Animal Science 1996, 62: 393-403
1357-7298/96/56060393$20·00

Customized selection indices for dairy bulls in Australia

P. J. Bowman, P. M. Visscher† and M. E. Goddard‡

Victorian Institute of Animal Science, 475 Mickleham Road, Attwood, Victoria 3049, Australia

Abstract

Customized sire selection indices were developed for Australian dairy bulls in order to promote more objective use of estimated breeding values in commercial breeding programmes. It was assumed that the breeding goal for commercial dairy farmers is the profitability of a bull's progeny. Seven characteristics of the progeny were identified as having a major impact on profitability and were included in the breeding objective: milk, fat and protein yield, survival, body weight, milking speed and temperament. Traits in the selection indices used to predict profit were milk, fat and protein yield, survival, milking speed, temperament, size, overall type and fore teat placement. Size was included because of its correlation with body weight, and overall type and front teat placement because of their correlation with survival. To avoid double counting the benefits of milk production traits, temperament and milking speed, the survival trait in the objective was defined as survival independent of voluntary culling for these traits. Customization of the breeding objective was achieved by adjusting the economic weights for traits in the objective to take account of important characteristics of farmers' herds, the milk payment system under which they operate and make allowance for their own value judgements. An assessment of the impact of customization suggested that, even though there is a wide range in the economic weights that are applicable in different areas of Australia, there would be little loss of efficiency in using a single national index. However, customization is still believed to be desirable given that it is likely that a substantial proportion of farmers will be reluctant to use a national index, especially in those states which have quotas and focus on the liquid milk market. The algorithms described in the paper have been incorporated into a user-friendly microcomputer program called $electabull *which is now commercially available to farmers.*

Keywords: *breeding programmes, milk production, productive life, selection index, sire evaluation.*

Introduction

In Australia, estimated breeding values of dairy bulls are called Australian Breeding Values (ABV). At present, the Australian Dairy Herd Improvement Scheme (ADHIS) publishes up to 33 ABV per bull (ADHIS, 1994); five milk production ABV (milk, fat, and protein yield, and fat and protein content), three workability ABV (milking speed, temperament, and likability), 23 type ABV, and an ABV for survival and calving ease. The ABV for production traits are predicted using best linear unbiased production (BLUP) with an animal model (Jones, 1985; Jones and Goddard, 1990). All other ABVs are from BLUP evaluations using sire or sire-maternal-grandsire models.

For dairy farmers, it is not straightforward to make a consistent and rational choice among the scores of bulls for which semen is for sale. Not only do farmers have to combine all the information available on bulls in some way, the bulls also vary in the number of ABVs which are published for them. For example, only production ABVs (converted from their home country proof) are calculated for overseas bulls which do not have lactating daughters in Australia. Most methods of ranking bulls used to date in Australia have been overly simplistic and tended to place too much emphasis on some minor traits. There have also been problems when

† Present address: Roslin Institute, Roslin, Midlothian EH25 9PS.
‡ Present address: Animal Genetics and Breeding Unit, University of New England, Armidale NSW 2351, Australia.

attempting to rank bulls which either do not have an ABV for a key trait or the reliability of the ABV is low. In addition, existing methods are able neither to take full account of the characteristics of farmers' herds and the milk payment system under which they operate nor make allowance for their own value judgements.

Assuming that for commercial dairy farmers the breeding goal is the profitability of a bull's progeny, it would be logical to combine all available (progeny) information to predict profitability. One way to predict profit is to combine data on production and herd life directly into a breeding value for profit (e.g. Visscher and Goddard, 1995b). Another predictor of profit is to combine published ABV into a selection index using economic weights of traits in the breeding objective and genetic parameters such as heritabilities and genetic correlations for traits in the breeding objective and traits in the selection index (Hazel, 1943). Breeding objectives may differ between dairy farmers implying that they should each use their own selection indices. However, rational calculation of economic weights is not a simple task and so a method of deriving economic weights and hence selection indices which can be customized for individual farmers is needed. Implementation of such selection indices in a commercial farm context is potentially constrained by the time-consuming and tedious nature of the calculations. Fortunately, modern microcomputers are well suited to indertake the necessary tasks quickly and efficiently and in a way that is specifically tailored to take account of a farmer's own situation and value judgements.

The aim of this paper is to describe the development of customized sire selection indices for Australian dairy bulls. Methods were derived to allow the economic weights of traits in the breeding objective to be customized to reflect the circumstances and preferences of individual farmers. In developing these methods, consideration was given to the likely availability on commercial dairy farms of the data to be used in the calculations and the speed and efficiency with which these calculations could be performed. Index calculations have been incorporated into a user-friendly microcomputer program called *$electabull* which is now commercially available to farmers (Bowman, Visscher and Goddard, 1994). To our knowledge, this is the first time that individual dairy farmers have been provided with a tool which can be used to predict for their herd the profitability of a bull's daughters.

Milk production and composition, milking speed, body size, type and length of herdlife are traits for which genetic evaluations are widely calculated. Past international research and industry practice has either developed a national index or has abandoned an economically rational index approach. Therefore we hope that a methodology for customizing index calculations which can be used by dairy farmers and the efforts of customization will be of interest in other countries.

ABV and breeding objectives

Definition of Australian Breeding Values

Definitions of ABV are described in detail by ADHIS (1994). ABV for milk, fat, and protein yield are calculated using an animal model (Jones, 1985; Jones and Goddard, 1990) and expressed in kg.

At present we do not use the ABV for calving ease in the selection index calculations as there are insufficient data to estimate key genetic parameters. However, the data required are accumulating steadily and it should be possible to include this trait in the index in future.

Breeding objective and economic weights

The farmer inputs which customize the breeding objective and an example of their default values are summarized in Table 1. We define farm profit as the breeding goal, and approximate this by a linear function of milk, fat, and protein yield, survival, mature body weight, milking speed, and temperament. Previously (Visscher, Bowman and Goddard, 1994), we described a generalized method to calculate economic weights for pasture based production systems for milk production traits, mature body weight, and survival. The following sections describe the method for calculating economic weights for milking speed and temperament and how we have applied these methods in developing customized economic weights.

Milk production traits

Payment systems throughout Australia differ widely and the program must be able to calculate economic weights which reflect the different circumstances. This is done by having the producer provide the payment formula under which they expect to be paid in future. In the states of Victoria and Tasmania most milk is used for manufacturing and paid for on the basis of the weight of protein and fat supplied with a charge for milk volume. Similar payment systems exist in other countries (e.g. Dommerholt and Wilmink, 1986; Rozzi, 1991; Gibson, Graham and Burnside, 1992). In states like New South Wales and Queensland most farmers hold a quota for the supply of liquid milk. Milk supplied above quota is paid for at manufacturing prices whilst quota milk is

Table 1 *Farmer inputs which customize the breeding objective and an example of default values for these inputs*

Farmer input	Default value†	Economic weight most affected by the input
Manufacturing market:		
protein price	\$4·80/kg	Protein
fat price	\$2·40/kg	Fat
volume charge	\$0·03/l	Volume
Liquid market:		
milk price	\$0·39/l	
Proportion of milk supplied used in liquid milk market‡	11%	
Replacement rate	20%	Survival
Costs of rearing replacement heifers§	\$70 per head	Survival
Costs of maintaining cows§	\$79 per head	Survival; Body weight
Price of culled stock:		Body weight
male calves	\$40 per head	Body weight
adult cows	\$500 per head	Body weight
Value of time spent milking	\$12/h	Milking speed
Size of dairy	8 sets of cups	
Proportion of cows culled for poor temperament	0·8%	Temperament
Milk production¶:		
protein	134 kg per head	
fat	174 kg per head	
volume	4039 l per head	

† Default values for the state of Victoria which accounts for more than 60% of total milk production in Australia. Prices are shown in Australian dollars.
‡ For states in which a milk quota applies, farmers are asked to enter their annual quota in litres per farm. In New South Wales, farmers also need to enter the bonus/penalty that is applied to milk for which protein and fat content is above or below a standard value.
§ Food costs are not included in these figures for reasons explained in Visscher *et al.* (1994).
¶ Average annual production of adult cows.

paid for at a higher price and on a different basis. Detailed calculations of marginal returns for volume, fat and protein yield are presented in **Appendix 1**.

Survival and body weight
Visscher *et al.* (1994) describe the economic weights for survival and body weight based on their farm model. Increased survival of cows in the milking herd, and hence longer herd life, means that fewer replacement heifers must be reared leaving more food for milking cows, and more of these milking cows are in the most productive age categories. To avoid double counting the benefits of milk production traits, temperament and milking speed, the survival trait in the objective is defined as survival independent of voluntary culling for these traits and is termed adjusted survival. Increased body weight leads to more returns per cow or calf sold but increased food requirements for maintenance and growth which usually leads to a negative economic weight for body weight.

Milking speed
Milking speed is defined as the time required to milk a cow in minutes. Our assumption with regard to the economic weight of milking speed (MS) was 'time is money'. Hence, the effect of a small change in milking speed on total time spent milking was used to calculate the economic weight for MS (see **Appendix 2**).

The economic weight is customized by farmers entering the value placed on the time spent milking. They are also asked to enter the size of their dairy in terms of the number of cows it can accommodate per 'round of milking'.

Temperament
The temperament of cows is scored by dairy farmers on a scale from 1 (very desirable) to 5 (very undesirable). In Australia (Mallamaci, Beard, Goddard and Jones, 1992) and New Zealand (Wickham, 1979) dairy farmers consider temperament of cows to be an important trait. Possibly it is more important in these countries where young stock receive relatively little handling compared with countries with more intensive farming practices. The economic weight for temperament is derived from the method of Wickham (1979). This method uses a multiple regression equation which predicts whether cows will be kept in the herd or culled based on their milk production and temperament. The relative sizes of the partial regression coefficients is used to set relative economic weights for temperament and milk production (see **Appendix 3** for details). In effect this method sets the economic weight for temperament by using the multiple regression equation to estimate the amount of milk a farmer will sacrifice in order to cull a cow of bad temperament.

The economic weight is customized by asking dairy farmers to enter the number of cows per year which are culled for whom the principal reason for culling was poor temperament.

Selection index calculations

Notation and definitions
Traits. M = milk yield; F = fat yield; Pr = protein yield; MS = milking speed; Temp = temperament;

S = survival (unadjusted); S_{adj} = survival adjusted for production and workability traits; B = (mature) body weight; Size = size; FTP = fore teat placement; OT = overall type.

Matrices, vectors and scalars. **a** = vector containing economic weights corresponding to Breeding Values in the breeding objective; **u** = vector containing breeding values; **x** = vector containing daughter means; **y** = vector containing ABV; t = intraclass correlation ($= h^2/4$); r_g = genetic correlation; r_p = phenotypic correlation; r_w = within sire correlation; $\mathbf{P}^\star$ = (co)variance matrix of traits (ABV) in the index; $\mathbf{G}^\star$ = covariance of traits in breeding goal (H) and traits in index; $\mathbf{C}^\star$ = variance in breeding values.

Others. Rel = reliability; n = effective number of daughters.

Note that for workability traits the elements of vector **a** are half that of the economic weights per unit change in ABV, since the ABV for the workability traits are half breeding values.

In the previous section we defined the breeding goal (**H**) where

$$\mathbf{H} = \mathbf{a}'\,\mathbf{u} \tag{1}$$

a = a vector of economic weights, **u** = a vector of breeding values.

To predict the breeding objective, we use a selection index (I) which is calculated using multivariate estimated breeding value (EBV) ($\hat{\mathbf{u}}$):

$$\mathrm{I} = \mathbf{a}'\,\hat{\mathbf{u}} \tag{2}$$

The multivariate EBV are calculated using the ABV, their reliabilities, and the covariances between the ABV and the breeding goal as described below. If ABVs were published for all traits in the breeding objective and if these ABVs were calculated by a multivariate BLUP analysis, then the selection index could be obtained simply by multiplying each ABV by its economic weight and summing over traits. However, ABVs are calculated in single trait analyses and no ABV is produced for body weight or adjusted survival. We use the following ABV to predict the breeding value of traits in the breeding objective; protein, fat, milk volume, milking speed, temperament, survival, size, fore teat placement and overall type. For a bull with a large number of daughters, the production and workability ABV effectively predicts the breeding value for the corresponding traits in the breeding objective. The survival ABV is adjusted to avoid double counting the benefits of milk production, milking speed and temperament. Of the type traits, size is included in the selection index because of its correlation with body weight, and overall type and front teat placement because of their correlation with survival.

Assumptions and calculations
ABV. Assume that

$$\mathrm{ABV}_j = c_j\,[n/(n+k)]\,[x_j - \mu] \tag{3}$$

with $k = (1 - t_j)/t_j$; $\mathrm{Rel}_j = n/(n+k)$.

Hence, given Rel and k, n can be calculated, or, given n and k, Rel can be calculated. For most ABV, $c_j = 2$, since the ABV are EBV. For the workability traits, $c_j = 1$ (see Table 2).

Index calculations. Let

$$\mathbf{D} = \text{diagonal matrix with elements } D_j = c_j\,\mathrm{Rel}_j\,\sigma_j \tag{4}$$

with $c_j = 2$ if ABV j is an EBV (estimated breeding value), 1 if ABV j is half an EBV (for workability traits); σ_j = phenotypic standard deviation for trait j; Rel_j = reliability of ABV_j.

Let

$$\mathbf{D}_g = \text{diagonal matrix with elements } D_{g(j)} = 2\,\sigma_j \tag{5}$$

where traits j are traits in the breeding objective.

Let $\mathbf{P}^\star$ = (co)variance matrix of traits (ABV) in the index = **DPD**, hence **P** is a matrix with standardized (co)variances of the daughter means (x) from which the ABV are calculated:

$$\begin{aligned} P_{jk} &= \mathrm{cov}_p \\ &= r_g(t_jt_k)^{1/2} + [(1-t_j)(1-t_k)]^{1/2}\, r_w/n \\ &= r_g(t_jt_k)^{1/2}[1 - 1/n] + r_p/n \end{aligned} \tag{6}$$

where $r_w = [r_p - r_g(t_jt_k)^{1/2}]/[(1-t_j)(1-t_k)]^{1/2}$; $n = \infty$ if the traits were measured on different animals; $n = n_k$ if $n_j < n_k$ and n_j animals have measurements on both traits.

It follows that

$$\begin{aligned} P_{jj} &= t_j + (1 - t_j)/n \\ &= t_j/\mathrm{Rel}_j \end{aligned}$$

Let $\mathbf{G}^\star$ = covariance of traits in breeding goal (**H**) and traits in index = $\mathbf{DGD}_g$. Elements of **G** are:

$$\begin{aligned} G_{jk} &= \mathrm{cov}_g \\ &= r_g(t_jt_k)^{1/2} \end{aligned} \tag{7}$$

The multivariate EBV are calculated as

Table 2 *Heritabilities (×100, on the diagonal), genetic correlations (×100, below diagonal), and phenotypic correlations (×100, above the diagonal) for traits in the index, units, phenotypic standard deviations (σ) and coding (c_j) for breeding value or transmitting ability for traits in the index, and genetic correlation (×100) between mature body weight (B), adjusted survival (S_{obj}) and traits in the index*

	M	F	Pr	S†	MS	Temp	Size	FTP	OT
M§	25	77	92	17	0	0	16	0	18
F	63	25	84	17	0	0	16	0	18
Pr	88	74	25	17	0	0	16	0	18
S†	50	50	50	2·5	5	6	6	5	10
MS	0	0	0	20	25	18	0	0	0
Temp	0	0	0	20	50	16	0	0	0
Size	20	20	20	20	0	0	45	17	44
FTP	0	0	0	10	0	0	17	33	45
OT	25	25	25	20	0	0	44	45	30
c_j	2	2	2	2	1	1	2	2	2
σ‡	800	32	24	40	20	20	8·0	9·6	10·2
units	l	kg	kg	%	%	%			
$r_g(\mathrm{B},x)$	0	0	0	0	0	0	60	0	0
$r_g(\mathrm{S_{obj}},x)$	0	0	0	72	0	0	11	14	6

† The phenotypic correlations between survival and other traits were calculated assuming that the genetic and phenotypic regression were equal (see **Appendix 4**).
‡ Phenotypic standard deviations for the workability traits assume: ABV = 100 × z × Rel × x, where x is the progeny average on an underlying (normal) scale with standard deviation equal to one, and z is the ordinate of the normal curve pertaining to the mean proportion of satisfactory daughters. Phenotypic standard deviations for type traits are derived from the standardized standard deviation of ABV, and the average reliability (based on the heritability and an assumed average number of progeny of 50).
§ In this and succeeding tables see section on **selection index calculations** for definitions.

$$\hat{\mathbf{u}} = \mathbf{G}^{\star}\mathbf{P}^{\star-1}\mathbf{y} \qquad (8)$$

where $\mathbf{y} = \mathbf{ABV} - \overline{\mathbf{ABV}}$ and $\overline{\mathbf{ABV}}$ = mean ABV for all bulls in the database.

Once we have the vector $\hat{\mathbf{u}}$ for each sire, we calculate the index using equation 2.

The reliability of the index is

$$\mathrm{Rel}_{\mathrm{I}} = v(\mathrm{I})/v(\mathbf{H}) \qquad (9)$$

with $v(\mathrm{I}) = \mathbf{a}'v(\hat{\mathbf{u}})\mathbf{a}$ and $v(\mathbf{H}) = \mathbf{a}'\mathbf{C}^{\star}\mathbf{a} = \mathbf{a}'\mathbf{D}_g\mathbf{C}\mathbf{D}_g\mathbf{a}$ where $C_{jk} = r_g(t_jt_k)^{1/2}$.

Parameters

Parameters were taken from Madgwick, Beard and Goddard (1991), Beard and Jones (1991), Madgwick and Goddard (1989), and Visscher and Goddard (1995a). Covariance matrices are presented in Tables 2 and 3.

Adjusted survival

The ABV for survival (S) is based on the relative survival of a bull's daughters, and is therefore influenced by voluntary culling for production and workability traits. Indeed, genetic correlations between survival traits and milk production traits were high (Visscher and Goddard, 1995a). In the

Table 3 *Heritabilities (×100, on the diagonal) and genetic correlations (×100, below diagonal) for traits in the breeding objective†*

	M	F	Pr	S_{obj}	MS	Temp	B
M	25						
F	63	25					
Pr	88	74	25				
S_{obj}	0	0	0	1·4			
MS	0	0	0	0	25		
Temp	0	0	0	0	50	16	
B	0	0	0	0	0	0	40
σ	800	32	24	39·1	20	20	60

† The phenotypic standard deviation for S_{obj} is calculated from the standard deviation of S and the phenotypic correlations between S and M, F, Pr, MS and Temp (see **Appendix 4**).

breeding objective, we have survival for involuntary culling (S_{obj}) (Visscher *et al.*, 1994). To avoid double counting of milk production and workability traits, we adjust the survival ABV for the average contribution of these traits (S_{adj}) (see **Appendix 4**). Furthermore, we think that even after adjustment for production and workability traits, the remaining adjusted survival does not solely reflect the ability to avoid involuntary culling. This is because we believe that some farmers tend to keep daughters of certain sires in the herd irrespective of their production and workability. For example, this can occur where they pay a high price for semen of the sire. Therefore, we assumed a genetic correlation between S_{adj} and S_{obj} of less than unity (**Appendix 4**). At present, we assume that this genetic correlation is 90%.

Relative importance of individual traits

Bulls differ in the number of traits for which they have published ABV and the number of daughters on which these ABV are based. This is most noticeable with young bulls and overseas bulls who do not have many lactating daughters in Australia. Proven bulls by definition must have ABV for milk, fat and protein but may be missing ABV for all other traits in the selection index. It is of interest to determine how the absence of key traits and the reliability of the ABV influence the response to selection.

In Table 4 selection indices are presented for bulls with different amounts of daughter information. The index calculations assume the following breeding objective which has economic weights that are characteristic of those which would be employed for a typical farm in Victoria:

$$\text{breeding objective } (\mathbf{H}) = -0{\cdot}02\text{M} + 1{\cdot}2\text{F} + 3{\cdot}9\text{Pr} + 4{\cdot}9\text{S}_{obj} + 1{\cdot}1\text{MS} + 1{\cdot}8\text{Temp} - 0{\cdot}7\text{B} \quad (10).$$

For all indices except number 10, it is also assumed that the ABV are derived from 80 effective daughters for production and survival traits and 50 effective daughters for workability and type traits. For index number 10 it was assumed that the bull has a large number of daughters such that the reliability of each ABV is 0·999. The index weights and index reliability were calculated for each selection index. The efficiency of the index was also calculated as the correlation between the index and the breeding objective. The first selection index is for a bull with the minimum number of ABV and its efficiency was used as the basis for comparison with the other indices.

It can be seen from Table 4 that traits other than milk production ABV contribute relatively little in increased response to selection. For example, if all ABV were known without error, the increase in

Table 4 *Selection index weights for ABV, reliabilities, relative efficiencies (first rows) for bulls with different numbers of daughters (second rows) for individual traits*

Index number	Trait (ABV) M	F	Pr	S	MS	Temp	Size	FTP	OT	Reliability of index	Relative efficiency†
1	−0·03	1·14	4·13							54	100
	80	80	80								
2	−0·03	1·14	4·13		3·64					60	105
	80	80	80		50						
3	−0·03	1·14	4·13			4·98				60	105
	80	80	80			50					
4	−0·03	1·14	4·13		2·55	3·60				62	107
	80	80	80		50	50					
5	−0·03	1·15	4·13				−3·31	0·20	2·27	59	104
	80	80	80				50	50	50		
6	−0·03	1·15	4·13		2·55	3·60	−3·31	0·20	2·27	66	111
	80	80	80		50	50	50	50	50		
7	−0·03	0·96	4·12	3·82						58	103
	80	80	80	80							
8	−0·03	0·99	4·12	3·05	2·34	3·32				64	109
	80	80	80	80	50	50					
9	−0·03	1·01	4·12	3·15	2·33	3·31	−3·40	0·08	2·25	69	113
	80	80	80	80	50	50	50	50	50		
10	−0·04	0·75	3·86	4·25	1·48	2·70	−4·11	0·14	2·13	91	129
	#	#	#	#	#	#	#	#	#	#	#

† Efficiency of the index (in %) relative to the efficiency of selection index number 1.
# Large number of daughters, with the number chosen such that the reliability of the ABV was 0·999.

Table 5 *Economic weights ($) of traits in the breeding objective for the four scenarios*

Scenario	M	F	Pr	S_{obj}	MS	Temp	B
Manufacturing	−0·030	1·30	4·24	4·69	1·52	2·81	−0·67
Liquid/Quota	0·001	0·88	3·21	4·18	1·69	3·71	−0·60
Workability	−0·030	1·30	4·24	4·69	0·00	7·36	−0·67
Altered prices	−0·038	0·13	5·86	4·53	1·52	2·81	−0·64

efficiency in sire selection was 29% relative to ABV for milk production traits based on 80 daughters. Note that even if all ABVs were known, the reliability of the index was only 91%. This is because we can never predict B and S_{obj} with 100% reliability. Workability traits add approximately 5% in efficiency, and type traits (in the absence of a survival ABV) approximately 4%. Most of the increased efficiency from including type traits comes from the ability to predict mature body weight. The contribution from FTP is essentially zero, but feedback from various industry sources suggested that the index would achieve greater acceptance if this trait was included.

Assessing the impact of customization

Method of comparison

Four scenarios were chosen to investigate the extent to which differences in farmer inputs would alter the ranking of bulls. The default values for farmer inputs shown in Table 1 were chosen for scenario 1 which yield economic weights for traits in the breeding objective that are typical of those in states where the majority of milk production is for the manufacturing market (Table 5). For convenience, this scenario has been termed Manufacturing. For scenario 2 (Liquid/Quota), default values for New South Wales were used to investigate the effect of a milk payment system where the majority of milk production is for the liquid milk market and quotas are in operation (**Appendix** 1). Scenario 3 (Workability) was used to investigate the effect of varying the emphasis on workability traits. In a survey of farmer attitudes Mallamaci *et al.* (1992) found that some farmers placed no value on increased milking speed but a high value on improved temperament. For scenario 3 the value of time spent milking was set to zero and the proportion of cows culled for poor temperament was increased three-fold to 2·4%. All other inputs were the same as for scenario 1. Scenario 4 (Altered prices) was also a variation on scenario 1. Manufacturing prices for milk components were altered to reflect a possible outcome of recent trends in these prices. The price for fat was halved, the protein price was increased by one third and the penalty for milk volume was also increased by one third.

Farmer inputs for each scenario were entered into the *$electabull* program and used to rank the 2074 Holstein bulls in the 1994 data base of proven bulls. Differences between the scenarios were assessed by calculating the correlations between the selection indices, the number of bulls in the top 10 which were shared by a pair of indices, and the mean ABV for the top 10 bulls selected for each index.

Results

Table 6 shows the correlations between the selection indices calculated for the bulls under each scenario.

Table 6 *Correlations (×100, above diagonal) between selection indices, and number of bulls (below diagonal) in the top 10 which were shared by a pair of indices*

Scenario	Manufacturing	Liquid/Quota	Workability	Altered prices
Manufacturing		98·0	98·2	96·5
Liquid/Quota	8		97·3	97·1
Workability	8	10		95·1
Altered prices	9	7	7	

Table 7 *Average ABV for the top 10 bulls selected for each selection index*

Scenario	M	F	Pr	S	MS	Temp
Manufacturing	1468	49·6	39·4	10·3	92·1	93·1
Liquid/Quota	1514	49·1	38·6	8·6	92·3	93·8
Workability	1514	49·1	38·6	8·6	92·3	93·8
Altered prices	1476	47·6	39·8	9·0	93·1	93·1

Even though the economic weights for the scenarios differed substantially, the correlations between the selection indices were very high. This is reflected in the high number of bulls in the top 10 which were shared by a pair indices. It is interesting to note that the top 10 bulls for the Liquid/Quota and Workability scenarios were the same, although the ranking of bulls within the top 10 differed. The same 10 bulls were chosen in spite of the different focus on traits conferred by the economic weights.

The average ABV for the top 10 bulls selected for each selection index were very similar (Table 7). Without a penalty for milk in the Liquid/Quota scenario and with additional emphasis placed on temperament in the Workability scenario, the ABV for milk volume was higher than for the other two scenarios. The highest mean protein ABV and lowest mean fat ABV were achieved with the Altered price scenario but the changes in mean ABV were small.

General discussion

One of the principal sources of variation in the economic weights for production traits in various regions of Australia arises from the different milk payment systems in operation. Milk income contributes approximately 85% of the total income for an Australian dairy enterprise and the economic weights for protein, fat and milk volume are particularly sensitive to differences in the payment systems. In states where the majority of milk is used in the liquid milk market and quotas apply, the economic weight for milk volume is positive, whereas in states where the bulk of milk produced is used in manufacturing, the economic weight for this trait is negative. In fact, the range in economic weights for production traits in Australia is not dissimilar to that found by Leitch (1994) when comparing selection or production indices in use in nine different countries.

Only three of the indices reviewed by Leitch (1994) included milking speed and there was only one occurrence each of temperament, stature and productive life. With the exception of productive life, very little emphasis was placed on these traits even when they were included. In consulting with the Australian industry as to which traits should be included in the objective, strong demand was expressed for inclusion of the two workability traits. The greater emphasis placed on temperament by Australian dairy farmers probably reflects the larger herd size and more extensive nature of production which results in less human contact with the cows, particularly at an early age. Our indices place less emphasis on type traits than is the case for a number of North American and European indices and then only as predictors of survival and body weight.

The methods we have developed should be reasonably robust with regard to the impact of errors in parameter estimates. Because of the importance of the production traits, errors in predicting the effect of the other traits are likely to be relatively minor. Also, where there was doubt about the relationship between traits, a zero correlation was assumed. In addition, the number of traits included in the index is sufficiently small to avoid the loss in response to selection which can arise where a genetic multiple regression is based on a large number of traits (Visscher, 1995).

The motivation for the development of customized selection indices was two-fold. First, we wanted to promote a more objective use of ABV. Secondly, we wanted to allow farmers to select for overall profitability on the basis of a single score which takes account of their own situation. It is the emphasis on profitability that distinguishes this approach from most other sire selection programmes which encourage farmers to set an arbitrary range of acceptable EBV.

In spite of the wide range in economic weights for traits in the breeding objective which are applicable in different areas of Australia, our assessment of the impact of customization suggests that there would be little loss of efficiency in using a single national index. However, there is evidence from surveys (Mallamaci *et al.*, 1992) and strong anecdotal evidence to suggest that a substantial proportion of farmers will, at least initially, be very reluctant to use a national index, especially in those states which have quotas and focus on the liquid milk market. Many of these farmers would most likely continue to use overly simplistic methods which can place too much emphasis on minor traits. Incorporation of the algorithms described in this paper into a user-friendly microcomputer program was a logical step in making the indices more accessible and understandable to farmers. In using a customized index, farmers should gain a sense of ownership of the bull ranking, thereby encouraging use of a more objective method of sire selection. The success of the program will largely depend on its rate of adoption. To date the reaction of farmers who have used the program has been very encouraging.

Acknowledgements

This work was supported by a grant from the Australian Dairy Research and Development Corporation. We thank Les Jones and Kevin Beard for their comments and suggestions.

References

Australian Dairy Herd Improvement Scheme. 1994. *The ABV book: Australian breeding values for dairy sires.* ADHIS, Melbourne.

Beard, K. T. and Jones, L. P. 1991. Traits affecting survival of cows in Australian dairy herds. *Proceedings of the ninth conference of the Australian Association of Animal Breeding and Genetics,* pp. 425-428.

Bowman, P. J., Visscher, P. M. and Goddard, M. E. 1994. *$electabull: users' guide.* Australian Dairy Herd Improvement Scheme, Melbourne.

Dommerholt, J. and Wilmink, J. B. M. 1986. Optimal selection responses under varying milk prices and margins for milk production. *Livestock Production Science* **14:** 109-121.

Gibson, J. P., Graham, N. and Burnside, E. B. 1992. Selection indexes for production traits of Canadian dairy sires. *Canadian Journal of Animal Science* **72:** 477-491.

Hazel, L. N. 1943. The genetic basis for constructing selection indices. *Genetics* **28:** 476-490.

Jones, L. P. 1985. Australian breeding values for production characters. *Proceedings of the fifth conference of the Australian Association of Animal Breeding and Genetics,* pp. 242-247.

Jones, L. P. and Goddard, M. E. 1990. Five years experience with the animal model for dairy evaluations in Australia. *Proceedings of the fourth world congress on genetics applied to livestock production, Edinburgh, vol. 13,* pp. 382-385.

Leitch, H. W. 1994. Comparison of international selection indices for dairy cattle breeding. *Interbull meeting, Ottawa, Canada. Interbull bulletin no. 10.*

Madgwick, P., Beard, K. and Goddard, M. 1991. Possibilities for incorporating selection for feed conversion efficiency into the national dairy herd improvement program. *Proceedings of the ninth conference of the Australian Association of Animal Breeding and Genetics,* pp. 45-48.

Madgwick, P. A. and Goddard, M. E. 1989. Genetic and phenotypic parameters of longevity in Australian dairy cattle. *Journal of Dairy Science* **72:** 2624-2632.

Mallamaci, K. F., Beard, K. T., Goddard, M. E. and Jones, L. P. 1992. What do Australian dairy farmers look for when selecting sires? *Proceedings of the tenth conference of the Australian Association of Animal Breeding and Genetics,* pp. 85-88.

Rozzi, P. 1991. The new quality milk index (ILQ) in Italy. *Bianco Nero, supplement 9,* pp. 14-33.

Visscher, P. M. 1995. Bias in multiple genetic correlation from half-sib designs. *Genetics Selection Evolution* **27:** 335-345.

Visscher, P. M., Bowman, P. J. and Goddard, M. E. 1994. Breeding objectives for pasture based dairy production systems. *Livestock Production Science* **40:** 123-137.

Visscher, P. M. and Goddard, M. E. 1995a. Genetic parameters for milk yield, survival, workability, and type traits for Australian dairy cattle. *Journal of Dairy Science* **78:** 205-220.

Visscher, P. M. and Goddard, M. E. 1995b. Genetic analyses of profit for Australian dairy cattle. *Animal Science* **61:** 9-18.

Wickham, B. W. 1979. Genetic parameters and economic values of traits other than production for dairy cattle. *Proceedings of the New Zealand Society of Animal Production* **39:** 180-193.

(Received 1 October 1995—Accepted 27 November 1995)

Appendix 1

Marginal prices for production traits in New South Wales and Queensland

In the states Victoria and Tasmania, the majority (approx. 90%) of milk production is for the manufacturing market. Prices for volume, fat, and protein yield are weighted averages for the component prices for the liquid and manufacturing market respectively.

In New South Wales and much of Queensland, the majority of milk goes to the liquid milk market, and quotas are in operation. These quotas are minimum quotas on volume only, and have their origin in a guaranteed milk supply to cities and other non-dairy areas. For over-quota milk, manufacturing prices are paid. Fat and protein yield is paid for in the quota part of the total production, but unfortunately, the implicit value of fat and protein for quota milk is not the same as the value of fat and protein for over-quota milk (see below). These differences can cause (long-term) unrealistic economic weights for milk, fat, and protein yield, and may send the wrong signal to farmers in terms of breeding policies.

Notation

M = average milk production in kg per cow; F = average fat production in kg per cow; P = average protein production in kg per cow; n = number of cows in milking herd; Q_m = volume quota in l per farm; p_l = milk price — liquid market (\$/l); p_m = milk price — manufacturing market (\$/l); p_f = fat price — manufacturing market (\$/kg); p_p = protein price — manufacturing (\$/kg); ref_f% = reference fat % for bonus/penalty for quota milk; ref_p% = reference protein % for bonus/penalty for quota milk; bon_f% = bonus for fat % in \$/% per l for quota milk; bon_p% = bonus for protein % in \$/% per l for quota milk.

Assume $Mn \geq Q_m$, i.e. the present (future) production is at or above the quota requirements. In reality, most dairy factories require their suppliers to supply far in excess of their quota. Typically, proportionately 0·5 to 0·7 of a supplier's total milk production would be quota milk.

Define $Q_f = (Q_m \times \text{ref\_}f\%)/100$ and Q_p $(Q_m \times \text{ref\_}p\%)/100$, which are the corresponding 'quotas' for fat and protein yield

$$Q' = Q/n.$$

Using a simplification of the milk price systems in New South Wales and Queensland, farm income from milk sales is:

$$\begin{aligned}\text{Income} = {} & Q_m p_l + (Q_m F/M - Q_f)\,100(\text{bon\_}f\%) \\ & + (Q_m P/M - Q_p)\,100(\text{bon\_}p\%) + (nM - Q_m)[p_m \\ & + p_f F/M + p_p P/M] \qquad \text{(A1.1).}\end{aligned}$$

Per cow, the income (I) is,

$$I = Q_m'p_t + [(Q_m'M)F - Q_f']100\text{bon\_}f\% + [Q_m'M)P - Q_p']100\text{bon\_}p\% + (M - Q_m')[p_m + p_fF/M + p_pP/M] \quad \text{(A1.2).}$$

Derivatives

$$dI/dM = p_m - [(Q_m'/M)(F/M)(100\text{bon\_}f\% - p_f)] - [(Q_m'/M)(P/M)(100\text{bon\_}p\% - p_p)] \quad \text{(A1.3)}$$

$$dI/dF = p_f + (Q_m'/M)(100\text{bon\_}f\% - p_f) \quad \text{(A1.4)}$$

$$dI/dP = p_p + (Q_m'/M)(100\text{bon\_}p\% - p_p) \quad \text{(A1.5).}$$

The actual price for quota milk does not appear in the marginal prices for milk, fat, and protein yield. The discrepancy between 100bon_f% and p_f (and correspondingly for protein yield) causes the marginal price for fat yield (and, therefore, the economic weight for fat yield) to deviate from the manufacturing price for fat.

Appendix 2

Economic value for milking speed using cost of labour
Assumption/notation
$\bar{x}$ = mean milking speed (MS), in kg/min; σ_x = phenotypic standard deviation of MS; p = mean proportion of satisfactory daughters for MS; m = mean milk yield (kg per lactation) for lactation length = *lacl*; n = number of cows per 'round of milking'; $z_{\bar{x}}$ = height of standard normal curve at cut-off point corresponding to p; wage = cost of labour ($/h).

It is assumed that measurements (e.g. classes 1 to 5 or % satisfactory daughters) reflect a continuous underlying scale of MS.

Underlying scale
The milking time per cow per day (t, in min/day) is,

$$t = (m/lacl)/x, \text{ and } \delta t/\delta x \text{ at } x = \bar{x},$$

$$\delta t/\delta x = -(m/lacl)/(\bar{x}^2) \quad \text{(A2.1).}$$

Hence, the change in the time spent milking by the farmer expressed on a per cow basis in h per cow per year (*time*) is,

$$\delta time/\delta x = (\delta t/\delta x)(lacl)/60n = -m/\{(60)(n)(\bar{x}^2)\} \quad \text{(A2.2).}$$

It should be noted that it is the time taken by the average group of cows that is important rather than the individual cow speed.

ABV scale
Consider the distribution of progeny within a sire

$$\delta p/\delta x = z_{\bar{x}}/\sigma_x, \text{ so } \delta x/\delta p = \sigma_x/z_{\bar{x}} \quad \text{(A2.3).}$$

For a 1% change in satisfactory daughters,

$$(\delta time/\delta p)/100 = (\delta time/\delta x)(\delta x/\delta p)/100 = -m\,\sigma_x/\{(60)(100)(n)(z_{\bar{x}})(\bar{x}^2)\} \quad \text{(A2.4).}$$

The economic value for a 1% change in the proportion of satisfactory daughters is in equation (A2.4) multiplied by the cost of labour (in $/h),

$$\delta Profit/\delta p(1/100) = (wage)(m)(\sigma_x)/\{(6000)(n)(z_{\bar{x}})(\bar{x}^2)\} \quad \text{(A2.5)}$$

with (A2.5) positive, since an increase in average MS means a decrease in labour cost.

Appendix 3

Economic value of temperament based on association with survival
Notation
S = survival; T = temperament; MP = 'milk production'; p = mean proportion of satisfactory progeny for temperament (0·88); $\bar{S}$ = mean survival; r_g = genetic correlation; r_p = phenotypic correlation; $1 - \bar{p}_T$ = mean proportion of cows culled because of bad temperament; $\bar{p}_T > \bar{S}$; i_T = standardized mean T corresponding to $\bar{p}_T$; $1 - p_o$ = proportion culled for reasons other than temperament; $b_p(S,T)$ = phenotypic regression of survival on temperament; $b_g(S,MP)$ = genetic regression of survival on 'milk production'; $EV(T\%)$ = economic value in ABV units (% satisfactory progeny); $EV(MP)$ = economic value for 'milk production' (e.g. milk, fat or protein yield, or a combination thereof).

On the temperament score scale, h^2 = 0·16, and so on a percentage scale $h_{\%}^2 = i^2(p/(1-p))h^2 = z^{2/}(p/(1-p))h^2 = 0{\cdot}061$ and $\sigma_g(T\%) = 8{\cdot}0\%$. Hence $\sigma_g(\text{ABV}) = 4{\cdot}0\%$.

We assume that survival can be written as a linear regression on MP and T:

$$S = b_g(S,T) \times T + b_g(S,MP) \times MP + e \quad \text{(A3.1).}$$

Then

$$EV(T\%) = EV(M)\, b_g(S,T)/b_g(S,M) \text{ if } r_g(T,M) = 0 \quad \text{(A3.2).}$$

In standardized units,

$$EV(T\%) = EV(M_{stand.})\, r_g(S,T)/r_g(S,M) \quad \text{(A3.3).}$$

At the phenotypic level
If $S = p_Tp_o$, then $\text{cov}(S,T) = i_Tp_Tp_o\sigma_T$, and $b_p(S,T) = i_Tp_Tp_o/\sigma_T \approx \bar{i}_TS/\sigma_T$.

At the genetic level
Consider the distribution of temperament of progeny within a sire. Assume that the within sire variance ≈ the phenotypic variance. $p_T \approx \bar{p}_T + z(T - \bar{T})/\sigma_T$, then $\text{cov}_g(S,T) \approx \bar{p}_o(z/\sigma_T)\, v_g(T) = \bar{p}_o\, z\, \frac{1}{4}\, h_T^2\, \sigma_T = \bar{S}\, i_T\, \frac{1}{4}\, h_T^2\, \sigma_T$ and $r_g(S,T) = \text{cov}_g(S,T)/[\frac{1}{4}h_Th_s\, \sigma_T\, \sigma_s] = i_T\,(h_T/h_s)\,(S/(1-S))^{1/2}$, $b_g(S,T) = p_oz/\sigma_T = b_p(S,T)$.

Appendix 4

Parameters for S and S_{adj}
The parameters we estimated previously (Visscher and Goddard, 1995a), were for observed survival (S). We require parameters for S_{adj}.

Define, at the genetic level,

$$S_{adj} = S - \beta'\mathbf{x},$$

with β a vector with genetic regressions of S on $\mathbf{x}_i$, and $\mathbf{x}$ a vector of traits for which survival is adjusted. No subscript refers to parameters at the genetic level, and subscripts 'p' are for parameters at the phenotypic level. Let all phenotypic standard deviations (i.e. for S and other traits, but not for S_{adj}) be unity. The genetic regression is calculated as

$$\beta = \mathrm{var}(\mathbf{x})^{-1}\mathrm{cov}(\mathbf{x},S) \quad \text{(A4.1).}$$

It follows that,

$$\mathrm{var}(S_{adj}) = \mathrm{var}(S) - \beta'\mathrm{var}(\mathbf{x})\beta$$
$$= h^2(S) - \Sigma[r(S,\mathbf{x}_i)\beta_i h(S)\, h(\mathbf{x}_i)] \quad \text{(A4.2)}$$

$$\mathrm{cov}(S_{adj},q) = \mathrm{cov}(S,q) - \beta'\mathrm{cov}(\mathbf{x},q)$$
$$= r(S,q)h(q)h(S) - \Sigma[r(\mathbf{x}_i,q)\,\beta_i h(q)\, h(\mathbf{x}_i)] \quad \text{(A4.3).}$$

q can be any trait in the index or in the breeding goal. If q is one of the traits in $\mathbf{x}$, then the covariance with S_{adj} is zero. From (A4.2) and (A4.3) we can now calculate the new (genetic) correlations between adjusted survival and other traits:

$$r(S_{adj},q) = \{r(S,q)\, h(S) - \Sigma[r(\mathbf{x}_i,q)\,\beta_i\, h(\mathbf{x}_i)]\} / \{\mathrm{var}(S_{adj})\}^{1/2} \quad \text{(A4.4).}$$

The genetic standard deviation of S_{adj} can be calculated if we know the phenotypic standard deviation of adjusted survival. If we assume that $\beta = \beta_p$, i.e. that the phenotypic regressions of S on traits in $\mathbf{x}$ are the same as the genetic regressions, then,

$$\mathrm{var}_p(S_{adj}) = \mathrm{var}_p(S) - \beta'\mathrm{var}_p(\mathbf{x})\beta_p$$
$$= 1 - \Sigma[r_p(\mathbf{x}_i,S)\,\beta_i] \quad \text{(A4.5).}$$

Hence, from (A4.2) and (A4.5), we can calculate the heritability and phenotypic standard deviation of S_{adj}.

To be consistent with regards to the assumption $\beta = \beta_p$, we can calculate the phenotypic correlations between S and traits in $\mathbf{x}$ as,

$$r_p = \mathrm{var}_p(\mathbf{x})\,\beta \quad \text{(A4.6).}$$

Now suppose that there are non-genetic factors (e.g. semen price) associated with the survival of a bull's progeny. Let $S_{adj} = S_{obj} + C$, with S_{obj} the ability to survive involuntary culling, and C a non-genetic component common to the survival of a bull's progeny. Only S_{obj} is in the breeding objective. Assume further that we know the (genetic) correlation between S_{adj} and S_{obj}, i.e. $r(S_{adj},S_{obj}) = \sigma(S_{obj})/\sigma(S_{adj})$. We assumed that this correlation was 90%. Then the genetic correlation between S_{obj} and any other trait (except S), is, $r(S_{obj},y) = r(S_{adj},y)/r(S_{adj},S_{obj})$. The correlation between S and S_{obj} is, $r(S_{obj},S) = \sigma(S_{obj})/\sigma(S) = r(S_{adj},S_{obj})\,\sigma(S_{adj})/\sigma(S)$.

For the parameters used in Tables 2 and 3, this correlation is 72%. Finally,

$$\mathrm{var}(S_{obj}) = [r(S_{adj},S_{obj})]^2\,\mathrm{var}\,(S_{adj}).$$

The phenotypic variance of S_{obj}, $\mathrm{var}_p(S_{obj})$, can be set arbitrarily, and was assumed to be the same as $\mathrm{var}_p(S_{adj})$. Then the implicit heritability of S_{obj}, $h^2(S_{obj}) = [r(S_{adj},S_{obj})]^2\, h^2(S_{adj})$.