, in that they relate to the same initial set of breeding lines for that generation. Many of the nurseries are not harvested, or even brought to full maturity. The results from these nurseries and from the main breeding plots are used to determine which of the breeding lines are carried forward to the next generation. Unwanted plots/rows need not be harvested, as harvesting is a major component of costs.

(Figure 1 about here)

The level of inputs for the nurseries varies with the type of nursery and the nature of the trait. For example, some characteristics such as plant height are readily assessed in the field by a low-skilled operator at a fast rate, and that assessment has a low cost. Other nurseries need elaborate field sampling and laboratory testing to determine the expression of that characteristic in a breeding population. Foliar disease resistance can be assessed in the field by growing the nursery in conditions to ensure an epidemic, and then scoring the disease expression in the field, a task that can be done rapidly and relatively cheaply by skilled operators. Root diseases are more difficult (and expensive) to score in the field, as they can require plant roots to be dug up for assessment. Glasshouse screening can be used for several characteristics, though it tends to be more expensive than field screening. The same trait can also be evaluated at different levels of accuracy in different tests. A broad characterisation of nurseries for phenotypic evaluation for some selected traits is shown in Table 2.

(Table 2 about here)

Typically, a large number of nurseries are used to screen the breeding lines at various stages of the program. They can relate to foliar diseases (such as rust), agronomic characteristics (such as boron tolerance and maturity) and a range of other disease and quality traits. Some nurseries are generally operated within the program, often in both the field and the glasshouse. However, many nurseries are out-sourced, where selected lines are sent to other programs to be screened for a range of important traits. In some cases, these are key screening facilities such as the National Rust Control Program at Sydney University, or specially-established screening facilities operated by other breeding organisations. In other cases, it is more convenient (and less expensive) to screen for those other diseases in different environments.

At the end of the early generation stages (F5) in the model wheat breeding program, from the 100 crosses made and 18,000 breeding lines in F3, approximately 1,524 lines remain to be assessed in the yield trials at F6.

2.3 Later-generation operations
From F6 generation, the formal yield measurement begins. By this stage, there is sufficient seed to enable replicated and/or multi-site trials. As the stages progress, fewer breeding lines are carried through to the next generation, but the number of replications and the number of sites at which testing is carried out increase.

In the later generations, for each stage, yield trials are established, with generally increasing levels of replication per trial and increasing numbers of sites through successive generations. In addition, some breeding lines are assessed in screening nurseries during these stages. In those cases, the results of the nurseries are used as part of the information for the breeder to select the breeding lines for advancement to the next stage.

3. Costs of Wheat Breeding Operations

3.1 Approach to costing
The cost function of the breeding program is estimated by examining each operation within the program and estimating the fixed and variable costs of that operation (as in Dreher *et al.* 2003 and Morris *et al.* 2003). In some cases, the costs are estimated per sample, and then aggregated by the number of samples involved. In others, the aggregate cost is estimated, and then allocated on a per sample, per plot or per line basis from the number of breeding lines, etc, involved in that stage of the program. The basis for estimation of the costs of the breeding operations is illustrated in Figure 2.

(Figure 2 about here)

From an economic point of view, the total costs are estimated for each operation, and then for each stage of the program. The average costs are estimated per line or per plot by allocating those costs equally across each breeding line in that stage of the program. The costs estimated are comparable to those estimated in Brennan and Khan (1989) and used in analysis of the economics of wheat breeding programs (Brennan 1989a,b).

3.2 Data on breeding operations
The data presented in this paper are based on those of a hypothetical breeding program using a modified pedigree selection method. While some confidential data were obtained from the Wagga wheat breeding program, those data have been adjusted and modified to ensure that they do not represent either the precise operations or the precise costs of the Wagga program.

Separate cost estimates were prepared for different stages of breeding operations. Data such as plot sizes, the number of breeding lines, replications and check varieties were determined on the basis of a representative program. For data on personnel involved, the levels of salaries and on-costs used in the analysis are based broadly on generic 2005 salary levels to avoid using confidential information. Estimates of typical travelling time and costs involved were obtained from members of the breeding program. The actual operations involved included site identification and preparation, field operations, machinery maintenance, trial design and management, seed preparation, sowing operations, field evaluations, harvesting operations, post-harvest seed management, data preparation and analysis and decision-making on breeding lines to advance. For each of these operations, the key issues were: (a) who performed the operation? (b) how many could be done in a day? or (c) how long did it take for the whole operation? From those estimates, the time involved for each person on the breeding team was estimated for each operation, and the costs were then determined by relating to their salary and associated costs.

Direct inputs such as parts, fertilisers, herbicides, bags, envelopes, etc, were estimated by experienced staff. The annual leasing costs for land used in the program were also included in the costs.

Capital costs were estimated for each piece of machinery or equipment used in a representative program. No attempt has been made to include the costs of sheds, storages and offices in these estimates, as those costs are assessed as sunk costs for these purposes. Two components of capital costs were included: (a) depreciation (the costs necessary to ensure that the equipment can be fully funded when in need of replacement), and (b) interest or opportunity costs (where an interest charge is applied to the funds tied up in the capital).

4. Estimated Breeding Costs

On the basis of the selection processes and breeding structure summarised in Table 1, the estimated total costs of the breeding operation for a complete cycle are $1.182 million (Table 3). The main costs are incurred in F3 and the later stages of the program, with costs in the other earlier stages being relatively small. Different breeding methodologies will have different distribution of costs through the stages of the program.

(Table 3 about here)

The average costs per breeding line varies widely between stages, from around $2 in F1, to $179 per line in F2 when single head selections are made, the falling to $8 per line in F5 seed increase where there is no selection. From F6, average increase rapidly to over $2,700 per line in F9 and over $6,000 per line in F10. The causes of the differences per breeding line between stages include differences in the traits screened for in each stage, the size of plots, the proportion of checks included in the trials, the number of replications in trials, the number of sites tested, the location of sites used, and the intensity of the evaluation carried out in each trial.

The costs and the components of the costs vary with each generation and stage of breeding. For example, the component costs of an early-generation field nursery that is not harvested are shown in Table 4. The main components are labour costs, with operating, travel and capital costs accounting for only 6% of total costs. The main labour inputs relate to the (labour-intensive) assessment and scoring process (54%) and to disease inoculation (13%), with the other activities less significant.

(Table 4 about here)

In contrast, the component costs of F9 yield trials are shown in Table 5. In those trials, 62 breeding lines are evaluated at 20 sites with 2 replications at each. Data management and decision-making (39% of total costs) represent the largest cost component for these trials, with travel costs (18%), labour for harvest (16%) and labour for sowing and growing the plots (11%) the other significant components of the cost. The cost components vary markedly between on-station and off-station trials as well as for the different stages of evaluation. These component costs differ markedly between stages of the program, with travel costs becoming increasingly important as the number of sites for testing increases in the later stages.

(Table 5 about here)

The costs for each of the key stages of the yield trials F6 to F10 are shown in Table 6. At the later stages of the program, the costs per breeding line increase as the number of replications and sites increase. For example, F9 trials cost $122 per breeding line (at each site), while the main-season trials in F6 ($21), F7 ($42) and F8 ($59) are markedly lower. The final F10 stage is the most expensive ($2843 per line) because of the intensive testing that takes place. The total costs per trial (that is, per site) decline through the advanced stages, as the number of lines tested declines. However, the total costs per stage do no similarly decline, as the number of sites increases through these stages.

(Table 6 about here)

These costs are the average costs incurred, incorporating all components. However, they do not represent the extra costs involved in including an additional breeding line for evaluation in the trial. The marginal costs of including an additional line in the yield trials are markedly lower than the average costs (Table 7). The marginal costs of including an additional breeding line in one trial is as low as $14 per breeding line per site in F6, increasing to $37 per line per site in F10. Where extra tasks or activities (such as separate reporting) are associated with the additional lines from outside the program, this analysis will not capture the full costs involved in incorporating them.

(Table 7 about here)

5. Estimating a Cost Function

From these results, a cost function that relates the level of inputs to the level of costs can be determined. Behind any single cost function is a given set of technology and a given program structure. The program structure is adjustable, as the breeder can (and does) readily change the selection pressure applied at any one of the stages of the program. As a result, there is no unique cost function for a given program, even if there is no change in technology used. Therefore, each cost function is only indicative for the program. For example, if the number of crosses is reduced, and the selection pressure is unchanged, the costs at each stage of the program will be reduced, as there will be fewer breeding lines at each stage of the breeding cycle. However, if selection is changed at one stage and remains unchanged for the other stages, costs will only reduce for the later parts of cycle.

The cost function from which the current program represents one point can be derived as follows. Within generation (or stage) *i*:

$$TC_i = F_i + (N_i V_i) \quad (1)$$

where TC_i is the total cost in stage *i*, F_i is the fixed cost in stage *i*, N_i is the number of breeding lines tested in stage *i*, and V_i is the variable costs per line in stage *i*.

Thus the total cost across all stages is:

$$C = O + \sum [F_i + (N_i V_i)], \text{ for all } i, \quad (2)$$

where C is total costs of all stages, and O is the total overhead cost.

The N_i are related between stages, such that:

$$N_{i+1} = N_i A_i , \quad (3)$$

where N_i is the selection intensity in stage *i*.

The average costs (C') are:

$$C' = C / N_i, \quad (4)$$

while marginal costs (C") are:

$$C'' = C \mid [N_i = n+1] - C \mid [N_i = n] , \quad (5)$$

or each generation, and

$$C'' = C \mid [N_1 = n+1] - C \mid [N_1 = n] , \quad (6)$$

for the whole program.

The key determinant of the costs of the program are the number of breeding lines in F3, from which population the selection is made to determine the superior breeding line(s). The F1 and F2 generations are not direct signals to the size of the program, as different breeding approaches can be used to develop the F3 population. While those activities are not costless, they are low cost compared to the later stages of the program. As a result, the cost function is developed as the relationship between the costs and the number of breeding lines at F3 stage. Applying these equations to the data obtained for the hypothetical wheat breeding program, the total and average costs for different numbers of breeding lines in the program (Figure 3). The total costs are almost linear as the number of breeding lines at F3 increases, with fixed costs of $284,000 and additional total costs of approximately $42 for each additional line included at F3 stage.

(Figure 3 about here)

The impact of variations in the number of breeding lines at F3 stage on the average and marginal costs across the whole program is illustrated in Figure 4. As the number of breeding lines at F3 increases, the overall average cost per line declines, from over $107 per line at 5,000 lines to $59 per line at 30,000 lines. In that range, the marginal cost per line remains at around $42 per line. Once over 20,000 breeding lines in F3, the average cost curve remains relatively flat.

(Figure 4 about here)

6. Discussion

The focus of this paper has been on the cost components of a wheat breeding program and the associated cost function. It is apparent that a detailed knowledge of the cost structure of a breeding program is a pre-requisite for informed decisions on the management of change within the program. The level of the total costs and the allocation of those costs between generations and stages is a key price of information for decision-makers. For example, any move towards more centralized breeding operations with regional evaluation needs to recognise the fact that the major costs are incurred when the breeding material is being tested across environments, and that centralizing the crossing, F1 and F2 stages does not lead to substantial cost savings. The real savings in reducing the number (and increasing the size) of breeding programs come through reduced testing in the mid- and later stages of the program (F3 and F6 to F9). In effect, to obtain significant cost savings from amalgamation and consolidation of breeding programs requires a reduction in the testing across potential production environments, or a reduction in the environments. Such savings are not part of the consolidation itself, but a separate decision to cut back testing across different environments before the release for commercial production.

The information on cost structure is also a significant piece of information for breeders. It allows them to identify the cost components, and allows them to focus on opportunities for cost reductions in the program. For example, it may be economic for robotics to replace manual seed preparation or high travel costs can indicate the importance of co-location of trials at one site, and so on. Similarly, breeders can address a range of options in the way that they use nurseries to apply selection pressure for different traits, and the extent to which additional selection pressure can have cost implications for other stages of the program. With this analytical tool, they are able to assess the cost impact of any change in he way in which breeding lines flow through the stages of the program.

The introduction of new technologies, such as genetic markers and physiological selection methods, results in direct changes in costs (where they are substituted for phenological testing and selection), and indirect impacts (where they allow changes to be made to other selection procedures in the program). To analyse the value of both levels of impacts, detailed cost analysis is required. Using the data obtained in this study, the impacts on costs of the use of markers, for example, can be readily assessed. A preliminary assessment of the role of markers was presented in Brennan *et al.* (2005).

Of course, addressing costs presents only a partial picture of the issue of the economics of breeding operations. Each of the selection programs has a different expected genetic outcome, as progress in breeding depends, *inter alia*, on the selection pressure on the different varietal traits, and the economic value of those traits. Brennan (1989a,b) provided an early attempt to introduce both costs and returns to the same analysis, to provide an economic assessment of breeding operations. The more detailed approach to the costing in this analysis, and the more detailed analysis of selection processes for different traits, allows this work to be further developed to incorporate expected returns, to enable a complete analysis of the costs and returns from alternative breeding approaches and different structures in the programs. That work is currently under way.

In conclusion, the cost estimates can provide valuable information to breeders to assist in decisions on changes to their programs. The analytical framework developed enables the cost consequences of any change in operations to be identified and the best trial operations to be adopted as new technologies such as genetic markers are incorporated into the breeding program. Future work incorporating expected returns as well as costs will provide breeders with the capacity to identify the best structures and optimal programs to meet the needs of industry.

References

Brennan, J.P. and Khan, M.A. (1989), *Costs of Operating a Wheat Breeding Program*, Rural and Resource Economics Report No. 5, Division of Rural and Resource Economics, N.S.W. Agriculture and Fisheries, Sydney.

Brennan, J.P. (1989a), "An analytical model of a wheat breeding program", *Agricultural Systems* 31(4), 349-66.

Brennan, J.P. (1989b), "An analysis of the economic potential of some innovations in a wheat breeding programme", *Australian Journal of Agricultural Economics* 33(1), 48-55.

Brennan, J.P., Martin, P.R. and Mullen, J.D. (2004), *An Assessment of the Economic, Environmental and Social Impacts of NSW Agriculture's Wheat Breeding Program*, Economic Research Report No. 17, NSW Agriculture, Wagga Wagga.

Brennan, J.P., Raman, H., Rehman, A. and Martin, P.J. (2005), "An economic assessment of the value of molecular markers in plant breeding programs", Contributed paper for the 49th annual conference of the Australian Agricultural and Resource Economics Society, Coffs Harbour

Dreher, K., Khairallah, M., Ribaut, J.-M. and Morris, M. (2003), "Money matters (I): Costs of field and laboratory procedures associated with conventional and marker-assisted maize breeding at CIMMYT", *Molecular Breeding* 11, 221-234.

Lindner, B. (2004), "Privatised provision of essential plant breeding infrastructure", *Australian Journal of Agricultural and Resource Economics* 48(2), 301-321.

Morris, M., Dreher, K., Ribaut, J.-M. and Khairallah, M. (2003), "Money matters (II): Costs of maize inbred line conversion schemes at CIMMYT using conventional and marker-assisted selection", *Molecular Breeding* 11, 235-247.

Table 1: Operations in Hypothetical Wheat Breeding Program

Stage	Number[a] of breeding lines	Evaluation conducted
Crossing		Cross parents
F1	100	Nil
F2	100	Select single plants in rust nursery
F3	18,000	Evaluate for a range of diseases and tolerances plus seed increase row
F4	2,326	Yield in replicated trials, early generation quality and selections from families
F5	5,079	Summer seed increase
F6	1,524	Yield in replicated trials small number of locations, early generation quality and evaluation for a range of tolerances disease resistance traits
F7	592	Yield in replicated trials medium number of locations, confirm evaluation for a range of tolerances disease resistance traits
F8	197	Yield in replicated trials medium number of locations, detailed quality evaluation
F9	62	Yield in replicated trials large number of locations, detailed quality evaluation, confirm previous disease evaluation and detailed evaluation of some diseases and tolerances.
F10	12	Yield in replicated trials large number of locations, detailed quality evaluation, confirm previous disease evaluation and detailed evaluation of some diseases and tolerances. Commence large scale seed increase.

[a] Indicative numbers only

Table 2: Examples of Phenotypic Selection for Some Traits

Trait	Where measured	Operator skill	Speed	Expected cost
Plant height	Field observation	Low	High	Very low
Septoria tritici blotch resistance	Field nursery	Medium-high	High	Low
Septoria tritici blotch resistance	Glasshouse	Medium-high	Medium	Medium
Cereal cyst nematode resistance	Field & laboratory	Medium-high	Low	Very high
Crown rot resistance	Field & laboratory	Medium-high	Low	High
Crown rot resistance	Glasshouse	High	Low	Very high
Leaf rust resistance	Field nursery	Medium-high	High	Low-medium
Dough glutenins in wheat	Laboratory	Medium-high	Medium	High
Small-scale quality tests	Laboratory	Medium	High	Low
Large-scale quality tests	Laboratory	High	Low	Very high
Karnal bunt resistance	Overseas (field)	Medium	Very low	High

Source: Brennan *et al.* (2005)

Table 3: Estimated Total Costs and Average Costs in Wheat Breeding Program

Stage	No. breeding lines	Total cost ($'000)	Average cost ($/line)
F1	100	$0.2	$2
F2	100	$18	$179
F3	18,000	$299	$17
F4	2,326	$73	$31
F5	5,079	$40	$8
F6	1,524	$169	$111
F7	592	$183	$309
F8	197	$153	$779
F9	62	$170	$2,735
F10	12	$76	$6,486
	27,991	**$1,182**	

Table 4: Component Costs of Unharvested Early-Generation Field Nursery

	% of total cost
Site and irrigation management	11%
Data management and decisions	7%
Seed preparation and sowing	10%
Disease inoculation	13%
Assessment and scoring	54%
Harvest & post-harvest	0%
Operating costs	2%
Travel costs	1%
Capital costs	3%
Total Costs	**100%**

Table 5: Component Costs of Later-Generation Yield Trial

	% of total cost
Travel costs to site	18%
Site operations	4%
Data management and decisions	39%
Labour: seed preparation	5%
Labour: Growing, evaluating	11%
Labour: Harvesting	16%
Machinery operating costs	2%
Other operating costs	3%
Land leasing costs	2%
Capital costs	1%
Total Costs	**100%**

Table 6: Costs of Multi-Location Yield Trials in Wheat Breeding Program

	Total Costs			
	per plot	**per line**	**per trial**	**per stage**
F6 trials	$18	$21	$32,554	$97,662
F7 trials	$19	$42	$24,671	$123,354
F8 trials	$26	$59	$11,552	$115,516
F9 trials	$49	$122	$7,554	$151,088
F10 trials	$68	$284	$3,332	$66,633
- Total			**$79,662**	**$554,253**

Table 7: Average and Marginal Costs for Entries in Yield Trials

	Costs per line[a]	
	Average	**Marginal**
F6 trials	$21	$14
F7 trials	$42	$31
F8 trials	$59	$31
F9 trials	$122	$37
F10 trials	$284	$37

[a] At one site

Figure 1: Structure of Operation in Early Generations

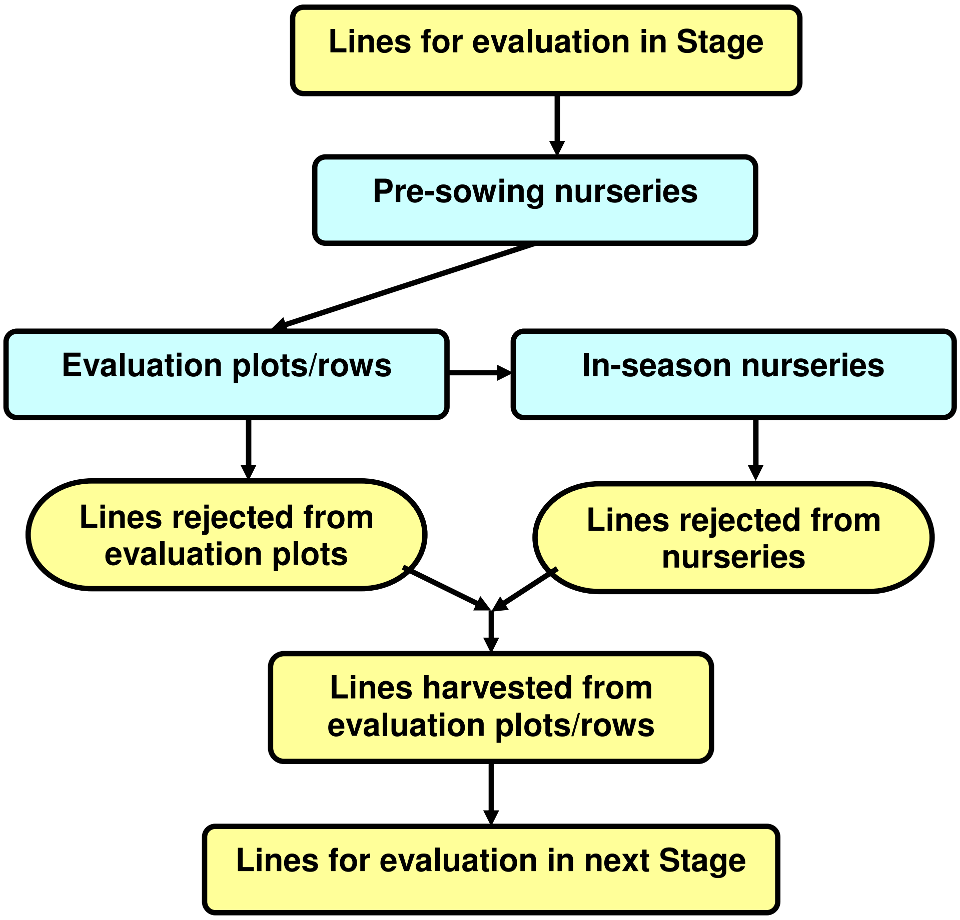

Figure 2: Estimation of Costs of Operations in Breeding Program

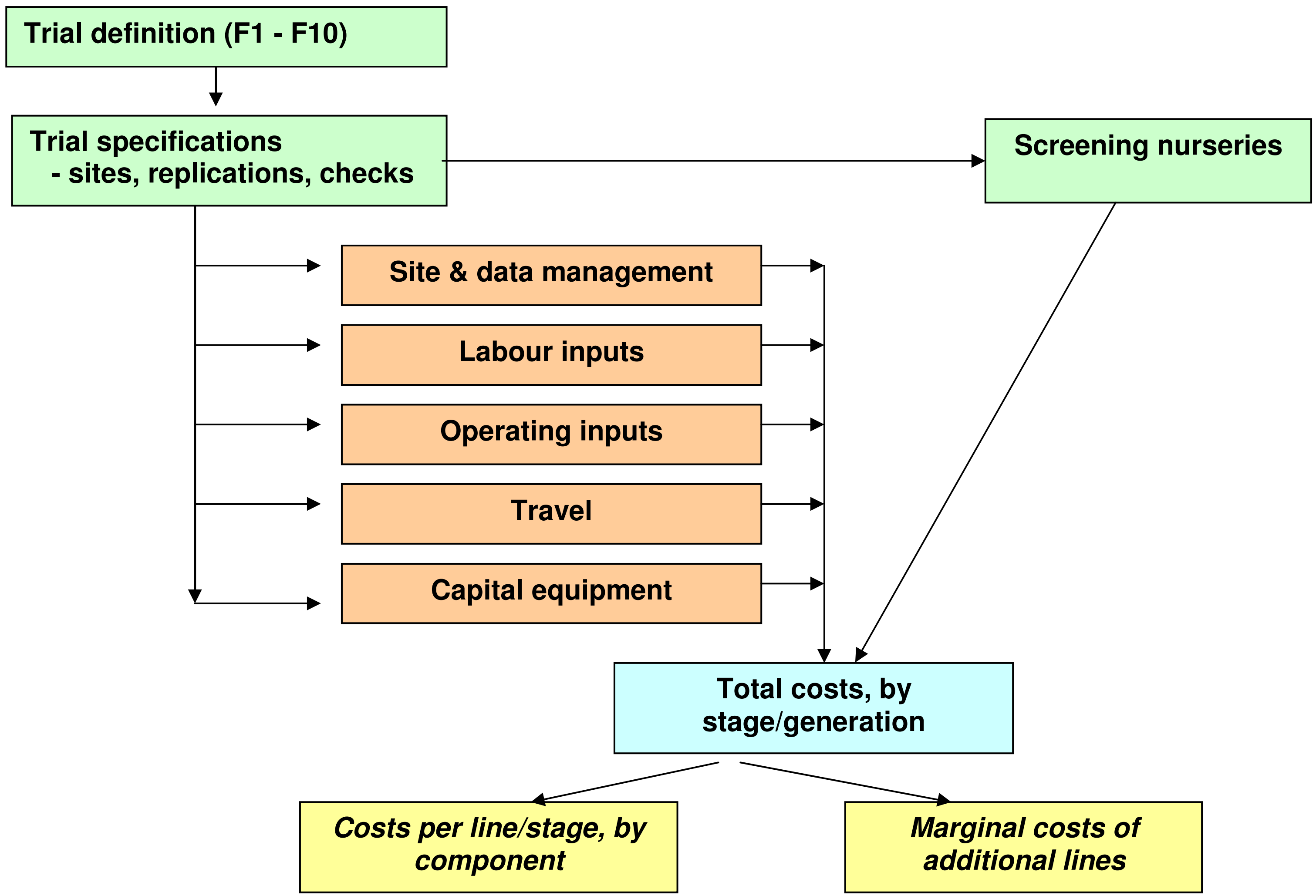

Figure 3: Wheat Breeding Program: Total and Average Costs

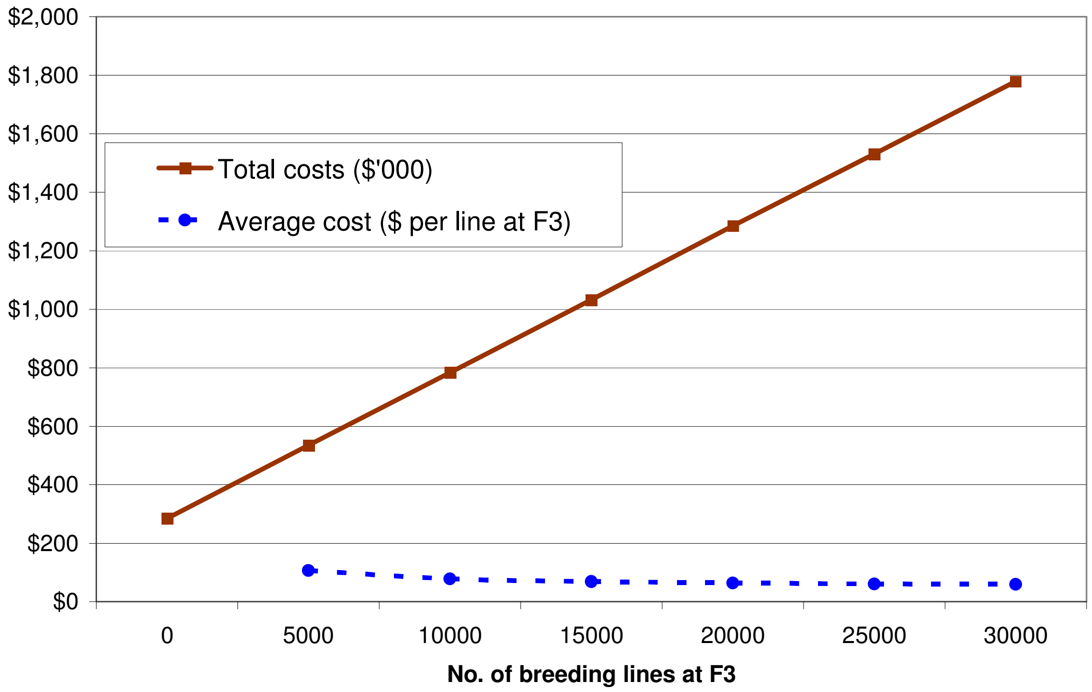

Figure 4: Wheat Breeding Program: Average and Marginal Cost