Economic evaluation of straight- and cross-breeding programmes

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Introduction

This document is part of a comprehensive study dealing with different aspects of the development of livestock breeding system strategies for use in sustainable intensification of production system incorporations, the planning and establishment of animal breeding strategies. It is closely linked to the companion document on breeding goal definition prepared by Ab Groen. The material presented summarises chapters 5, 6, 7, 8 and 11 of *Economic Aspects of Animal Breeding* (Weller, 1994). The presentation has been simplified somewhat for a more general audience, with emphasis on practical application to actual commercial conditions in both developed and developing countries. A basic understanding of genetics and calculus is assumed.

1. The main elements of returns and costs

Any economic evaluation should begin by considering two classes of variables, returns and costs. Often the concepts of returns and products have been confused in the economic evaluation of animal production. In a multi-enterprise production system, the returns of one enterprise may be quite different from the products that the consumer buys. For example, in the production of poultry broilers, one enterprise might produce breeding stock, which is sold to a second enterprise in the form of chicks. These chicks are raised at a second enterprise, which might sell the progeny as either eggs or chicks to a third enterprise that actually raises the broilers, which are sold to the public. The same situation is common in beef production where one enterprise raises calves until weaning in range conditions and a second fattens the calves in feedlot conditions.

Of course, the costs will also be different for the different enterprises. Dickerson (1970) noted that the main costs of animal production for most species would be dependent on three main functions: 1) female production;

2) reproduction; and 3) growth of young. He excluded the costs related to male production because for nearly all economically important species, this cost will be negligible compared to the factors listed above. Thus, economic efficiency, E, can be expressed by the following general equation for most production systems:

$$E = \frac{R}{C} = \frac{R_d + R_o}{EF_d + I_d + EF_o + I_o} \qquad [1]$$

where R_d is return from female production, R_o is return from offspring production, EF_d and I_d are feed and non-feed costs per dam, respectively; EF_o and I_o are feed and non-feed costs of her progeny; and the other terms are as defined previously. Calculations will generally be made on an annual basis for all terms. Various studies have preferred to estimate economic trait values based on the inverse of economic efficiency, which we will define as E_i. If E_i is selected as the criterion for economic evaluation, then the goal will be to minimised E_i, as opposed to maximising profit or E.

Economic objectives will consist either of increasing returns or decreasing the costs of production. We will consider the main elements of costs and returns that can be affected by breeding.

1.1. Elements of female production

The main animal products consumed are meat, milk, eggs and wool. We will use the notation of Moav (1973) with slight modifications. In general, economic constants will be denoted with uppercase subscripted letters and biological variables with subscripted xs and other variables with other lowercase subscripted letters. The value of female production can be expressed by the following equation:

$$R_d = m_d x_D A_d \qquad [2]$$

where R_d is the yearly return per enterprise, due to female production, m_d is the number of females per enterprise, x_D is yearly volume of product/female and A_d is the value of product per unit volume. For example, assume a herd of 100 milk cows, each producing 8 000 kg milk/year, with a value of US$.25/kg. R_d will be equal to (100)(8 000)(0.25) = US$200 000. Generally speaking, breeding has attempted to increase return by increasing x_D, although from the point of view of the producer, R_d could also be increased by increasing m_d or A_d. However, increasing m_d merely means increasing the size of the enterprise and is therefore not relevant to breeding. A_d can be affected by changing the quality of the product. This is clearly important for most agricultural products, but in practice, much more emphasis has been put on increasing quantity, rather than quality of produce. There are two main reasons for this. First, measuring quality of a product is generally more difficult than measuring quantity. For example, a simple scale can score quantity of milk produced, while measuring protein concentration requires at least a spectrophotometer. Second, there will generally be an antagonistic genetic correlation between quantity and quality of product. Continuing the previous example, both fat and protein concentration have negative genetic correlations with milk production.

Although most economic evaluations of breeding objectives have been made based on equation [2], it is inadequate for many situations. How do you compare milk production by goats and cows, or even compare milk production by different breeds, which may differ markedly in size? To account for this factor it is sometimes useful to rewrite this equation as follows:

$$R_d = m_d x_{3d} x_{2d} A_d \quad [3]$$

where x_{3d} is the mean weight of females and x_{2d} is production per unit female weight. It is now possible to consider whether the total enterprise consists of a few big animals or many small ones. Total production, as computed in the equation can be increased by increasing m_d, x_{2d} or x_{3d}. Various researchers have suggested that metabolic body should be used rather than body weight. Metabolic body size is generally estimated as $x_3^{0.75}$. This value has been shown to be accurate over a large range of species.

Just as increasing the number of animals per enterprise is irrelevant to breeding, increasing the size of the production unit (animal) may not in fact increase either profit or economic efficiency.

1.2. Evaluation of female reproduction rate

Female reproduction rates differ markedly among domestic animals. This is illustrated by the examples in Table 1, from Moav (1973). Weight of dam, number of marketable offspring / year, market weight per offspring and reproduction ratio are listed for six species of domestic vertebrates. Reproduction ratio is defined as: the ratio of total market weight of offspring per weight of dam. At one extreme are large mammals such as horses and cows with one progeny per year and the other extreme are fish and crustaceans with thousands of offspring per year.

Return from female reproduction can be evaluated by the following equation:

$$R_o = x_{1o} x_{2o} A_o \quad [4]$$

where R_o is the return from offspring / year, x_{1o} is the number of offspring marketed / female / year, x_{2o} is the weight of offspring product and A_o is the value per unit offspring product.

Table 1. Dam weight, number of marketable offspring/year, marker weight of offspring, and reproduction ratio for different domestic species.

Species	Weight of dam (kg)	No. of marketable offspring / year	Market weight per offspring	Reproduction ratio
Cattle	600	1	500	0.8
Sheep	60	2	40	1.3
Swine	200	15	100	7.5
Poultry	3	70	1.5	35
Turkeys	7	40	9	51.4
Carp (fish)	5	100,000	1	20,000

Breeding can increase R_o by increasing x_{1o}, x_{2o}, or A_o. Although we have designated A_o as an economic constant, there is generally some differential pricing, based on the quality of product, which can be affected by breeding. Generally, the effect of breeding on R_o will be greatest by selecting for x_{2o}, rather than x_{1o} or A_o. The reasons are as follows: x_{2o} will generally be dependant on growth rate, which usually has high heritability and variance; while x_{1o} generally has low heritability and A_o has low phenotypic variance, is generally difficult to measure and as stated above, will be negatively correlated with x_{2o}. The number of offspring marketed is determined by several different genetically unrelated traits, such as interval between litters, number of offspring per litter and juvenile mortality rates. Since these traits are related to natural fitness, they generally have low heritabilities. Furthermore, selection for an index of several unrelated traits is inherently less efficient than selection for a single trait. In addition, as will be shown below, the economic importance of changes in x_{1o} decreases as the mean value of x_{1o} increases. Thus, for animals with low reproduction rates, slight changes in x_{1o} will be of major economic importance, while for high fertility species, the economic importance of changes in this variable will be negligible. However, for most domestic species, the coefficient of variation for x_{1o} increases with mean x_{1o}. Thus, those species with the lowest reproductive rates and therefore the highest economic value for this variable, have the lowest relative variance for this trait.

Despite these considerations, significant emphasis in selection has been devoted to increasing the reproductive rate in most species. Moav and Hill (1966) give two reasons for this. In most cases one enterprise (which we will denote the breeder) produces juveniles or eggs, which are then sold to a second enterprise (which we will denote the rearer) that raises the animals for slaughter. The rearer will generally purchase young animals or eggs on a per unit basis. Thus, the breeder will be primarily interested in the reproduction rate of his females. Although in theory the rearer should be willing to pay a premium price for a superior product, i.e. animals with a higher growth rate, in practice, it is often difficult to evaluate the animals bought. Thus, while a feedlot manager may be willing to pay a higher price for a Simmental calf than a Holstein, a one day old chick looks just like any other. The second reason has to do with the difference of estimation of profit for a constant versus an expanding market and is explained below.

1.3. Evaluation of feed costs

Feed costs can be divided into feed for the breeding female and feed for the offspring. For each individual, feed costs can further be divided into feed for maintenance and production. In the case of the breeding female, feed for production consists of the feed needed to produce offspring. Thus, total feed costs of an integrated enterprise can be expressed by the following equation:

$$F_a = C_d m_d[x_{3d}F_{Md} + x_{1o}(F_{Pd} + x_{3o}F_{Mo}D + F_{Po}x_{2o})] \qquad [5]$$

where F_a is the annual feed costs of the enterprise, C_d is the unit feed costs, x_{3d} is the metabolic body weight of the breeding female, F_{Md} is the maintenance feed required per unit metabolic body weight of the dam, F_{Pd} is the feed required by the dam per offspring produced, x_{3o} is the mean metabolic body weight of the offspring, F_{Mo} is the maintenance feed required / x_{3o} / day, D is the number of days from weaning to slaughter for the offspring, F_{Po} is the feed required per unit product and the other terms are as defined previously. In this equation, x_{3o} is considered a biological variable and D is considered a constant. This will be true for animals that are slaughtered at a constant age. However, if animals are slaughtered at a constant weight, then D will be a biological variable and x_{3o} will be the economic constant.

Assuming slaughter at a constant age, the only terms in equation [5] that can be significantly effected by breeding are x_{3d}, x_{1o}, x_{3o} and x_{2o} and increasing any of them will have a positive effect on F_a. Increasing m_d will have a proportional effect on both costs and returns. That is by changing m_d we merely change the size of the enterprise. The effect of changing x_{3d} will depend mainly on x_{1o} as illustrated in Table 1. For large domestic animals, x_{1o} is relatively small and changes in x_{3d} can have a significant effect on total feed costs. However, for more prolific species, feed for dams is negligible as compared to feed for progeny. The effect of changing x_{1o} will also depend on the mean of x_{1o}. Although from this equation, it would appear that breeding for reduction in mean offspring weight is a desirable goal, this is hardly ever done in practice. This is because there is generally a strong positive genetic correlation between x_{3o} and x_{2o}. This is of course evident when the main offspring product is meat, but is also true for most other important products, such as milk or wool. Finally, decreasing x_{2o} can reduce feed costs. However, since x_{2o} is directly proportional to returns, unless profit is negative, it is in the interest of the enterprise to increase x_{2o}.

1.4. The relationship between growth rate and feed efficiency

For most domestic animals raised for slaughter, the main trait under selection is growth rate. This is because growth rate is usually highly correlated with feed efficiency. This will be illustrated by considering two cases, rearing to a constant slaughter weight and rearing to a constant age. Assume that body weight increases linearly over time. This is approximately true for most domestic animals. Then x_{3o} will be equal to the mean of initial and final body weight. Since differences in initial body weight are minimal, x_{3o} will be equal to ½ final body weight, plus a constant. Rearing to a constant slaughter weight is illustrated in Figure 1. Body weight as a function of age is plotted for two growth weights. The integral of this curve will be equal to the product of x_{3o} and D. In this case, increasing growth rate decreases D, but does not effect either x_{3o} or x_{2o}. Thus, x_{3o}D is decreased and feed efficiency is increased. This is the common situation for poultry production.

Figure 2 illustrates the situation of slaughter at a constant age for two different growth rates. In this case, D is constant, but both x_{3o} and x_{2o} increase with increase in growth rate. Assuming that the initial weight is negligible to the final weight, the relationship is that feed for maintenance is proportional to ½ final weight, while x_{2o} is proportional to final body weight. The importance of this relationship can be illustrated as follows: if the number of offspring are doubled, with all other factors constant, then both maintenance feed and the quantity of meat produced will be doubled. However, if growth rate is doubled and all other factors remain constant, then x_{2o} is still doubled, but maintenance feed increases only by 50 percent. Beef cattle are generally slaughtered at a constant age.

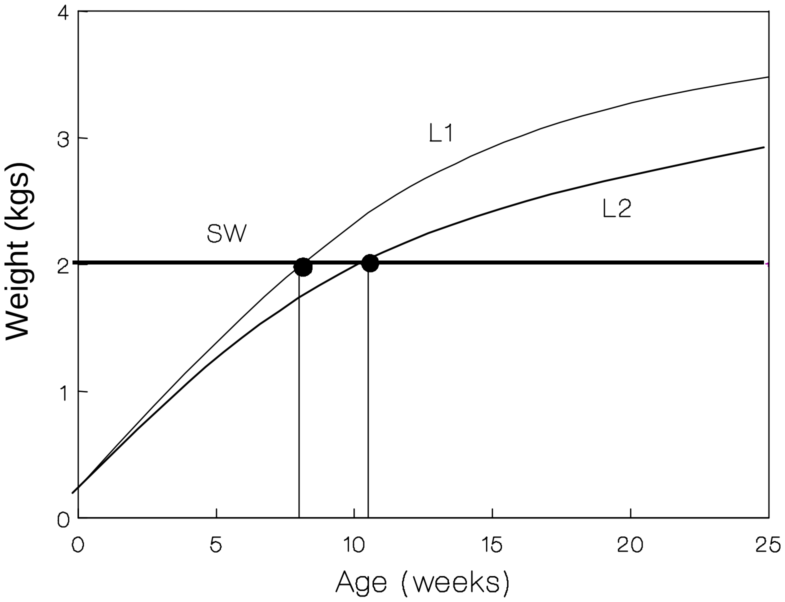

Figure 1. Effect of growth rate for slaughter at a constant weight. SW is slaughter weight. L1 and L2 are growth curves for two poultry strains.

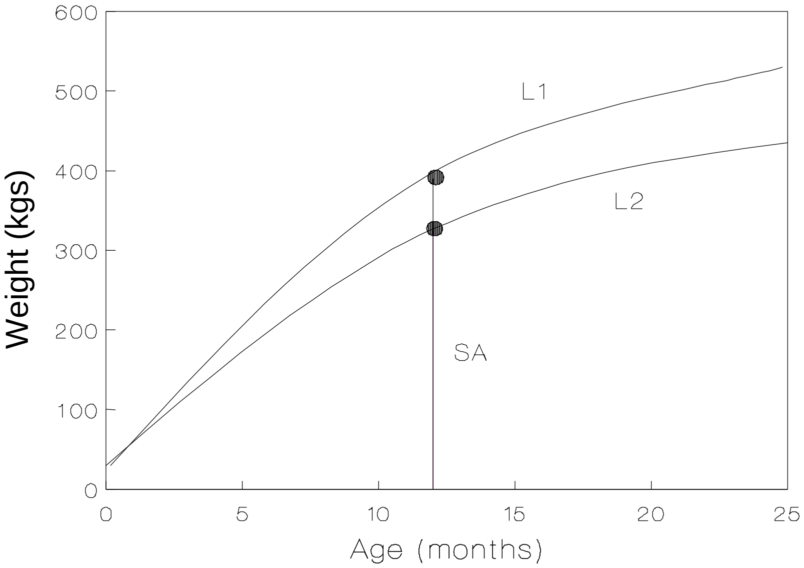

Figure 2. Effect of growth rate for slaughter at a constant age. SA is slaughter age. L1 and L2 are growth curves for two cattle strains.

It becomes apparent, that other factors being equal, there is an optimum slaughter age for all animals. Growth rates for most domestic animals are roughly linear until a given age and then decline. As animals approach maturity, growth rates decline and fat production, which requires more energy for production than muscle, also increases. The optimum slaughter time for beef calves is near the onset of sexual maturity. Extending the linear growth phase can therefore increase the economical efficiency of beef production. This is the main difference between large and small beef cattle breeds.

There is probably an economically important genetic variance for feed efficiency between individual animals after correction for differential growth rates. Although individual feed consumption has a high genetic correlation with growth rate, it is still less than unity. This relationship has been shown both for poultry and beef cattle. Furthermore, both traits have high heritability. However, selection for increased feed efficiency independent of growth rate, requires measuring individual feed intake and this is prohibitively expensive under commercial growth conditions for all domestic species.

1.5 Non feed costs of production

Although the major production costs will be feed related, there will also be significant non-feed costs. These can be divided into fixed costs per enterprise, per breeding female and per progeny. The major non-feed fixed costs were labour, rent, interest, buildings, veterinary costs and replacement breeding females. The only element of these costs that can be directly affected by breeding is veterinary costs. Even though disease related costs are significant, relatively little emphasis has been devoted to breeding animals for disease resistance, because of poor recording and generally low heritabilities. Although the other elements of non-feed costs can generally not be affected by breeding, we will see that they will affect the calculation of the economic evaluation of genetic differences. As is the case for feed costs, non-feed costs that are a function of the number of breeding females will be relatively more important for low fertility species.

2. Evaluation of genetic differences from profit equations

We will now explain how to evaluate differences between individuals or strains for traits of economic importance based on profit. In general terms this is accomplished by expressing profit as a function of the component traits. The economic values of the traits are then computed as the partial differentials of these traits with respect to profit. The notation and most of the examples will be based on Moav (1973). We will show that the estimation of marginal profit can be quite complex under certain circumstances and will depend both on the characteristics of the traits under selection and market constraints. Alternative criteria for evaluating genetic differences is discussed later.

2.1. The basis for evaluation of trait differences

In order to construct profit equations, it is necessary to first consider the unit of comparison. For example, we can consider profit per unit product, per production unit (animal), per unit animal weight, per enterprise (farm), or for the entire national economy. At a first glance, this question may not seem important. The reader may consider this analogous to asking whether a trait is measured in grams or pounds. In fact it will be demonstrated that radically different results can be obtained, depending on the unit selected as the basis of evaluation.

We will start with the example of egg production in poultry, assuming that the objective is to compute the economic value of a unit change in the number of eggs laid per hen. At the beginning it was assumed that all cost and returns from the layer mother are negligible compared to the costs and returns of the layer. Profit per unit of product, in this case profit per egg produced, is computed as follows:

$$P_1 = A_1 - F_1 - V(x_1) = K - V(x_1) \qquad [6]$$

where P_1 is profit / egg, A_1 is income / egg, F_1 is fixed costs / egg, x_1 is the number of eggs / hen and $V(x_1)$ is the variable costs of egg production. F_1 and $V(x_1)$ will include both feed and non-feed costs. $V(x_1)$ denotes that the variable costs of egg production are some function of x_1. Since both A_1 and F_1 are independent of x_1, they can be combined into a single constant denoted K in the right-hand-term of equation [6].

It has been explained that it is convenient to divide costs into feed and other costs. In equation [6] feed costs included in F_1 will be the feed required to produce eggs, while other feed costs will be included in $V(x_1)$. Similarly non-feed costs that are a direct function of the number of eggs produced, such as egg handling labour, will be included in F_1; while other non-feed costs will be included in $V(x_1)$.

In order to obtain a simple algebraic expression for $V(x_1)$, we will assume that all costs not included in F_1 are a direct function of the number of layers. Then equation [6] can be rewritten as follows:

$$P_1 = A_1 - F_1 - F_2/x_1 = K - F_2/x_1 \qquad [7]$$

where F_2 is the fixed costs per hen and the other terms are as defined above. In this equation profit is now expressed as an inverse function x_1. Increasing x_1 increases profit/egg by distributing the fixed costs per hen over a greater number of eggs.

The marginal change in profit/egg/hen (the a-value of the selection index) is computed by differentiating equation [7] with respect to x_1 as follows:

$$\frac{d(P_1)}{d(x_1)} = \frac{F_2}{(x_1)^2} \qquad [8]$$

We note first that as long as x_1 is positive, the change in profit per added egg/hen will be positive. However, the marginal increase in profit is *not* a constant, but rather a non-linear function of x_1. In fact, as the number of eggs/hen increases, that additional profit/egg decreases. This equation points out one of the main difficulties in application of selection index. Selection index assumes that the economic values of the traits under selection are constants. In reality the economic values are generally functions of the phenotypic trait values.

We will now rewrite equation [7] to evaluate profit per hen. This can be done by multiplying both sides of equation [7] by x_1:

$$P_2 = x_1(P_1) = K(x_1) - F_2 \qquad [9]$$

where P_2 is profit per hen and the other terms are as described above. Differentiating this equation with respect to x_1 yields:

$$\frac{d(P_1)}{d(x_1)} = K \qquad [10]$$

That is, profit/hen is a linear function of x_1 and the marginal change in profit is now a constant. Thus, the economic value of a unit change in the number of eggs per hen will be different if profit is computed per hen or per egg.

2.2. Multiple-trait economic evaluation

We will now consider the case of simultaneous economic evaluation of several traits. In the example given above, in addition to number of eggs/hen, mean weight of eggs and hen body weight will be important economic traits. Following the notation of Moav (1973) these two additional traits will be denoted x_2 and x_3, respectively. We will first assume that x_2 is constant and compute the economic value of the two remaining traits on profit. The fixed costs per hen can now be computed as follows:

$$F_2 = (K_4 + K_3x_3) \qquad [11]$$

where K_4 is the fixed cost per hen, K_3 is the fixed cost per unit weight of hen and the other terms are as defined previously. Substituting equation [11] into equation [9], profit per hen can now be expressed by the following equation:

$$P_2 = x_1[K - (K_4 + K_3x_3)/x_1] \qquad [12]$$

with all terms as defined above. Substituting equation [11] into equation [7], profit per egg can be computed as follows:

$$P_1 = P_2/x_1 = K - (K_4 + K_3x_3)/x_1 \qquad [13]$$

Finally, we can also compute profit per gram hen, P_3, by dividing equation [12] by x_3 as follows:

$$P_3 = P_2/x_3 = (x_1K)/x_3 - K_4/x_3 + K_3 \qquad [14]$$

with all terms as defined above. The economic values of x_1 and x_3 are the partial differentials of these variables with respect to profit. These values are summarised in Table 2 for the three profit criteria in equations [12] through [14].

Table 2. Partial differentials of profit with respect to eggs/hen (x_1) and hen body weight (x_3).

Profit criteria	Partial derivatives	
	x_1	x_3
Per egg (P_1)	$[K_4 + K_3x_3]/x_1^2$	$-K_3/x_1$
Per hen (P_2)	K	$-K_3$
Per gram hen (P_3)	K/x_3	$[K_4 - Kx_1]/x_3^2$

We first note that the economic values for both traits will be different for each of the three profit criteria. Under the assumptions that K, K_3 and K_4 are all positive and that x_1 and x_3 are greater than unity, then the economic value of x_1 will be greater if profit is computed per hen than if profit is computed per gram hen. Likewise, the absolute economic value of x_3 will be greater if profit is computed per hen, as opposed to per egg. We further note that the economic values are equal to constants only in the case of profit per hen. Thus, linear selection index cannot be directly applied for either of the other two profit criteria.

2.3. Choice of the appropriate profit criteria

Most studies that have attempted to evaluate genetic differences have done so by the criteria of profit per animal. This criterion is probably justifiable only under a very short-term profit horizon. For example, it may be difficult for a dairy farmer to significantly change the number of cows in his herd within a week, but there is no reason why he cannot appreciably change this number over a space of several months or years. Two alternative constraints which will apply both in the short- and long-term are constraints on production or constraints on investment. We will first consider the case of constraints on production.

In order that production does not exceed demand, most developed countries have imposed production quotas on many agricultural products. If each enterprise has a production quota, then production will be a fixed quantity for both the enterprise and the national economy. We will now compute profit per enterprise, P_E, as profit per animal, times m, the number of animals raised:

$$P_E = mP_2 = mx_1P_1 = Q(P_1) \qquad [15]$$

where Q, the quantity of the demand, is equal to m times x_1 and the other terms are previously defined. (We have designated the product of m and x_1 as “demand” rather than supply because it is demand that we assume to be fixed.)

With fixed Q, an increase in x_1 will cause a reduction in m. Thus, m can be computed as a function of x_1 and Q as follows:

$$m = Q/x_1 = (m_0x_{10})/x_1 \qquad [16]$$

where m_0 and x_{10} are the original values for m and x_1 prior to the change in x_1. Profit for fixed demand, P_Q can then be expressed as follows:

$$P_Q = m_0x_{10}P_1 = m_0X_{10}[K - (K_4 + K_3x_3)/x_1] \qquad [17]$$

Note that the only variables in this equation are x_1 and x_3. Therefore, since m_0x_{10} is a constant, the profit equation in [17] is proportional to profit per egg in equation [13]. Thus, the partial derivatives of this equation will be equal to the partial derivatives of equation, multiplied by the constant, m_0x_{10}.

We will now consider the other two possibilities of profit for a fixed number of animals (production units) and profit for a fixed total weight of animals. The latter alternative can be considered approximately equal to profit for fixed investment. Profit for a fixed number of animals, P_M, is computed as follows:

$$P_M = m_0P_2 = m_0x_1[K - (K_4 + K_3x_3)/x_1] \qquad [18]$$

with all terms as defined previously. This is of course, profit per hen, multiplied by the constant, m_0. For the case of fixed investment, it is required that the total weight of hens be fixed. That is:

$$W = mx_3 = m_0x_{30} \qquad [19]$$

where W is total weight of hens (investment), x_{30} is the initial hen weight and the other terms are as defined previously. From this equation we see that with fixed weight of hens, x_3 will be an inverse function of m. Profit with fixed investment, P_W, is computed as follows:

$$P_W = mx_3P_3 = m_0x_{30}x_1P_1/x_3 = m_0x_{30}[(x_1K)/x_3 - K_4/x_3 - K_3] \qquad [20]$$

with all terms as previously defined. As in previous cases, P_W is equal to P_3 times m_0x_{30}, which is a constant.

Since the objective of breeding is to increase profit, we need to chiefly consider those situations that result in increased profit relative to the original situation, specifically $x_1 > x_{10}$ and $x_3 < x_{30}$. Within this parameter space we can then deduce the following inequality:

$$P_W > P_M > P_Q \qquad [21]$$

This relationship can be explained as follows: for P_Q profit can be increased only be decreasing costs per unit product; for P_M, profit can also be increased by increased production; and for $P_{W,}$ it is possible to further increase profit by decreasing the production unit with fixed investment. The partial differentials for these three profit criteria are listed in Table 3. As should be clear from the previous discussion, the values for each row in Table 3 are proportional to the corresponding row in Table 2.

Table 3. Partial differentials of profit with respect to eggs/hen (x_1) and hen body weight (x_3) by three different enterprise criteria.

Profit criteria	Partial derivatives		
	x_1	x_3	ratio x_1:x_3
Fixed demand (P_Q)	$m_0x_{10}[K_4+K_3x_3] / x_1^2$	$-m_0x_{10}K_3/x_1$	$-[K_4+K_3x_3]/ x_1k_3$
Fixed number of production units (P_M)	m_0K	$-m_0K_3$	$-K/K_3$
Fixed investment (P_W)	$m_0x_{30}K/ x_3$	$m_0x_{30}[K_4-Kx_1]/ x_3^2$	$-Kx_3/Kx_1-K_4$.

Multiplication of the vector of economic values by a constant is equivalent to changing the scale of measurement for the economic values. For example, if the economic values and index co-efficients are measured in US$/kg, multiplication of the index co-efficients by 2.2 changes the scale to US$/lb, but does not change the ratios among the economic values. Thus, the *ratios* among the economic weights is more important than their actual values. We have therefore also included the ratio of the partial derivatives in this table. These ratios are also different for the three profit criteria and except for P_M they are also functions of the trait values. In conclusion, the profit criterion can have a marked effect on the economic values of the traits included in a selection index.

2.4. Differential production quotas

We will now consider an example of profit computed as a function of three traits. In addition to the two previous traits of eggs/hen and hen weight, we will add a third trait of egg weight, x_2. If eggs are priced by weight, then this variable will affect both income and costs. Profit per hen can now be expressed as follows:

$$P_2 = K_1x_1x_2 - K_2x_1 - K_3x_3 - K_4 \qquad [22]$$

where K_1 is income per gram egg less fixed costs per gram egg, K_2 is fixed costs/egg and the other terms are as defined previously. As in the previous discussion, profit per egg can be computed by dividing equation [22] by x_1, while profit per gram hen can be computed by dividing this equation by x_3. In addition, it is now possible to define a fourth profit criteria, namely profit per gram egg, which can be computed by dividing equation [22] by x_1x_2. The co-efficients of the four constants K_1 - K_4 are summarised in Table 4.

Table 4. Coefficients of the economic constants with four different profit criteria.

Profit criteria	Coefficients			
	K_1	K_2	K_3	K_4
Per egg (P_1)	x_2	1	x_3/x_1	$1/x_1$
Per hen (P_2)	x_1x_2	x_1	x_3	1
Per gram hen (P_3)	x_1x_2/x_3	x_1/x_3	1	$1/x_3$
Per gram egg (P_4)	1	$1/x_2$	$x_3/(x_1x_2)$	$1/(x_1x_2)$

As in the previous example, the economic values of the three traits can be computed as the partial derivatives of each profit criteria with respect to each trait. These values are given in Table 5. As in the two-trait case, the partial differentials are quite different, depending on the profit criteria. Since the partial differentials for profit per egg and profit per gram egg are also different, which criteria is appropriate for conditions of fixed demand? The answer will depend on how fix demand is determined. For example, if each producer has a production quota computed in number of eggs, but is paid by egg weight, then the proper criteria would be profit per egg. Note that in this case the economic value of egg weight is K_1. That is with respect to weight of eggs, the producer is effectively in an unconstrained market and it will be to his advantage to put most of the emphasis of selection on increasing egg weight. However, if each farmer receives a quota in weight of eggs produced, or one considers the viewpoint of the national economy, then the proper criteria will be profit per weight of eggs produced.

Another example of this problem is calculating the economic weights for components of milk production. The economically important components of whole milk are butterfat, protein and lactose. Total milk produced and concentrations of milk components can be affected by both breeding and management. In many countries there is a price differential based on protein and fat concentration. In addition, the energy requirements to produce these components are not equal. It requires more energy to produce a gram of fat than a gram of protein, but production of protein requires ingestion of protein, which generally costs more than other feed components. If production quotas are in kg fluid milk, while a price differential is paid for protein and fat production, then the added profit for additional production of these components may be much greater than from additional milk production.

Table 5. Partial differentials of profit with respect to eggs/hen (x_1), egg weight (x_2) and hen body weight (x_3).

Profit criteria	Partial derivatives		
	x_1	x_2	x_3
Per egg (P_1)	$[K_3x_3 + K_4] / x_1^2$	K_1	$-K_3 / x_1$
Per hen (P_2)	$K_1x_2 - K_2$	K_1x_1	$-K_3$
Per gram hen (P_3)	$[K_1x_2 - K_2] / x_3$	K_1x_1 / x_3	$[K_2x_1+K_4-K_1x_1x_2] / x_3^2$
Per gram egg (P_4)	$[K_3x_3 + K_4] / [x_1^2x_2]$	$K_2 / x_2^2 + [K_3x_3 + K_4] / [x_1x_2^2]$	$-K_3 / x_1x_2$

2.5.Graphical representation of profit; reproductivity versus productivity

The relationships previously described can also be represented graphically by plotting one trait as a function of a second trait for a given profit level. If this function is plotted for a number of different profit levels, then this figure is denoted a “profit map” and the curves for the individual profit levels are denoted “profit contours”. For example, x_3 in equations [17] or [20], can be plotted as a function of egg number and profit for fixed number of eggs (demand) or fixed weight of hens (investment). Solving for x_3 from these equations we obtain:

$$x_3 = \frac{1}{K_3}\left[\frac{x_1(m_0x_{10}K - P_Q)}{m_0x_{10}} - K_4\right] \quad [23]$$

$$x_3 = \frac{m_0x_{30}(Kx_1 - K_4)}{P_W + m_0x_{30}K_3} \quad [24]$$

Since the other terms are constants, x_3 is now expressed as a function of x_1 and profit.

The profit maps derived from equations [23] and [24] are plotted in Figure 3 for the constant values of Moav (1973). The solid lines represent the profit contours for fixed demand (fixed number of eggs) and the broken lines represent the profit contours for a fixed number of hens. Since profit is an inverse function of body weight, the scale of body weight is inverted. Thus, on this graph, profit is a maximum in the upper right-hand corner and a minimum in the lower left-hand corner. This convention will be followed throughout. By both criteria, x_3 is a linear function of x_1. Thus, the profit contours are straight lines by both profit criteria. However, the profit contours are not parallel. Furthermore, only the zero profit contour is congruent by both criteria. Thus, if individuals are ranked for selection based on their expected profit, the ranking will be different for different criteria.

Other things being equal, moving at right angles to the current profit contour will maximise profit. Since the profit contours for a given criteria are not parallel, the direction of maximum profit will change as profit increases. Furthermore, since the profit contours computed by the two criteria are also not parallel, except at zero profit, the direction of change for maximum profit at a given profit level will also depend on the profit criteria.

For most species, costs can be partitioned in costs of production and costs of female reproduction. To date, only the first element has been considered. In addition to the cost involved in keeping the laying hens, there will also be costs of keeping the mother hens that produce the laying hens. For an integrated enterprise that raises both mother hens and layers, profit can be expressed by the following equation:

$$P = K - V_2 - V_1 \quad [25]$$

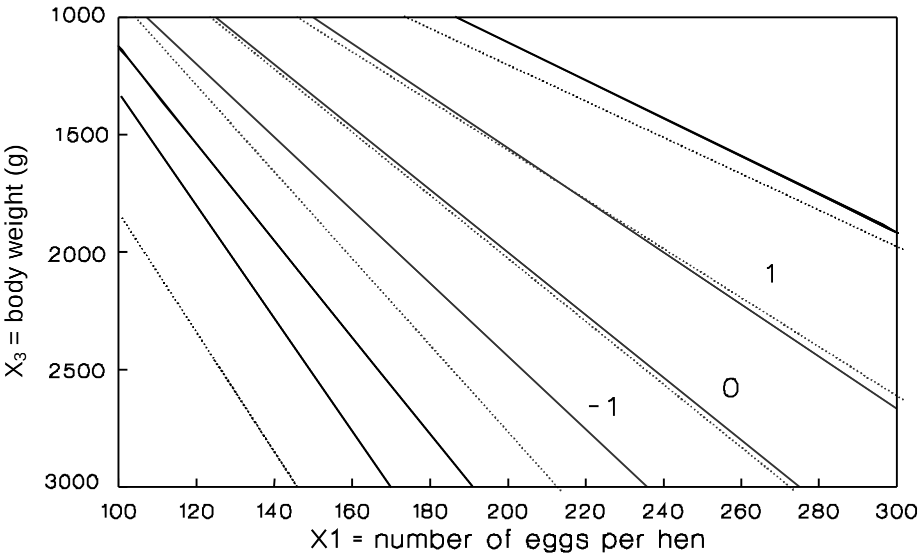

Figure 3. Profit map for laying hens. Body weight is a function of number of eggs per hen for the constant values of Moav (1973). The solid lines are the profit contours for fixed demand (fixed number of eggs) and the broken lines are the profit contours for a fixed number of hens. Since profit is an inverse function of body weight, the scale of body weight is inverted. Profit contour units are arbitrary monetary units.

where V_2 represents the variable costs of production, V_1 represents the variable costs of reproduction and K is return per unit production less fixed costs per unit production. We will now expand this equation following the specific example (Moav, 1973) of pig production in an integrated enterprise that raises both sows and pigs for slaughter :

$$P_1 = K_1 - K_2x_2 - K_3/x_1 \qquad [26]$$

where P_1 is profit per pig marketed, x_1 is number of pigs weaned per sow per year, x_2 is age to a fixed market weight, K_1 is income less costs independent of x_1 and x_2, K_2 is costs dependant on x_2 and K_3 are fixed costs (feed and non-feed) per sow. x_2 can also be defined as the food conversion ratio growth rate. In several previous equations, profit was also an inverse function of x_1. Note, however, the difference between this equation and equation [13]. The importance of this difference will become apparent shortly.

Increasing growth rate will also increase feed efficiency. In equation [26] we assume that pigs are marketed at a constant weight. Thus, increasing growth rate reduces expenses by decreasing the number of days that the pig must be fed prior to slaughter. For simplicity this function is assumed to be linear. Similar to the previous examples, we will now consider profit per fixed demand (pigs marketed), P_Q; and fixed number of production units (sows), P_M. These equations are derived in a parallel manner to equations [17] and [18]:

$$P_Q = m_0 x_{10} P_1 = m_0 x_{10}(K_1 - K_2 x_2 - K_3 / x_1) \qquad [27]$$

$$P_M = m_0 x_1 P_1 = m_0(K_1 x_1 - K_2 x_1 x_2 - K_3) \qquad [28]$$

where m_0 is the number of sows / enterprise, x_{10} is the original number of pigs / sow and the other terms are as defined previously. The profit contours can then be computed by solving for x_2 as a function of profit and x_1, as follows:

$$x_2 = \frac{1}{K_2}\left[K_1 - \frac{K_3}{x_1} - \frac{P_Q}{m_0 x_{10}}\right] \qquad [29]$$

$$x_2 = \frac{1}{K_2}\left[K_1 - \frac{K_3}{x_1} - \frac{P_M}{m_0 x_1}\right] \qquad [30]$$

with all terms as defined previously. The profit contours for these functions are given in Figure 4 for the constant values of Moav (1973) for a swine enterprise.

As in Figure 3, x_2 is plotted on a reverse scale, because of the negative relationship between x_2 and profit. Profit contours for fixed demand and fixed number of sows are denoted with solid and broken lines, respectively. Note first that in both equations, x_2 is an inverse function of x_1. Therefore, the profit contours are non-linear functions. As in Figure 3, the profit contours are congruent only when $P_M = P_Q = 0$. The profit contours with $P_M = P_Q$ cross at $x_1 = x_{10}$. That is, if the number of pigs per sow remains constant, then profit by both criteria will be equal for any value of x_2. As in the previous example, animals will be ranked differently by these two profit criteria.

The significance of the non-linearity will be two-fold. Firstly, we will consider the effect of changes in x_2 as a function of x_1. At any combination of values for x_1 and x_2, the effect on profit of a unit change in x_2 will be equal. However, for P_Q and a constant value for x_2, a unit change in x_1 will have a greater effect on profit at a lower number of pigs than at a higher number. This relationship is of course evident from the partial derivatives of equation [27]. Secondly, profit is increased most rapidly by progressing at right-angles to the profit contours. In the example in Figure 3 the direction of maximum increase in profit will be parallel for all points along

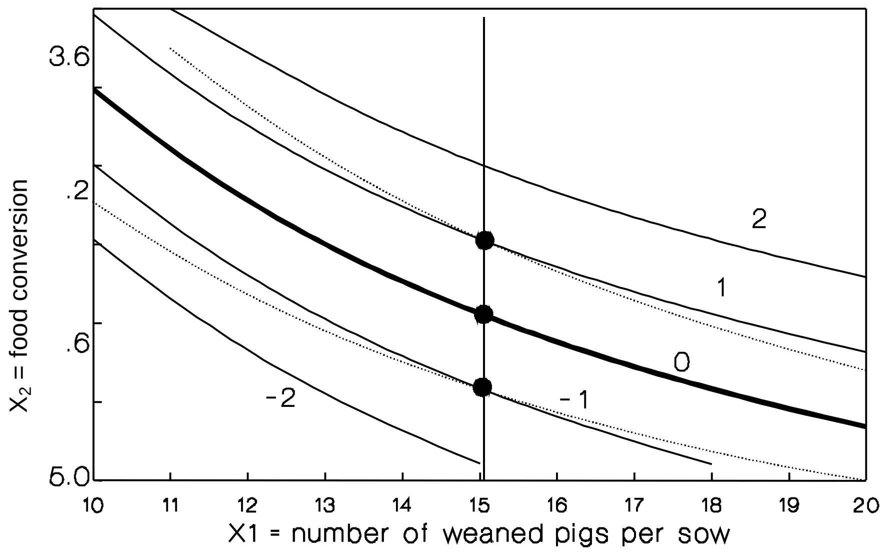

Figure 4. Profit map for a swine enterprise for the constant values of Moav (1973). x_2 is plotted on a reverse scale, because of the negative relationship between x_2 and profit. Profit contours for fixed demand and fixed number of sows are denoted with solid and broken lines, respectively. Profit contour units are arbitrary monetary units. The vertical line is the initial value for x_1.

a profit contour. In Figure 4, for points with equal profit, the direction of maximum increase in profit will be different.

3. Evaluation of genetic differences by alternate methods

There are several disadvantages of using maximisation of profit as the criteria for economic evaluation. Therefore, other criteria for economic evaluation have been suggested. The main alternatives to profit are economic efficiency, biological efficiency and return on investment. We will discuss the advantages and disadvantages of these methods, as compared to profit and will explain in detail the conditions for equality between different profit criteria and economic efficiency. It will be seen that these conditions are general enough that the problem of differing economic values for different profit criteria is less serious then originally thought. Finally, we will consider empirical methods for estimating economic values, based on actual prices and field data.

3.1. Economical and biological efficiency and return of investment as alternative criteria to profit for economic evaluation of trait unit changes

Profit (net income) and economic efficiency are defined as follows:

$$P = R - C \qquad [31]$$

$$E = R / C \qquad [32]$$

where P is profit, E is economic efficiency, R and C are returns and costs per unit production. Some studies have also used the inverse of economic efficiency to estimate economic values. The reasons for this will be explained below. One advantage of economic efficiency, as compared to profit, that should already be apparent is that economic efficiency is independent of the units used to compute R and C. We indicated that profit will be different if computed per unit product, per animal or per enterprise. This will not be the case for economic efficiency. Since the units of R and C will be the same, E is a unitless number. Thus, on the basis of economic efficiency it is also possible to compare different species and production systems. Furthermore, since R and C will generally be approximately equal, E will generally be close to unity.

One important disadvantage of both these criteria is that both R and C will tend to vary over time. Thus, "biological efficiency" (Dickerson, 1982) has been suggested as alternative to economic efficiency. Biological efficiency is defined as unit output per unit feed energy input. Assuming all quantities are measured on an enterprise basis, we can construct the following equations:

$$R = A_1(x_1) \qquad [33]$$

$$C = C_n + C_dF \qquad [34]$$

$$E_B = x_1 / F = [C_dR] / [A_1(C - C_n)] \qquad [35]$$

where A_1 is the price of a unit product, x_1 is quantity of product produced per enterprise, C_n is non-feed costs of the enterprise, C_d is the cost of a unit feed, F is the quantity of feed given, E_B is biological efficiency and the other terms are as defined above. Note that the middle term of equation [35] is in terms of biological inputs and outputs, while the right-hand term is in terms of economic units. Since in many production systems, the main economic component of both feed and product is protein, biological efficiency can alternatively be defined in terms of input and output of protein, rather than gross feed energy and product.

Although biological efficiency will be more constant in the long-term than either profit or economic efficiency, it is not a very useful criterion for economic evaluation. As pointed out by Dickerson (1982) it ignores the differing costs of feed for different species and the differing value of products (e.g. protein versus milk fat, or meat of old versus young animals). In addition it is possible to increase economic efficiency without changing biological efficiency. For example, breeding for disease resistance or calving ease may reduce non-feed costs and therefore, economic efficiency without affecting biological efficiency.

A fourth criterion that can be considered is return on investment, I_W, defined as follows:

$$I_W = P / C_W = (R - C) / C_W \qquad [36]$$

where C_W is investment and the other terms are as defined previously. Similar to efficiency, I_W will be a pure number. If all costs are included in C_W then I_W will be equal to E - 1. Moav (1973) suggested that costs that are a function of the quantity of production, but independent of weight and number of animals raised should not be included in C_W, specifically the feed required to produce the product. This is because decisions on the quantity of investment are taken before the product is produced. Thus, Moav (1973) defined I_W as costs per unit weight of animal. This criteria is probably only of interest to a potential new investor, or an investor who is contemplating expansion. Similar to other profit-based criteria, I_W will be correct only for a given situation. Since the results of nearly all breeding decisions will be long-term, it is difficult to justify this criteria for economic evaluation of trait changes.

3.2. Economic evaluation of trait differences by economic efficiency

In the previous chapter, the economic values of unit changes in trait values were computed by taking the partial differentials of profit equations with respect to each trait. This method can also be applied to economic efficiency. This will be illustrated using the example of egg production given in equation [22]. Profit per hen, P_2 was computed as follows:

$$P_2 = (A_1-F_1)x_1x_2 - K_2x_1 - K_3x_3 - K_4 \qquad [37]$$

where A_1 is income per gram egg; F_1 is fixed costs per gram egg; x_1 is number of eggs, x_2 is egg weight, x_3 is hen weight; and K_2, K_3 and K_4 are fixed costs per gram egg, per egg and per hen, respectively. In order to differentiate between costs and returns, K_1 was replaced by $A_1 - F_1$. The inverse of economic efficiency is now computed as follows:

$$E_i = \frac{F_1x_1x_2 + K_2x_1 + K_3x_3 + K_4}{A_1x_1x_2} \qquad [38]$$

The economic values of x_1, x_2 and x_3 can now be computed by taking the partial differentials of E_i with respect to these three traits. One reason that E_i has been preferred is that calculation of partial differentials will generally be easier for this function. These partial differentials will be equal to the partial differentials presented in the last row of Table 5, divided by A_1, which is a constant. Multiplying the economic values by a constant will not affect the rate of genetic progress. Thus, we can conclude that at least in this example, economic values by the criteria of economic efficiency and by profit per unit product will be the same. This result is generally true and will now be explained in more detail.

3.3. Conditions for equality of economic values as computed for different profit criteria and economic efficiency

Different economic values are obtained when profit is computed by different criteria, such as per dam, per progeny or per unit product. Brascamp, Smith and Guy (1985) and Smith, James and Brascamp (1986) derived three conditions for equality of economic weights as computed by different profit criteria and by economic efficiency: 1) zero profit; 2) disregarding increased profit that can be achieved by rescaling of the enterprise; and 3) disregarding increased profit that can be obtained by correcting inefficiencies in the production system. Following their explanation, we will first use illustrative examples and then prove the general principles.

We will start with the example of pig production, with zero profit. “Zero profit” does not mean that the producer does not receive any compensation from production, but rather that a “reasonable profit”, necessary to make production worthwhile, is included in the “costs” of production. In the long-term, the price for any commodity will tend towards both equal marginal and average cost of production. Thus, if profit is computed as returns minus costs, profit will tend towards zero.

In equation [26] profit per pig, P_1 was computed as follows:

$$P_1 = K_1 - K_2x_2 - K_3/x_1 \qquad [39]$$

where x_1 is number of pigs weaned per sow, x_2 is slaughter age, K_1 is income per pig less costs independent of x_1 and x_2, K_2 is costs dependant of x_2 and K_3 is fixed costs per sow. Defining K as income per kg pig, less costs per kg pig and x_3 as slaughter weight we can rewrite this equation as follows:

$$P_1 = Kx_3 - K_2x_2 - K_3/x_1 \qquad [40]$$

as in the previous chapter we can compute profit per kg pig marketed, P_3, by dividing equation [40] by x_3 as follows:

$$P_3 = K - K_2x_2/x_3 - K_3/(x_1x_3) \qquad [41]$$

Similarly, profit per sow, P_2, can be computed by multiplying equation [40] by x_1:

$$P_2 = Kx_1x_3 - K_2x_1x_2 - K_3 \qquad [42]$$

The partial differentials of these three profit criteria with respect to x_1, x_2 and x_3 are given in the top three rows of Table 6. Under the assumption of $P_1 = P_2 = P_3 = 0$, these partial derivatives can be rewritten in the form appearing in the bottom three rows of Table 6.

Table 6. Partial differentials of profit with respect to pigs/sow (x_1), slaughter age(x_2) and slaughter weight (x_3).

Profit criteria	Partial derivatives		
	x_1	x_2	x_3
Per pig (P_1)	K_3 / x_1^2	$-K_2$	K
Per sow (P_2)	$Kx_3 - K_2x_2$	$-K_2x_1$	Kx_1
Per kg pig (P_3)	$K_3 / [x_1^2x_3]$	$-K_2 / x_3$	$[K_2x_2] / x_3^2 + K_3 / [x_1x_3^2]$
Per pig (P_1=0)	K_3 / x_1^2	$-K_2$	K
Per sow (P_2=0)	K_3 / x_1	$-K_2x_1$	Kx_1
Per kg pig (P_3=0)	$K_3 / [x_1^2x_3]$	$-K_2 / x_3$	K / x_3

We see that the partial derivatives by each criterion are now proportional. That is, the partial derivatives of P_2 are equal to the corresponding partial derivatives of P_1, multiplied by x_1, while the partial derivatives of P_3 are equal to the partial derivatives of P_1, divided by x_3. Since, as shown above, it is the *ratios* of the economic values rather than their *absolute values* that determine the direction of selection, the economic values are now the same by all three criteria.

3.4. Conclusions on the choice of criteria to compute economic values

Although all of the criteria suggested have advantages and disadvantages, those considered most appropriate were profit and the inverse of economic efficiency. We reviewed the anomaly of Moav (1973) that the relative economic values of different traits are different for different profit criteria. This means that different entities involved in breeding could have different objectives. Accepting the conditions for equality presented above, this problem can now be considered resolved.

In practice rescaling is often not a viable option. A farm may be set to handle a set number of cows. Thus, even if the enterprise is in a positive profit situation, it may not be possible to increase the scale of the operation, even if increasing production per cow would increase both returns and profit. However, these considerations are generally only short-term considerations for individual producers. Thus, overall producers, or for the national interest, it would seem that economic values should be computed either for economic efficiency, its inverse, or a profit criteria which is unaffected by scale and these criteria will result in proportionate economic values for all traits under selection.

3.5. “Empirical” methods for estimating economic values

The methods presented above to estimate the economic values of different traits assume that the simple equations presented are basically correct and that the economic constants in these equations can be accurately estimated. Often in practice neither of these assumptions are correct.

Dickerson (1982) suggested computing the partial regression co-efficients of the individual traits on economic efficiency from a simulation model. The advantages of these "empirical" methods for computing economic trait values are: 1) the economic values will be by definition of linear functions of the trait values; and 2) it is possible to include factors and relationships that may not be readily included in profit equations. The disadvantages are: 1) lack of generality. These methods are applicable only to the sample populations measured or simulated; 2) they do not account for changes in relative economic values due to selection. This is, in fact, the reason why the economic values of some traits are non-linear; and 3) can only be applied if an appropriate data sample is available, or if the parameter values of the simulation are known. Thus, in conclusion, it does not seem that these alternative methods can be recommended over the analytical methods described previously.

4. Long-term considerations

Animal breeding is by its nature a long-term process. For example, some results of the most important breeding decisions in dairy cattle are only realised after ten years. Thus, a number of considerations that may not be important for relatively short-term processes are of major importance for most animal breeding programmes. Furthermore, the different costs and returns in animal breeding procedures are realised at different times and with differing probabilities. Thus, factors that effect costs and returns in the long-term must be considered in the economic evaluations of genetic differences. Long-term consideration will affect both the attractiveness of investment in breeding programmes and the relative economic values of the individual traits included in the selection index. The main long-term considerations of animal breeding programmes are the discount rate, risk, profit horizon and reproduction rates.

4.1. Discounting of costs and returns

The first consideration with respect to discounting of costs and returns is which discount rate is appropriate. Most studies that have discounted costs and returns in animal breeding programmes have used rates of five to 15 percent. Smith (1978) lists three alternative criteria for setting discount rates in breeding programmes. First, d_s, the social time preference rate. This is the lowest rate and is appropriate for minimal risk investments in the national interest, such as building roads, ports, or public buildings. Second, the opportunity cost rate, which is the cost of borrowing in the financial market. The third alternative is a synthetic rate which allows for the returns foregone by diverting capital from the higher return rate to the lower d_s rate, but discounts the returns foregone and the actual returns by the d_s rate. The main causes for divergence between the two rates are due to the effects of inflation, risk and taxes on private investment.

"Nominal" interest rates are strongly affected by the inflation rate. Inflation will affect the nominal values of both costs and returns of a breeding programme. Thus, for breeding programmes it is necessary to correct the nominal interest rate, d_i, by the rate of inflation, d_t as follows:

$$1 + d_i = (1 + d_q)(1 + d_t) \qquad [43]$$

$$d_q = (d_i - d_t) / (1 + d_t) \qquad [44]$$

where d_q is the “real” interest rate corrected for inflation. For moderate rates of inflation d_q can be computed approximately as $d_i - d_t$. Although nominal interest rates have varied greatly over the last century, the real interest rate has remained quite stable in the long-term at close to three percent (Smith, 1978).

In addition to inflation, risk and taxation should also be included in the required nominal rate of return. Considering these factors, the required nominal rate of return, d_r, can be computed as follows:

$$d_r = \frac{(1 + d_q)(1 + d_t) / (1 - d_k) - 1}{(1 - d_x)} \qquad [45]$$

where d_k is the risk, d_x is the tax rate and the other terms are as defined above. Clearly the nominal rate can be considerably higher than d_q, even for relatively low rates of inflation, risk and taxation. For example, if $d_q = 0.04$, $d_t = 0.05$, $d_k = 0.02$ and $d_x = 0.1$; then $d_r = 0.127$ or 12.7 percent. This rate is similar to current nominal interest rates in most developed countries with moderate inflation rates, but considerably higher than d_q, which should approximate the d_s rate discussed above.

4.2. Estimating discounted returns and costs for a single trait with discrete generations

Returns from breeding programmes, unlike nearly all other investments, are *cumulative*. This important distinction will be elaborated with an example. A company invests in a new piece of machinery, which increases the efficiency of production and therefore, the net income of the enterprise. Eventually the machine will either be discarded or replaced. Therefore, this investment will generate additional income for a finite period. We will compare this example to the situation in genetic improvement. Assume that milk production per cow is increased genetically by 100 kg. Once this genetic gain has been achieved in the population, no additional investment is necessary to maintain this gain and contrary to the previous example, this gain will never “wear out” or need to be “replaced.” Unless returns are discounted, the same gain in profit is obtained year after year and the total gain from any amount of genetic improvement will tend to infinity. If returns are discounted, the gain of a single cycle of genetic improvement extended to infinity is the minimum acceptable annual return, V, from an initial investment of N with a discount rate of d_r, which is computed as follows:

$$Nd_i = V \tag{46}$$

If V is now taken as the value of one year of genetic improvement, then the cumulative return (R), extended to infinity will be:

$$R = V / d_i \tag{47}$$

Note that R, return from the breeding programme, has replaced N of equation [46]. If the annual value of a cycle of genetic improvement is US$10 and the discount rate is 0.1, then the discounted value of this gain, year-after-year, to infinity is US$100. Alternatively, equation [47] can be derived as follows: the return from a breeding programme to infinity, will be equal to the sum of a geometric progression of the form $V(r^1 + r^2 + ... + r^n + ... + r\infty)$, where $r = 1/(1+d_i)$ and n is the number of years from the beginning of the programme. The sum, S, of a standard geometric progression of the form Vr^n from n = 0 to n = T-1 is computed as follows:

$$S = \sum_{n=0}^{T-1} Vr^n = V(1-r^T)/(1-r) \tag{48}$$

Thus, in our case, the net return is computed as S with T = ∞ less V, as follows:

$$R = \sum_{n=0}^{\infty} Vr^n - V = \frac{V}{1 - r} - V = \frac{Vr}{1 - r} = V/d_i \tag{49}$$

Generally there will be a lag period of several years until the first realisation of any gain from genetic improvement. This will require a further discounting of returns as follows:

$$R = \sum_{t=0}^{\infty} Vr^n - \sum_{t=0}^{t-1} Vr^n = \frac{V}{1 - r} - \frac{V(1 - r^t)}{1 - r} = \frac{Vr^t}{1 - r} = \frac{V}{d_i(1+d_i)^{t-1}} \tag{50}$$

where t is the number of years until the first return is realised.

Certainly no economic enterprise and not even a government will make decisions now based on returns expected one hundred years in the future. A more realistic alternative is to estimate returns and costs for a given time period, say twenty years, under the assumption that all returns accruing after the "profit horizon" have a current value of zero. Cumulative return will then be equal to the sum of a geometric progression of the form $V(r^t + r^{t+1} + ... + r^T)$, where T is the profit horizon in years. The net return is then computed as the difference of two progressions, as follows:

$$R = \sum_{t=0}^{T} Vr^n - \sum_{t=0}^{t-1} Vr^n = \frac{V(1 - r^{T+1})}{1 - r} - \frac{V(1 - r^t)}{1 - r} = \frac{Vr^t(1 - r^{T-t+1})}{1 - r} \qquad [51]$$

Substituting r = 1/(1+d) gives (Smith, 1978):

$$R = \frac{V}{d_i(1+d_i)^{t-1}} [1 - 1/(1+d_i)^{T-t+1}] \qquad [52]$$

As T approaches infinity, the term in brackets approaches unity and equation [52] becomes equal to equation [50]. The term in brackets can be used to estimate the proportion of the total returns of a cycle of genetic improvement for a given discount rate and lag time. For example, the "half life" of a cycle of genetic improvement can be calculated by setting this term equal to 0.5 and solving for T with known values for y and d_i. For example, if $d_i = 0.03$ and y = five years, then the half-life of a cycle of genetic improvement will be 27 years. Thus, if the profit horizon is set at 20 years, less than half of the total gain will be realised within the profit horizon with this particular interest rate. Conversely if $d_i = 0.1$, the half-life will be 13.3 years with the same lag period and the 90 percent life will be 30 years. For the simple case of t = 1 and T = infinity, the ratio of expected gain for two different interest rates and equal genetic gain can be computed as follows:

$$R_1 / R_2 = d_2 / d_1 \qquad [53]$$

where R_1 and R_2 are the expected cumulative gains with interest rates of d_1 and d_2, respectively. In conclusion, for relatively low discount rates, determination of the profit horizon can have a major effect on the expected total gain; while for relatively high discount rate, the difference between a finite and infinite profit horizon will be minimal.

We can now extend this equation to consider an on-going breeding programme with a genetic gain of V each year. The *cumulative* discounted return can then be computed as the sum of a progression of the form $V[r^t + 2r^{t+1} + ... + (T-t+1)r^T]$. The sum of this progression is computed as follows (Hill, 1971):

$$R = V \left[\frac{r^t - r^{T+1}}{(1-r)^2} - \frac{(T-t+1)r^{T+1}}{1-r} \right] \qquad [54]$$

for a discount rate of 0.08, a profit horizon of 20 years and first returns after five years, R = 32.58V. For an infinite profit horizon, equation [54] reduces to:

$$R = \frac{Vr^t}{(1-r)^2} = \frac{V}{d^2(1+d)^{t-2}} \qquad [55]$$

Continuing the previous example of a discount rate of 0.08 and y = 5, for an infinite profit horizon, R = 124.04V. Thus, even with a relatively high discount rate, a little bit of genetic improvement goes a long way.

Until now we have been considering additive genetic improvement, which is generally considered to be cumulative. Not all genetic improvement is additive and therefore cumulative. In many domestic species the commercial animal is a cross-bred produced by breeding different lines. Since it is necessary to reproduce the cross-bred for each generation, any gain in efficiency specific to the cross-bred will not be additive. Thus, for cross-breeding we can set T equal to the generation interval. Therefore, with low discount rates, it is much more profitable to utilise additive genetic variance than heterosis. For example, if t = 1 and d_i = 0.03 the net present value of one unit of genetic gain extended to infinity will be 1/0.03 = 33. To obtain the same discounted value by cross-breeding with T = 1, it is required that V/1.03 = 33, or a nominal gain of V = 34 units. This is, of course, an extreme example, but even with T = 10 and d = 0.15, the nominal gain from cross-breeding must be six-fold the nominal additive gain, so that the current discounted values extended to the profit horizon will be equal.

We will now briefly consider the net present value of the costs of a breeding programme under the assumption of constant costs per year. Unlike genetic gain, costs of a breeding programme are not cumulative. With an infinite profit horizon, equation [47] can be used to compute the costs with V replaced with C_c, the annual costs of the breeding programme. For a finite profit horizon, equation [51] can be used to compute the net present value of the costs, C. With first costs in the following year, C is computed as follows (Hill, 1971):

$$C = \frac{C_c r(1-r^T)}{1 - r} \qquad [56]$$

Using the values of T = 20, d = 0.08 and r = 0.926; the net present value of the costs of the breeding programme will be 9.82C_c. Thus, for t = 5, net profit will be positive if V > 0.31C_c. Note that profit can be positive even if yearly costs are greater than the revenue from yearly genetic gain. Again, this is due to the fact that genetic gains are *cumulative*, while costs are not. Extended to an infinite profit horizon, $C = 12.5C_c$. As computed above for this case $R = 124V$. Thus, profit will be positive if $V > 0.1C_c$.

4.3. Dissemination of genetic gain in populations for a single trait

In the previous section we considered the net present value of genetic selection on a single trait expressed once per generation with discrete generations. In this section we will expand the calculations of the previous section to a situation of overlapping generations and multiple trait expressions per individual. Annual genetic gain in the population can be computed as the sum of the genetic gains per generation by the four paths of genetic inheritance; sire-to-sire, sire-to-dam, dam-to-sire and dam-to-dam; divided by the sum of the four generation intervals. However, this equation will be correct only for a well-balanced breeding programme. If a new programme is started, or if an existing programme is modified, there will be a lag before any gain is obtained and then genetic gains will fluctuate around the equilibrium value for several generations. Equations [47] through [55] are correct only under the assumption that the rates of genetic gain and generation intervals are the same along the four paths of inheritance. Generally this is not the case. Fertility rates and therefore possibilities for selection, are generally greater for males, while many important traits, related to female reproduction, are expressed only in females. Due to both biological and breeding considerations, generation intervals are also different along the four paths. Finally, the time and frequency of trait expression can vary.

These last considerations will be explained with the example of dairy cattle. The main traits under selection are related to milk production. To evaluate the net present value of a sire’s semen for milk production, we must first consider the probability that an insemination from this sire will result in a milk-producing daughter. If a milk-producing daughter occurs, this cow can have several lactations. It is necessary to account both for the probability that a given lactation will occur and also the differing time lag from the initial investment to realisation. Finally, the daughter will have a variable number of offspring, each of which will receive only half of the genetic compliment passed to the original daughter.

If we wish to compare the net present value of genetic improvement for meat production from the dairy herd, we are faced with an entirely different situation. Generally calves will be slaughtered at the age of one year. Thus, the gain from increased meat production will be realised sooner, but will of course be realised only once. Furthermore, no gain will be accrued in future generations from these individuals, since they will invariably be slaughtered prior to mating. Thus, increasing slaughter rate increases the probability of the realisation of this trait in the short-term, but decreases the rate of genetic dissemination in the long-term. A number of studies have addressed various aspects of these problems. We will first consider the economic evaluation of the genotype of a single individual for a single trait, with a single expression per animal, such as meat production (McClintock and Cunningham, 1974). They called their method the “discounted gene flow technique”. Representations require the use of matrix algebra. (Readers unfamiliar with matrix algebra should skip to the beginning of the next section.)

Extending the calculations of the previous section, the net present value of the unit semen from a given sire, N, for a single trait can be computed as follows:

$$N = \mathbf{d}'\mathbf{u}(BV)a \qquad [57]$$

where **u** is a column vector and **d**’ is a row vector both of dimension equal to the number of years from insemination to profit horizon; BV, a scalar, is the sire’s breeding value for the trait in question; and a, also a scalar, is the economic value of a unit change in the trait. The elements of **u** represent the expectation of the fraction of the sire’s genotype that will be expressed in his progeny in a given year. The elements of **u** are computed by multiplying the probability of the trait expression in a given year by the faction of the genome of the original sire passed to each descendant and assessing all possible descendants that could express the trait in that particular year. The elements of **d** are the appropriate discounting factors for the elements in **u**. The j^{th} element of **d**’ is computed as follows:

$$d_j = 1/(1 + d_i)^k \qquad [58]$$

where k is the time period in years from original investment to mean trait expression and d_i is the discount rate. Although there is no general formula for computing the elements of **u**, McClintock and Cunningham (1974) provided formulas to compute this vector for the specific situation in their study. We assumed that the trait in question is expressed once a year. If this is not the case, then the dimension of **u** will be the number of different times that the trait can be expressed to the profit horizon over all possible descendants of the original sire and k must be computed accordingly.

For a trait that can be expressed several times by each individual, such as milk or wool production, equation [57] can be expanded as follows (McGilliard, 1978):

$$N = \mathbf{d'Um}(BV)a \qquad [59]$$

where **m** is a column vector of length equal to the possible number of expressions of the trait (lactations), **U** is a year-by-parity matrix and the other terms are as previously defined. If all expressions of the trait have equal value then **m** will be a column of ones. If, as in the case of milk production, lactation yield increases with parity, then one element of **m** will have the value of unity and the other elements will have values in proportion to the “standard” trait expression. The breeding value will be estimated relative to the “standard” trait expression. The elements of **U** are computed by multiplying the probability of the trait expression in a given year-lactation combination, times the faction of the genome of the original sire passed for each descendant and assessing all possible descendants that could express the trait in that particular year-parity combination. As in the previous example, there is no general formula for computing **U**, but McGilliard (1978) provided an algorithm for computing this matrix for the specific example of dairy cattle.

Equations [57] and [59] can readily be expanded to deal with the multi-trait situation. If several traits are expressed jointly, for example, milk, butterfat and milk-protein production, then it is only necessary to replace (BV)a with the aggregate genotype, H = **y’a**, where **y** is the vector of breeding values for the traits included in the index. H is also a scalar. If the different traits are expressed at different times and with differing probabilities, it will be necessary to compute **du**’ or **d’Um** for each trait. We are now confronted with the rather undesirable result that, unless all traits are expressed jointly, the relative economic values of the different traits will depend both on the discount rate and the profit horizon.

We have so far only considered the net present genetic value of a single individual. As we have already noted in the previous examples, generations for most domestic animals overlap. For example, both a cow and her daughter may be producing milk at the same time. Thus, although both records must be discounted equally, the expected genetic gains will be different. Hill (1974) derived general formulas to evaluate the net present value of single trait selection for a complete population with differing rates of male and female selection. These equations will become quite complex for most realistic population structures. It is likely that for most situations a reasonable approximation of the true economic values can be obtained by the equations of the previous section, which assume a constant rate of genetic gain per year. From the results of several studies it can be concluded that in general, the relative economic values of traits are robust to realistic changes in the profit horizon, the discount rate and the probability of income realisation.

5. Economic evaluation of breeding programmes

We will first consider the main cost elements of breeding programmes and then derive equations for the economic evaluation of breeding programmes. We discussed above whether the basis for economic evaluation of traits should be profit, economic efficiency or return on investment. This same question will of course apply to breeding programmes. The general theory has been developed only in terms of profit, although Hill (1971) also considered the criterion of return on investment. This question is more acute for the commercial breeder and will be discussed in some detail.

5.1. Major cost elements of breeding programmes

Traditionally costs of breeding programmes are minimal when compared to increased income or efficiency generated by these programmes. Many costs that traditionally have been considered part of breeding programmes would have accrued in any event, or generate information that has value beyond the breeding programme. For example, the main impetus for milk recording of individual cows was to use this information in progeny tests. However, this information once available is useful to the producer for other farm management decisions. The costs of keeping sires and collecting semen is generally considered a part of the cost of the breeding programme, even though it would be necessary to keep a minimum number of sires and inseminate females, even if no genetic selection was practised.

Until the advent of biotechnology the main cost elements of breeding programmes were measuring and recording traits, progeny testing, maintaining of breeding stock and statistical analysis. The first important technological innovation in recent times was the ability to freeze and thaw mammalian semen without loss of fertility. This made large-scale artificial insemination (AI) economically feasible and resulted in major increases in the rate of genetic gain for large farm animals (Van Vleck, 1981). Although AI has not had a major impact on the direct costs of breeding programmes, other new technologies will. At present multiple ovulation and embryo transplant are becoming economically viable options. In addition, embryo sexing and marker assisted selection are technologically possible. For the first time, the cost of breeding programmes has become a major factor in their economic evaluation.

In breeding programmes for large animals, recording traits are often the major cost of breeding programmes. Although it is now possible to automatically record milk production of each cow, milk samples must still be analysed for component concentration, which is still a relatively costly procedure. Although the main objective of most recording systems is genetic selection, it should be noted that the information recorded also has other uses, such as cow culling and predicting future production. Certain traits are not included in breeding objectives merely because recording is too expensive. The best example of this is feed consumption for large animals. A question of importance is whether breeding programmes should rely on data recorded by individual producers. This data tends to be less reliable then data collected by professionally trained personnel. Furthermore, the producer sometimes has an economic interest in the values recorded for his own animals. In this case, this data will tend to be biased.

For most large animals, female fertility is very limited, even though many traits of economic importance are only expressed in females. Thus, most genetic progress is achieved by progeny testing. A similar situation exists in poultry, in which most selection is based on family, rather than individual selection. Progeny testing can either be performed at regular commercial farms or at specific enterprises dedicated to this goal. In the first case, the cost of progeny testing will be the possible reduction in breeding value by mating to unproven sires, rather than the best sires available, plus an additional factor for risk. It is standard procedure in many countries for AI institutes to pay farmers to inseminate cows with semen from unproven bulls. In other countries, farmers are obliged by cooperative agreements to inseminate a fraction of their cows with semen from young sires. In poultry, progeny testing is generally performed at special stations. The commercial producers then buy breeding stock in the form of eggs from the commercial breeder. Often there is an additional stage in which the commercial breeder sells breeding stock to multipliers who then sell eggs to the general producers.

In species in which the traits of economic importance are expressed chiefly in females, males are maintained only for breeding or for progeny testing. In the absence of genetic selection, it is still necessary to maintain a minimal number of males for breeding, but this number is generally much less than the total number of males that are progeny tested. Only about one in ten progeny tested sires are returned to service as proven sires. Rather than maintain the males, it is possible to collect and freeze large quantities of semen over a relatively short period and slaughter the animals. Thus, the cost of animal maintenance is reduced, but the cost of semen collection and storage is increased

Previously, statistical analysis was a non-negligible cost of most breeding programmes. However, recent advances in computing equipment have rendered the direct costs of data analysis virtually insignificant compared to other costs. The cost of writing new programmes may still be important, but this cost is rarely borne by commercial breeding programmes in any event. Over the past several decades statistical methods have become consistently more complex without regard to the increased cost of analysis.

5.2. Alternative methods to economically evaluate breeding programmes

Similar to the economic evaluation of individual traits, several different methods have been considered to economically evaluate breeding programmes. The long-term profit from a breeding programme will be a function of the discount rate and profit horizon, in addition to the returns and costs of the breeding programme. Thus, one alternative is to assume that the discount rate and profit horizon are fixed and to compute aggregate profit until the profit horizon is reached. Alternatively, since gains in the distant future will have a negligible economic value with any reasonable discount rate, some studies have suggested estimating the cumulative costs and returns of one cycle of selection with a fixed discount rate and the profit horizon set at infinity. Since new breeding programmes generally require large initial investments, a third alternative is to fix the profit horizon and estimate the discount rate necessary to achieve a net profit of zero. Finally, it is possible to fix the discount rate and compute the number of years required to achieve zero net profit.

5.3. Accounting for differential discounting of costs and returns

We will recall that, on the one hand, genetic changes are cumulative and permanent; but, on the other hand, these changes must be discounted and gains that accrue after the profit horizon have zero value. We developed above expressions to compute the net present value of a genetic change for successively more complex situations. We will assume that all costs and returns are discounted to the beginning of the breeding programme. In the simple programme considered above, there is only one product. Thus, the cumulative discounted returns can be computed as in equation [54]. In addition to the return from the breeding programme, Hill (1971) noted that there is an additional "return", R_i, that can be realised by selling possessions belonging to the breeding enterprise at the termination of the breeding programme. (In practice this return is rarely realised, but should be factored into the equation.) Similarly, costs should be divided into initial costs, which need not be discounted and continuing costs, which should be discounted as given in equation [56]. Thus, the net present value of the breeding programme can be computed as follows:

$$P = V \left[\frac{r^t - r^{T+1}}{(1 - r)^2} - \frac{(T-t+1)r^{T+1}}{1 - r} \right] - \frac{C_c r(1-r^T)}{1 - r} - C_i + R_i r^T \qquad [60]$$

where C_c and C_i are the continuous and initial costs, respectively; and the other terms are as defined above. Assuming that $R_i r^T - C_i$ is negligible with respect to the first two terms, this equation can be rewritten as:

$$P = VD_r - C_c D_c \qquad [61]$$

where D_r and D_c are the net present value discounting factors for annual returns and cost respectively. If the profit horizon, T, is extended to infinity, equation [60] simplifies as follows:

$$P = \frac{Vr^t}{(1-r)^2} - \frac{C_c r}{(1-r)} - C_i = \frac{R}{d^2(1+d)^{t-2}} - \frac{C_c}{d} - C_i \qquad [62]$$

with discount rates below 0.1, the profit horizon can have a marked effect on the net profit of the breeding programme.

5.4. Commercial breeders versus the national interest

Although these equations will apply both to a commercial breeder and to the whole industry, the specific values of the parameters will be different. The national market will be more-or-less fixed. However, a commercial breeder can increase his market share at the expense of other breeders. In addition, depreciation of genetic gains will be more rapid for the commercial breeder who must recoup his investment in a relatively short period, as opposed to the national aspect. Furthermore, in a competitive market, the economic value of genetic improvement is likely to be non-linear. That is, if the breeding stock of a particular breeder is below the genetic value of his competitors, it might have close to no economic value, while if the breeding stock is above the level of his competitors, it might have an economic value well in excess of the expected gain to the producer in either profit or economic efficiency.

5.5. Multi-trait breeding programmes

Nearly all breeding programmes consider more that one trait. Although in general genetic progress will be maximised by linear selection index, this does not provide a solution as to the economically optimum multi-trait breeding programme. In addition to the individual economic value of each trait, the different traits may vary as to the time and probability of expression, in which sex the traits are expressed and the cost of recording for the traits. For example, in dairy cattle, milk production is expressed only in females, while beef production is expressed in both sexes. In addition, the main income from beef will be from yearling male calves. Furthermore, milk production is expressed later, but several times during a cow’s life, while return for beef production of yearling calves occurs earlier, but only once per individual.

The differential cost of recording various traits is also important. For example, pricing for milk is now generally based on an index of carrier, fat and protein. It is less expensive to measure milk production than fat and more expensive to measure protein than either fluid milk or fat. Thus, in an optimum breeding programme, it is possible that only a fraction of those individuals that are milk-recorded will also be analysed for fat and only part of those with fat records will also be assayed for protein. In addition, it is possible that in the future, many cows will be assayed for individual milk proteins, as these proteins have differential values in cheese production.

Conclusions

Although rates of genetic gain are at most only a few percent per year, animal breeding programmes are very profitable in the long-term. This is because gains obtained by breeding are cumulative and eternal. At present, nearly all major breeding programmes are centred in the developed countries. However, this does not have to be the case in the future. Advanced breeding programmes do not necessarily require large initial investments. Furthermore, the genetic material developed by breeding programmes for high maintenance genetic strains in temperate climates are generally not appropriate to developing countries with tropical or sub-tropical climates. The main difficulty that must be addressed is development of procedures for accurate data collection in conditions of low-input management.

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