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ECONOMIC WEIGHTS AND INDEX SELECTION OF MILK PRODUCTION TRAITS WHEN MULTIPLE PRODUCTION QUOTAS APPLY

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ABSTRACT

The generation of profit in dairy production can be approximated by a generalized profit equation, which is a function of the genotype of the animals used. In the absence of legislated quotas on production, the economic weights for traits contributing to profit, for use in a selection index, have been shown to be simple functions of the partial derivatives of profit with respect to output of the traits. These functions reflect the fact that output in most agricultural industries will already be maximized, either because of saturated markets or limitations on total inputs. When a single quota applies, different functions result, which reflect the downward rescaling of enterprise size as output per animal of a trait under quota is increased. Difficulties arise when multiple non-independent quotas apply, such as in the United Kingdom (UK) milk market where quotas are triggered by both milk volume and fat concentration. The functions describing the economic weights are then dependent on the form of the dependency between the quota criteria and on the genetic change resulting from the applied selection index. Economic weights for milk volume, fat, protein and lactose yield applicable to Holstein/Friesian cattle in the UK were found to be −1·6 p/l, 76·6 p/kg, 170·0 p/kg and 7·0 p/kg, scaled to 1986 prices. These weights would not change much if the quota were changed to fat yield only. Use of appropriate selection indexes should result in genetic increases of milk volume, fat, protein and lactose yield, with gradual increases in fat and protein concentrations and the fat to protein ratio. In most situations, selecting on the combined evaluation for fat plus protein yield would be a simple procedure with high efficiency (0·995 of maximum efficiency).

INTRODUCTION

THE goal of genetic improvement of livestock is maximum improvement in economic merit. When several traits contribute to economic merit a suitable method of selection is by use of a selection index as first proposed by Smith (1936) and Hazel (1943). The selection index is a discriminant function (Fisher, 1936) of available information which maximizes the expected genetic progress of the aggregate genotype, which in this case is economic merit. The aggregate genotype is a linear function of the additive genotypic values of the component traits, with the regression coefficients being the partial regressions of profit on genetic output of the trait.

Several assumptions are inherent in this approach. Economic merit is assumed to be a linear function of genetically controlled outputs. In practice, profit functions are often non-linear. However, since rates of genetic progress are relatively modest, of the order of 0·5 to 2·0% of the mean per annum (Smith, 1984), the non-linear component will usually be very much a second-order effect and can be ignored. It is also assumed that a profit equation is applicable. Economic optimization procedures will often be based on production functions (e.g. McArthur, 1987), or linear programming allocations of resource use (Heady and Chandler, 1958). It has therefore been argued (e.g. McArthur, 1987) that genetic changes should be evaluated against any changes in the optimum economic production system that such changes cause. Again, unless the change in the production system is a markedly non-linear function of genetic alteration of outputs, a linear approximation of economic weights derived from a profit function will yield essentially identical results. A proviso is that the profit equation should be appropriate to the optimized production system.

Smith, James and Brascamp (1986) argued that animal breeding is a medium- to long-term exercise and that in the long-term, fixed enterprise costs become variable costs. Thus, for the purposes of animal breeding, total enterprise profit, T, can be described by the function,

$$T = N(R - C),$$

where R (returns) and C (costs) are functions of the traits of interest and N is an enterprise scaling factor, usually the number of animals. Traditionally, in a free market, the economic weight of a trait, y, contributing to economic merit would then be taken as,

$$\frac{1}{N}\frac{\mathrm{d}T}{\mathrm{d}y} = \frac{\mathrm{d}R}{\mathrm{d}y} - \frac{\mathrm{d}C}{\mathrm{d}y}.$$

However, Smith *et al.* (1986) argued that this method overvalues outputs, since no account is made of alternative methods of increasing production, or that output is presumably already maximized, because of either saturated markets or limits on total inputs. Several methods of scaling were introduced appropriate to various situations that produced economic weights which differed between situations in absolute but not relative values. For example, economic weights appropriate for a saturated market would be,

$$\frac{1}{N}\frac{\mathrm{d}T}{\mathrm{d}y} = \frac{C}{R}\frac{\mathrm{d}R}{\mathrm{d}y} - \frac{\mathrm{d}C}{\mathrm{d}y} \qquad (1).$$

In practice, dairy farmers often have to operate within legislated quotas. If such quotas have medium- to long-term stability, it is appropriate for the farmer to breed for such quotas, even though this may be suboptimal from a national perspective (Gibson, 1989a). A specific example of deriving economic weights in the presence of a single quota was given by Van Arendonk, Wilmink and Dijkhuizen (1985) and the general case was discussed by Gibson (1989a).

In the United Kingdom (UK), there is currently a two-tier quota system in operation (S. Amies, personal communication). Each farm receives a quota on volume of milk produced and a quota related to fat concentration. If the national quota on volume is exceeded, farmers are penalized for exceeding their quota on a pro-rata basis. Similarly, if the national average fat concentration exceeds the national base, set by the European Community at 39·8 g/l, an adjustment is made to each farmer's notional volume produced according to the amount by which his fat concentration differs from 39·8 g/l.

The objective of this paper is to present a method of deriving economic weights in the presence of multiple non-independent quotas and to apply these for the breeding of Holstein/Friesian cattle in the UK. The effect of ultimately moving to a simpler single quota system is also examined.

MATERIAL AND METHODS

Notation

Several abbreviations are used repeatedly through the paper. For easy reference these are summarized in the APPENDIX.

Theory

Generalized economic weights. It is assumed that a continuous profit function can be found in the absence of quotas of the general form $P = N(R - C)$ as described above. The imposition of quotas introduces discontinuities into this function for those traits constrained by quota, because economic returns are drastically reduced, possibly becoming negative, for production exceeding the quota threshold. However, provided the economic penalties for exceeding quota are sufficiently high that farmers always aim not to exceed the quota, the problem becomes one of rescaling. Any genetic increase in the output per animal of the trait under quota must be matched by a reduction in the number of animals so that total production of that trait remains constant. (It is implicitly assumed that the initial production enterprise is designed to just match the quota; see DISCUSSION.) The appropriate economic weight for the trait under quota was then shown by Gibson (1989a) to be,

$$\frac{1}{N}\frac{dT}{dy} = \frac{dR}{dy} - \frac{dC}{dy} - \frac{P}{y} \qquad (2)$$

where $P = R - C$, i.e. profit per animal. Economic weights for other traits are as given by equation 1 since increased enterprise output is allowed for these traits. A point not discussed by Gibson (1989a) is that equation 2 is appropriate only where the response to selection after index selection is an increased output per animal of the trait under quota. If the output decreases, equation 1 becomes appropriate even for the trait under quota. If, however, use of equation 1 leads to increased output whilst equation 2 leads to decreased output, some compromise method of selection must be found (see DISCUSSION).

Extension to two or more independent quotas is straight forward. The economic weight of each trait under quota should be derived using equation 2, and for remaining traits using equation 1. Again, equation 2 is appropriate only for those traits under quota which increase in output per animal after selection.

It is possible that there may be two or more quotas that are not independent of each other. In this situation, there is no general solution for the derivation of economic weights. The appropriate economic weights will depend on the nature of the relationship between the quotas. Such a situation exists in the UK dairy industry. Formulae for the derivation of economic weights appropriate to the UK payment and quota systems are derived below.

Economic weights for UK quotas. It has been argued (Gibson, 1989c) that selection indexes for milk production should usually be aimed at output traits (yields) rather than composition (concentrations). In the UK, payment for milk is based on yields of fat (F), protein (Pr) and lactose (L), so that these traits naturally contribute to the aggregate genotype. Output of carrier (C; water plus minerals) should also be included since it incurs costs in production. However, since carrier forms proportionately over 0·90 of the volume of milk, in what follows, milk volume (V) is used in place of carrier in the aggregate genotype. Appropriate allowances are made for any costs which are already incurred by the F, Pr and L in V. Because C forms approximately 0·90 of V and the economic returns and costs of C are small (see below), autocorrelations of V with F, Pr and L can safely be ignored.

It is assumed that individual farmers and the national milk production operate at the volume and fat quota bases so that genetic increases in volume per cow or fat concentration trigger quota penalties. Exceeding the volume quota introduces penalties per litre over quota which are higher than the normal returns per litre of milk of average composition. Exceeding the base fat concentration of 39·8 g/l, introduces a scaling of the volume of milk produced from V to a nominal amount V', where,

$$V' = V\,(1 + 18\Delta f),$$

where f is fat concentration in g/ml (S. Amies, personal communication). Quota penalties then apply as if V' were the actual volume of milk produced. These are sufficiently high that it may be assumed that it is unprofitable to produce above the fat concentration base.

If the traits in the aggregate genotype are V, F, Pr and L, it is clear that the two quotas as they affect V and F are not independent. If V is constant, any increase in F causes an increase in fat concentration, f, which triggers quota penalties. However, an independent increase in V decreases f, which allows F to increase until f is returned to the base value before the fat quota is triggered.

If selection leads to an increase in V but no change or a reduction in f, quota applies to volume only. Appropriate economic weights are therefore given by equation 2 for V and equation 1 for F, Pr and L. Appropriate economic weights in other situations depend on the joint effects of changes in F and V on V'.

The joint effect of changes in V and F on V' when f increases can be derived as,

$$V' = (V + \Delta V)(1 + 18\Delta f)$$

and since,

$$\Delta f = \frac{F + \Delta F}{V + \Delta V} - \frac{F}{V} = \frac{V\Delta F - F\Delta V}{V(V + \Delta V)},$$

$$V' = V + \Delta V - \frac{18F\Delta V}{V} + 18\Delta F.$$

If F increases and V decreases in such a way that quota penalties are avoided (i.e. $V' \leqslant V$), appropriate economic weights are given by equation 1 for all four traits since no quotas operate.

If $V' > V$, the following derivation applies. Increase in V' leads to rescaling of the enterprise by altering animal numbers such that $(N + \triangle N)V' = NV$, i.e. $\triangle N = -N/V((1 - 18F/V)\triangle V + 18\triangle F)$ ignoring second-order terms. If the total enterprise profit, T, before genetic change is, $T = N(R - C) = NP$ as before, then profit after genetic change, T_1, is, $T_1 = (N + \triangle N)(P + \triangle P)$ and, ignoring second-order terms, the change in profit, $\triangle T$ $(= T_1 - T)$, is,

$$\triangle T = N\triangle P + \triangle NP \qquad (3).$$

The change in profit per animal, $\triangle P$, is given by

$$\triangle P = \frac{\mathrm{d}P}{\mathrm{d}V}\triangle V + \frac{\mathrm{d}P}{\mathrm{d}F}\triangle F + \frac{\mathrm{d}P}{\mathrm{d}Pr}\triangle Pr + \frac{\mathrm{d}P}{\mathrm{d}L}\triangle L$$

Thus, substituting for $\triangle P$ and $\triangle N$ and dividing by N in equation 3 gives,

$$\frac{\triangle T}{N} = \frac{\mathrm{d}P}{\mathrm{d}V}\triangle V + \frac{\mathrm{d}P}{\mathrm{d}F}\triangle F + \frac{\mathrm{d}P}{\mathrm{d}Pr}\triangle Pr + \frac{\mathrm{d}P}{\mathrm{d}L}\triangle L - \frac{1}{V}((1 - 18\frac{F}{V})\triangle V + 18\triangle F)P$$

and regrouping gives,

$$\frac{\triangle T}{N} = (\frac{\mathrm{d}P}{\mathrm{d}V} - \frac{P}{V}(1 - 18\frac{F}{V}))\triangle V + (\frac{\mathrm{d}P}{\mathrm{d}F} - 18\frac{P}{V})\triangle F + \frac{\mathrm{d}P\triangle Pr}{\mathrm{d}Pr} + \frac{\mathrm{d}P\triangle L}{\mathrm{d}L}.$$

The change in profit per animal per unit change in any one trait, its economic weight, is given by those right-hand terms that are dependent on the change in that trait. The resulting economic weights, along with those for the situations where no quota penalties are incurred ($V' \leqslant V$) and where only the volume quota is triggered, are summarized in Table 1 (items c, a, b).

Item d in Table 1 shows the economic weights if a single quota on fat yield were operating, derived from equation 2 for fat and equation 1 for the remaining traits. It is worth noting that if the scaling factor used to adjust milk volume when over quota for fat concentration was equal to the inverse of the fat concentration (approx. 25·1) instead of 18 as at present, the economic weights in items c and d of Table 1 would be identical. Provided that selection leads to the need for rescaling due to increasing fat concentration, the current two-tier quota system leads to economic weights which are similar to those for a single quota on fat yield.

The profit equation

The profit equation, describing expected changes in profit for a given enterprise as genetic parameters are altered, was defined as,

$$T = N(r_1V + r_2F + r_3Pr + r_4L - c_1V - c_2F - c_3Pr - c_4L - M)$$

TABLE 1

Derivations of economic weights for milk volume (V)*, fat* (F)*, protein* (Pr) *and lactose* (L) *yields when various quotas are triggered*†

Situation‡	Volume	Fat	Protein	Lactose
(a) No quota triggered	$\frac{\mathrm{d}P}{\mathrm{d}V}$	$\frac{\mathrm{d}P}{\mathrm{d}F}$	$\frac{\mathrm{d}P}{\mathrm{d}Pr}$	$\frac{\mathrm{d}P}{\mathrm{d}L}$
(b) Only volume quota triggered	$\frac{\mathrm{d}P}{\mathrm{d}V} - \frac{P}{V}$	$\frac{\mathrm{d}P}{\mathrm{d}F}$	$\frac{\mathrm{d}P}{\mathrm{d}Pr}$	$\frac{\mathrm{d}P}{\mathrm{d}L}$
(c) Quota triggered due to excess fat concentration	$\frac{\mathrm{d}P}{\mathrm{d}V} - \frac{P}{V}(1 - 18\frac{F}{V})$	$\frac{\mathrm{d}P}{\mathrm{d}F} - 18\frac{P}{V}$	$\frac{\mathrm{d}P}{\mathrm{d}Pr}$	$\frac{\mathrm{d}P}{\mathrm{d}L}$
(d) Single quota on fat yield	$\frac{\mathrm{d}P}{\mathrm{d}V}$	$\frac{\mathrm{d}P}{\mathrm{d}F} - \frac{P}{F}$	$\frac{\mathrm{d}P}{\mathrm{d}Pr}$	$\frac{\mathrm{d}P}{\mathrm{d}L}$

† $\frac{\mathrm{d}P}{\mathrm{d}y} = \frac{\mathrm{d}R}{\mathrm{d}y} - \frac{\mathrm{d}C}{\mathrm{d}y}$

‡ a, b and c refer to a two-tier quota on milk volume and fat concentration.

where r_i and c_i are the returns and costs per unit production per animal of trait i and M is the net economic maintenance cost per animal.

Economic information was collated from analyses of the economic parameters of 406 dairy farms in England and Wales during 1985/86 (Milk Marketing Board, 1986), hereafter referred to as the MMB survey.

The various costs and returns, described below, are summarized in Table 2.

Returns. The current (1988) prices for milk volume, fat, protein and lactose were adjusted to 1985/86 values as follows. The average milk sold from farms in the MMB survey had concentrations of fat, protein and lactose of 39·7, 32·7 and 46·3 g/l, and sold for 15·854 p/l. Milk of the same composition would fetch 16·694 p/l at the current prices of fat, protein and lactose of 208·6, 212·8 and 31·4 p/kg (S. Amies, personal communication). Adjusting for the change in average milk price, gives prices for volume, fat, protein and lactose (i.e. r_1, r_2, r_3 and r_4) of 0·0, 198·1, 202·1 and 29·8 p/kg.

Costs related to output per animal. In the present case, two costs related to output per animal are identified, food costs and non-food production costs. The cost of processing components, which should be separately identified (Gibson, 1989a), are in this case assumed automatically included in the payments.

Following Dommerholt and Wilmink (1986), it is assumed that every kg extra production of fat, protein and lactose will require 69·9, 35·6 and 25·1 MJ metabolizable energy (ME) extra food intake. The cost of food was estimated in three ways.

From the MMB survey data classified by herd level of production (Tables 7.1 and 7.2 of MMB, 1986), estimated energy requirements per cow, based on Agriculture Research Council (ARC, 1980) predictions, were plotted against total food costs. The total food costs included all variable and fixed food costs plus farm rental and overheads. With the exception of the point for the highest yielding herds (average yield 6986 kg per cow per year), the plot was almost perfectly linear with a slope of 0·89 p/MJ of predicted ME intake. This was taken as the most likely average food cost.

A minimum estimate of the food cost was obtained by dividing 0·89 by 1·235, the estimated regression of actual food energy use (converted from Table 7.1 of MMB (1986) using ARC (1980) estimates of expected energy concentration of foods) on predicted energy requirement. The resulting estimate of 0·72 p/MJ predicted ME intake would apply if the conversion factor of 1·235 represents avoidable inefficiencies of food usage rather than unavoidable inefficiencies or underestimates of requirements by ARC (1980).

A maximum food cost was obtained by assuming that all increases in output could only be achieved by feeding purchased concentrates. The average cost of purchased concentrates was 14·06 p/kg with an assumed energy concentration of 12·15 MJ/kg wet weight (ARC, 1980), giving a cost of 1·16 p/MJ ME.

The MMB survey data do not allow a definitive allocation of non-food production costs. However, some of the power bills and labour costs will be directly related to the amount of milk produced. Therefore, one-half of the average consumable stores and fuel bills and one-quarter of the dairy labour costs were arbitrarily allocated to output, giving a cost of 0·744 p/l milk produced. Allowing for the specific gravities of fat, protein

TABLE 2

Summaries of costs and returns appearing in the profit equation†

	Returns or cost per unit (p/l or p/kg)			
	Volume	Fat	Protein	Lactose
Returns				
Scaled 1986 prices	0·0	198·11	202·10	29·82
Costs				
Food cost 0·89 p/MJ ME	0·74	62·98	32·15	22·81
Food cost 0·72 p/MJ ME	0·74	51·10	23·27	16·55
Food cost 1·16 p/MJ ME	0·74	81·86	41·76	29·51

Total maintenance cost = £452·42 per cow per year

† The base profit equation uses food costs of 0·89 p/MJ metabolizable energy (ME); alternative food costs are used only in deriving economic weights of genetically increased output.

and lactose being 0·96, 1·60 and 1·60, gives respective costs of 0·775, 0·465 and 0·465 p/kg. The cost for milk volume should be adjusted for the included costs of fat, protein and lactose, giving a cost of 0·656 p/l. The costs appearing in Table 2 are the sum of the food and non-food costs for various assumptions of food costs.

Economic maintenance costs. The food and non-food costs of maintenance were separately identified. The average annual food cost of maintenance was estimated from ARC (1980), assuming an average body weight of 550 kg, a calving interval of 380 days, an average annual growth of 30 kg and making allowances for pregnancy; giving an estimated annual requirement of 23349 MJ ME. At the observed regression of food costs on predicted requirements of 0·89 p/MJ ME, this gives an estimated food maintenance requirement of £207·81 per cow per year. The non-food costs of maintenance were estimated as the residual cost after allowing for all food costs and non-food costs related to output, giving £244·61 per cow per year. Along with the usual costs of maintaining cows, this cost includes the cost of replacing cows and allows a deduction for income from calves sold. Total economic maintenance costs, M, the sum of food and non-food maintenance costs were £452·42 per cow per year.

Estimation of economic weights

Economic weights were calculated using a food cost of 0·89 p/MJ ME for the four algebraic definitions of economic weights described above. In addition, economic weights were calculated using the algebraic solution for when the fat concentration threshold is exceeded using the two alternative food costs of 0·72 and 1·16 p/MJ ME.

Responses to selection

Responses to selection were calculated for all sets of economic weights, applying standard selection index theory, using a modified version of the SELIND computer programme (Cunningham and Mahon, 1977). Selection was assumed to be on (1) an individuals own records, one first lactation record for each trait, or (2) sire selection based on five effective first lactation daughter records for each trait, or (3) sire selection based on 50 effective first lactation daughter records for each trait. Phenotypic and genetic covariances applicable to each situation were derived from population parameters using standard formulae (see Gibson, 1989b).

For each index, the apparent economic response (assuming that the given set of economic weights were correct) and the correlated genetic responses of each of the four component traits were estimated. For both individual and sire selection the most appropriate set of economic weights were identified based upon the genetic changes they each induced (see earlier). The consequences of using alternative derivations of economic weights were then judged against the most appropriate set by calculating the response the alternative set induced if the most appropriate set actually applied. This response was then expressed as a proportion of the maximum response, which is the response induced by the index resulting from the most appropriate set of economic weights. The use of reduced indexes was examined by successively dropping one or more milk components from the selection index and expressing the economic response as a proportion of the response when all four components appeared in the index.

A full set of recently estimated phenotypic and genetic covariances for the UK Holstein/Friesian cattle population were not available. Two recent estimates of heritabilities from non-overlapping data sets from the British Holstein/Friesian population (Hill, Edwards, Ahmed and Thompson, 1983; Meyer, 1987) both estimated heritabilities for protein yield that were considerably lower than literature averages collated by Maijala and Hanna (1974). The heritabilities and coefficients of variation of volume, fat and protein yield were therefore taken from Hill *et al.* (1983). For want of more appropriate estimates, it was assumed that phenotypic and genetic correlations among traits were equal to literature averages (Maijala and Hanna, 1974). Parameters for lactose were taken from the averages provided by Gibson (1987).

The resulting population variances and covariances are presented in Table 3.

Parameter estimates were tested for consistency by checking that the four principal components among the four traits each had positive variance for the genetic (G), phenotypic (P) and $GP^{-1}G$ covariance matrices, for both individual and sire selection.

TABLE 3

Means and coefficients of variation, and genetic variances (on diagonal), covariances (above diagonal) and correlations (in parenthesis) and phenotypic covariances (below diagonal) among volume, fat, protein and lactose†

			Genetic and phenotypic covariances			
	Mean	CV	Volume	Fat	Protein	Lactose
Volume	5186	0·142	0·250	0·203 (0·82)	0·200 (0·87)	0·240 (0·96)
Fat	205·9	0·139	0·88	0·244	0·195 (0·86)	0·165 (0·67)
Protein	169·6	0·130	0·95	0·93	0·211	0·186 (0·81)
Lactose	240·1	0·140	0·96	0·75	0·87	0·250

† Traits standardized so that phenotypic standard deviations (σ_p) are 1·0.

TABLE 4

Estimates of economic weights for four methods of derivation and different food costs

	Economic weight (£/σ_p)†			
Basis of derivation‡	Volume	Fat	Protein	Lactose
1. Food costs 0·89 p/MJ ME				
(a) No quota applied	−5·45	38·65	37·39	2·36
(b) Volume quota only	−29·38	38·65	37·39	2·36
(c) Quota due to exceeding fat concentration base	−12·30	21·90	37·39	2·36
(d) Single quota on fat yield	−5·45	15·22	37·39	2·36
2. Food costs 0·72 p/MJ ME				
(c) Quota due to exceeding fat concentration base	−12·30	25·30	39·34	4·46
3. Food costs 1·16 p/MJ ME				
(c) Quota due to exceeding fat concentration base	−12·30	16·51	35·27	0·10

† Phenotypic standard derivations (σ_p) taken to be 736·4, 28·6, 22·0 and 33·6 for volume, fat, protein and lactose.

‡ Derivations a, b and c based on different genetic responses under the UK two-tier quota system.

RESULTS

Estimates of economic weights for the four methods of derivation and examples of different food costs are presented in Table 4, expressed per phenotypic standard deviation. Economic weights for volume and fat differ substantially among the three derivations applicable to different genetic outcomes under a two-tier quota system. In contrast, there are modest differences in the economic weights when quota penalties are applied due to exceeding fat concentration base (1.c in Table 4) compared with those under a single fat production quota, assuming the quota is triggered (1.d in Table 4). Of the alternatives examined, altering the food cost (by proportionately +0·30 or −0·19) had the smallest effect on economic weights (1.c *v.* 2.c and 3.c).

The predicted results of index selection of individuals and of sires, based on 50 effective first lactation daughter records, when various economic weights apply are summarized in Tables 5 and 6. Because heritabilities of the four milk components are close to 0·25, selection of sires based on five effective daughters gives very similar results to individual selection, so these results are omitted.

All sets of economic weights in index selection of individuals and sires promote broadly similar relative genetic changes in the four milk components. The genetic changes presented in Tables 5 and 6 are expressed in phenotypic standard deviations. However, since the coefficients of variation of milk volume (V) and fat yield (F) are almost equal and that for protein yield (Pr) slightly lower (Table 3), it is clear that all selection indexes result in increased milk volume per cow, increased fat concentration and increased fat to protein ratio.

Since fat concentrations increase, the most appropriate set of economic weights, assuming average food prices, are 1.c of Table 4. The

TABLE 5

Results of individual selection with intensity 1·0 for various derivations of economic weights†

Economic weights	Apparent economic response (£)	Correlated responses (σ_p)				Actual economic response‡	Reduced response of reduced indexes including			
		Carrier	Fat	Protein	Lactose		$V + F + Pr$	$F + Pr$	F	Pr
1.a	16·10	0·222	0·251	0·192	0·185	0·979	1·000	0·994	0·994	0·917
1.b	11·60	0·141	0·225	0·182	0·100	0·965	0·996	0·965§	0·961	0·861
1.c	10·60	0·191	0·230	0·202	0·160	1·000	0·998	0·997	0·993	0·965
1.d	10·45	0·209	0·227	0·206	0·183	0·993	0·999	0·999	0·985	0·977
2.c	12·14	0·203	0·235	0·201	0·172	0·997	0·999	0·999	0·995	0·956
3.c	8·63	0·167	0·216	0·201	0·139	0·992	0·997	0·984	0·976	0·952
$F + Pr$‖		0·205	0·223	0·207	0·179	0·992				

† Absolute responses are of individuals additive genetic value.
‡ Assuming true economic weights are 1.c; expressed as proportion of response using true economic weights.
§ Two-trait index of volume (V) and fat (F) gave reduced response of 0·987.
‖ Index of total yield of fat (F) plus protein (Pr).

TABLE 6

Results of sire selection, based on progeny test of 50 effective daughters, with intensity 1·0 for various definitions of economic weights†

Economic weights	Apparent economic response (£)	Correlated responses (σ_p)				Actual economic response‡	Reduced response of reduced indexes including			
		Carrier	Fat	Protein	Lactose		$V + F + Pr$	$F + Pr$	F	Pr
1.a	28·90	0·375	0·417	0·376	0·323	0·992	1·000	1·000	0·980	0·955
1.b	20·69	0·299	0·405	0·355	0·237	0·976	1·000	0·963	0·954	0·902
1.c	19·49	0·355	0·403	0·383	0·308	1·000	1·000	0·995	0·956	0·971
1.d	19·32	0·374	0·397	0·389	0·334	0·997	1·000	0·999	0·943	0·986
2.c	22·28	0·365	0·406	0·383	0·319	0·999	1·000	0·998	0·960	0·973
3.c	15·85	0·338	0·395	0·381	0·291	0·996	1·000	0·987	0·941	0·968
$F + Pr$§		0·378	0·412	0·380	0·328	0·993				

† Absolute responses are of sires additive genetic value.
‡ Assuming true economic weights are 1.c; expressed as proportion of response using true economic weights.
§ Index of summed genetic merit for fat (F) and protein (Pr).

consequences of using alternative derivations of economic weights are therefore evaluated against these, most appropriate, economic weights and presented in Tables 5 and 6 under the column heading 'actual economic response'. Of the derivations included here, use of inappropriate derivations of economic weights reduced the economic response to selection by no more than proportionately 0·035.

In all cases, dropping lactose from the index had little or no effect on the economic response to selection. In all but one case (1.b in individual selection, Table 5) the next least important trait was milk volume. Thus, if only two traits were to be included in the index, in all but the one case, fat and protein would give the maximum economic response. For the most appropriate economic weights, 1.c, use of a two-trait index would reduce economic response by proportionately 0·005 or less compared with use of all four traits. A simple option of selecting on the combined weight of fat and protein (or the combined estimates of genetic merit for fat and protein in the case of sires) reduced economic responses to selection by about 0·008 compared with optimum use of all four components (last lines of Tables 5 and 6).

For individual selection, the most efficient single-trait index was selection on fat yield, whilst for sire selection it could be fat or protein yield, depending on the economic weights. The best single-trait indexes reduced economic responses by proportionately 0·046 (fat selection for economic weights 1.b, Table 6) or less. For the most appropriate economic weights, 1.c, selection of individuals on fat yield and selection of sires on protein yield were the most efficient single trait selection indexes, reducing responses by 0·007 and 0·029 respectively.

DISCUSSION

The general derivations of economic weights presented in this paper require that profit can be described by returns and costs functions of genetically determined outputs and inputs, all of which are subject to the same proportionate scaling factor, such as the number of animals in an enterprise. Although in the specific examples dealt with here the profit functions were linear, in practice any degree of desired complexity can be accommodated. An assumption is made that partial derivatives of costs and returns higher than first order are unimportant. This assumption will be seriously in error only in the face of severe non-linearity of the cost and return functions, a situation which is difficult to envisage in the case of milk production.

The profit equations used here made several assumptions. One assumption is that food intake is entirely determined by a linear dependence on production and a fixed (uncorrelated) maintenance requirement. Although there is likely to be genetic variation in net efficiency of food conversion, current evidence indicates that the correlation between production and food intake is high (see Gibson, 1986). In a rather crude way, the possibility that increased production might lead to different responses of food intake is dealt with by varying the cost of food. Thus, determination of economic weights at the high food price (1·16 p/MJ ME) is close to assuming that a genetically improved cow would have to meet her extra energy requirements by switching part of her roughage intake to concentrates. Since different food prices hardly affected the outcome of selection, the present simple model of the relation of intake to production is likely to be robust.

The largest determinant of maintenance requirement is body size. Selection for milk production was shown not to alter body size of British Friesian cattle and studies in other breeds have given contradictory results (Gibson, 1986). Thus, an assumption of no genetic correlation between production traits and maintenance requirements seems reasonable.

Another assumption is that it is valid to use as economic inputs data derived as averages of economic performance from surveys of dairy farms. It seems reasonable that genetic improvement should be evaluated at maximum economic efficiency or profit maximization, so that genetic improvement does not make up for deficiencies in other management practices (Smith *et al.,* 1986). Thus, the validity of the present use of survey data depends on the farmers surveyed being at profit maxima. This is unlikely to be true, at least in terms of the simple profit equations used here, which do not include such factors as farmer effort, aesthetic preferences and desired life styles. However, in the MMB survey data, indicators of general management performance, such as cost per unit food, and cost per unit milk produced were roughly constant and food costs were linearly related to production for herds with moderate to high average production per cow and for moderate to high numbers of cows. This suggests a reasonable stability of economic performance. Thus, the economic weights derived here should have general applicability across a wide range of dairy farming enterprises.

The appropriate economic weights depend on the genetic change resulting from selection and the quotas triggered. All the indexes examined led to increases in both milk volume per cow and fat concentration. On the assumption that farmers will operate close to or at the current quotas, economic weights 1.c seem most appropriate, since both volume and fat concentration quota penalties will be triggered by the genetically improved cows. In practice, however, it may be difficult for a farmer to operate simultaneously at both his volume and fat concentration quota, especially since manipulation of fat concentration by standard management practices is difficult (e.g. Sutton, 1989). Thus, it is likely that some farmers whilst operating at or close to their volume quota, will fall below the fat concentration quota. For these farmers index 1.b would be more appropriate, provided the genetic change induced leaves them still operating under the fat concentration quota. The importance of this difference in economic weights depends on how many traits are included in the selection index (see below).

In all cases optimum economic response is made by including information on all traits in the selection index, although in practice the contribution of lactose is negligible. Optimum selection could easily be accomplished if all genetic evaluations included an evaluation for economic merit. Such an evaluation procedure is long overdue in the UK. Until such evaluations are automatic, the farmer will need simple guidelines for the selection of both dams and sires. The best advice is probably to select on genetic merit for fat plus protein yield if his appropriate economic weights are 1.c or volume plus fat yield if 1.b. Single trait selection can also be relatively efficient, though the appropriate trait differs between 1.b and 1.c and between individual and sire selection. Moving to a single quota on fat yield would unify selection goals. Though here too, the optimum single trait selection depends on the amount and source of the information contributing to the genetic evaluation (e.g. individual *v.* sire selection).

Finally, it is worth noting that if quotas were disbanded, it does not follow that economic weights 1.a are appropriate since these do not account for other physical constraints on production. This issue is fully discussed elsewhere (Gibson, 1989a).

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APPENDIX

Notations used repeatedly through the paper are:

T	total enterprise profit;
N	scaling factor (usually the number of animals);
R	economic returns per animal;
C	economic costs per animal;
P	profit per animal ($= R - C$);
V	milk volume per cow per annum;
V'	apparent milk volume used to assess quota penalties after scaling actual volume (V) when exceeding the quota on fat concentration;
F	fat yield per cow per annum;
Pr	protein yield per cow per annum;
L	lactose yield per cow per annum;
r_i	economic returns per unit yield of ith trait;
c_i	economic costs per unit yield of ith trait;
$i =$	1, 2, 3, 4 = volume, fat, protein and lactose yields;
M	economic maintenance cost per cow per annum.