EFFECTS OF CROSSBREEDING AND SELECTION ON THE PRODUCTIVITY AND PROFITABILITY OF THE NEW ZEALAND DAIRY INDUSTRY

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ABSTRACT

This aim of this thesis was to evaluate some effects of crossbreeding on the New Zealand dairy industry. The study started with a review of crossbreeding parameters, followed by the development of two models.

A farm model was developed to evaluate the productivity and profitability (net income per hectare) of mating strategies involving the main breeds farmed in New Zealand; Holstein-Friesian (F), Jersey (J) and Ayrshire (A). Under current production costs and values for milk and beef, dairy herds using rotational crossbreeding systems had higher net income per hectare than straightbred herds. The ranking of mating strategies on profitability altered with changes in the relative values of fat and protein (1:4, 1:2.2 and 4:1) but rotational FJ and FJA herds had higher net incomes than straightbred herds across three values for the fat to protein ratio and two values for meat (current and 50% higher than current).

An industry model was constructed to evaluate the effects of mating strategies on the rate of genetic gain and the productivity (yields of milk, fat and protein) of the dairy industry over 25 yr. The mating strategies simulated were upgrading to F (UPGF), upgrading to J (UPGJ), upgrading to A (UPGA), rotational crossbreeding using two or three breeds, and use of best bulls (UBB) irrespective of breed. Upgrading to either J or F increased the number of potential bull mothers from 0.27 million to 2.03 and 2.15 million and resulted in genetic gains of 0.27 genetic SD/yr, for both options. Rotational FJ decreased the number of potential bull mothers to 0.17 million and resulted in a genetic gain of 0.24 genetic SD/yr. Upgrading to F and UPGJ resulted in divergent averages of live weight and yields of milk, fat and protein per cow. On the basis of production per hectare, UPGF resulted in lower stocking rate, higher milk yield, and less fat and protein than UPGJ. Effects of the rotational FJ strategy on live weight per cow, and yields of milk per cow and per hectare, were slightly different from the average values for UPGJ and UPGF, due to the effects of heterosis.

The farm and industry models were combined to calculate industry profit for the different mating strategies for 25 yr. Industry yields of standardised whole milk powder, butter and casein were calculated from industry yields of milk and its components. Profitability was calculated as income from dairy products and salvage animals less on-farm costs of production and off-farm costs of milk collection, manufacture and marketing. The ranking of the different mating strategies was affected by the value for butter. When marginal butter sales (above the total industry yield in the base year) were worth only NZ$0.45/kg, UPGF resulted in the highest industry net income (NZ$1119 million) followed by straightbreeding (NZ$1086 million) and rotational FJ (NZ$1076 million). However, if the marginal value of butter production was assumed to be equal to the average base value, then UPGJ resulted in the highest industry net income (NZ$1185 million) followed by rotational FJ (NZ$1177 million) and UBB (NZ$1173 million). Despite the widely different mating strategies used for 25 yr, the largest difference in net income was only 10%.

Rotational crossbreeding systems can increase the profitability of commercial herds, but wide implementation of crossbreeding in the dairy industry reduces the number of active cows (bull mothers) and therefore penalises the rate of genetic gain of the entire population. Future values of dairy products have a major impact on the relative value of breeds and are therefore important to any decisions about mating strategies.

If I take the wings of the morning,
and dwell in the uttermost parts of the sea;
Even there shall thy hand lead me,
and thy right hand shall hold me.

Psalms 139:9-10.

Dedicated to Silvia

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CONTENTS

Chapter 1

General introduction

Milk production in New Zealand is based on cows grazing on ryegrass-clover pastures almost the entire year with little feed supplementation. For the 1996-97 season the dairy industry comprised 3.1 million lactating cows. The breed structure of the national herd was 57% Holstein-Friesian (F), 16% Jersey (J), 18% crossbred F × J, 2% Ayrshire (A) and 7% other dairy breeds and their crosses (7). Ninety per cent of the milk was manufactured into several dairy products and exported to many countries (9). There is a seasonal pattern of milk production because cows are calved in early spring (July-August) to match the pattern of feed requirements, dictated by the lactation curve, with pasture growth (6). Milk payment to farmers rewards yields of fat and protein but penalises milk volume, with values determined by the price received for the resultant dairy products on the world market minus costs of processing and marketing (10). Dairy farmers supplying milk for the internal market (10% of the total production) generally calve some cows in autumn in addition to those calved in spring. They use feed supplementation during winter (mainly hay and silage) and receive a premium on the price paid for milk produced during winter.

Under these environmental and market conditions, the breeding objective of the New Zealand dairy industry is to breed cattle which increase net farm income. Genetic evaluation is across breeds, and animals are selected on the basis of an economic index (breeding worth, BW) that measures net farm income per 4.5 tonnes of pasture dry matter consumed. Breeding values for milk, fat, protein, live weight and survival are estimated for all animals (including crossbreds), but current selection schemes consider only straightbred cows and bulls as bull parents.

Ahlborn-Breier and Hohenboken (1) provided evidence of breed and heterotic effects for milk and fat yield in crosses between F and J breeds. These results were confirmed by Harris et al. (5) who also provided evidence of heterosis for protein yield, live weight and survival in crosses between F, J and A breeds. For the current situation of the New Zealand dairy industry, crossbred FJ cows show higher net income than straightbred F, J and A cows (5). These results have encouraged dairy farmers to mate their cows to bulls from another breed to generate crossbred replacements with the aim of exploiting the effects of breed and heterosis to increase their net income.

Dickerson (4) described crossbreeding systems in which effects of breed and heterosis can be exploited systematically. The three basic crossbreeding systems are specific crossing systems, rotational crossbreeding, and formation of composite breeds. Crossbreeding is also used to expand a breed by upgrading an existing breed. The type of crossbreeding used depends upon the reproductive rate of the population (12), i.e., the number of young females in excess over the number of young female replacements needed to maintain a constant size of the entire population. When the population has a high reproductive rate (poultry and pigs), specific crossing systems can be used and the final cross is given to the commercial producers. Specific crosses include first crosses, backcrosses, three-breed crosses, four-breed crosses etc. These matings enable heterotic effects to be fully exploited (4) but require the maintenance of a proportion of straightbred animals. In the pig and poultry industries, stratified breeding schemes have been developed (12, 2); nucleus herds producing high genetic merit animals (through within-breed selection and crossbreeding), breeders at the multiplier level replicating those animals, and end users benefiting from the genetic improvement occurring at the higher levels.

For species with lower reproductive rates, such as dairy cattle, rotational crossbreeding systems are required to exploit breed and heterotic effects. These schemes allow commercial farmers to produce crossbred female replacements from their own herds. For example, a two-breed rotation between F and J breeds proceeds by making a first cross with a F bull and J cow. In the next generation a backcross is made using a J bull, in the third generation a F bull is used again. This alternate use of straightbred F and J bulls continues and at equilibrium the breed composition stabilises at 2/3 of the sire breed and 1/3 of the maternal grandsire breed. Such a systematic crossbreeding system exploits 67% of the heterosis expressed in the first F × J cross (4). A similar approach can be followed in the three-breed rotational crossbreeding system using F, J and A straightbred sires to exploit 86% of the heterotic effects (4). The advantage of rotational crossing over specific crossing systems is that only straightbred sires are required, as crossbred dams are self-replacing.

Crossbreeding in other countries and other times has often been ill-advised (14). Holstein-Friesian cattle have been widely exploited in temperate climates, largely because of their notable merit for liquid milk production, which is the most important trait determining income for the dairy farm enterprise in many countries. However, if the merit of breeds is evaluated on the basis of net income determined under different environmental and economic conditions (different milk payment systems), breeds other than F or crossbreeds involving F sometimes provide better alternatives. This is the situation in New Zealand, where crossbred cows have higher merit for farm income than straightbred F, J and A cows (5, 7).

In New Zealand there is one selection scheme for each of the main breeds of the dairy industry: F, J and A. The objective for each scheme is to improve, through selection, the genetic merit for net farm income of the next generation of dairy animals. Selection is through four pathways (11), namely, cows to breed cows, cows to breed bulls (CB), bulls to breed cows and bulls to breed bulls. Artificial insemination companies select the best cows to use as bull mothers and also select the best bulls to mate to these cows, and determine which of the resultant sons should be progeny-tested and finally made available to farmers via artificial insemination. Farmers only decide which cows to breed replacements from and, in the case of frozen semen (nominated service), which bulls to choose from the catalogues.

In New Zealand, bull mothers are known as active cows, which are defined as registered (pedigree) or nonregistered (grade) animals provided that they are the result of at least 3 generations of artificial breeding to sires of one breed (8). A large number of active cows results in high selection intensity in the CB selection pathway and leads to high rates of genetic gain (13). If crossbreeding is widely used for dairy farmers, the number of active cows might be eroded because these cows are spread across 6000 herds, mixed with the commercial cows (8). The owners of these cows might follow the same crossbreeding strategy over all cows. Reduction in the number of active cows will compromise the merit of future bulls and consequently the rate of genetic gain would be penalised.

The general objective of this thesis was to evaluate the effects of some crossbreeding systems on the productivity and profitability of the New Zealand dairy industry, when superimposed on the current selection schemes. The study provides a review on estimates of heterotic effects for traits of economic importance for dairy cattle (chapter 2). Chapter 3 develops a farm model to compare the profitabilities for herds using different mating systems exploiting three breeds of straightbred sires. The productive and economic performances are simulated using breed and heterotic effects estimated from the routine genetic evaluation of New Zealand dairy cattle (Livestock Improvement, 1997, unpublished data). Net income per cow and per hectare are calculated for different values of milk and salvage animals.

In chapter 4, an industry model is developed to evaluate the effects of wide spread adoption of various mating strategies on the number of active cows and rates of genetic gain for each of the breeding schemes and the entire population over 25 yr. Breed and heterotic effects, change in the breed composition of the national herd and correlated responses to selection on BW are used to calculate the live weight and yields of milk, fat and protein per cow. The farm model (chapter 3) is then combined with the industry model to calculate the industry average production of milk, fat and protein per hectare.

In chapter 5, the industry model is extended to calculate the total industry yields of milk, fat, protein, lactose and ash over 25 yr for each of the simulated mating strategies. Yields of whole milk powder, butter and casein are calculated following the models proposed by Creamer and McGillivray (3) and Wiles (15). Using both the farm and industry models, net incomes for the whole dairy industry were calculated for the different mating strategies over 25 yr. Effects of selection and mating strategies on changes in the milk payment are evaluated.

In chapter 6, the general results are discussed, and related to other topics which are not covered in this thesis. These topics include nucleus herds and reproductive technologies, multibreed selection indexes, use of crossbred cows and bulls as bull parents and future payment systems.

REFERENCES

1 Ahlborn-Breier, G., and W. D. Hohenboken. 1991. Additive and nonadditive genetic effects on milk production in dairy cattle: evidence for major individual heterosis. J. Dairy Sci. 74:592-602.

2 Bichard, M., P. J. David, and M. Bovey. 1986. Selection between and within lines and crossbreeding strategies for worldwide production of hybrids. Proc. 3rd World Congr. Genet. Appl. Livest. Prod., Lincoln, NE X:130-142.

3 Creamer, L. K., and W. A. McGillivray. 1972. Payment for milk. II. Relationships between net value of milk supplies and pay-out calculated by different methods. N. Z. J. Dairy Sci. Technol. 7:80-91.

4 Dickerson, G. E. 1969. Experimental approaches in utilising breed resources. Anim. Breed. Abstr. 37:191-202.

5 Harris, B. L., J. M. Clark, and R. G. Jackson. 1996. Across breed evaluation of dairy cattle. Proc. N. Z. Soc. Anim. Prod. 56:12-15.

6 Holmes, C. W., G. F. Wilson, D. D. S. MacKenzie, D. S. Flux, I. M. Brookes, and A. W. F. Davey. 1987. Milk Production from Pasture. Butterworth Agric. Books, Wellington, New Zealand.

7 Livestock Improvement. 1997. Dairy Statistics 1996-1997. Livestock Imp. Corp. Ltd., Hamilton, New Zealand.

8 Macdonald Committee Report. 1992. Herd Testing and Related Services. N. Z. Dairy Board. Wellington, New Zealand.

9 MAF. 1997. Situation and outlook for New Zealand agriculture 1997. Ministry Agric., Wellington, New Zealand.

10 Marshall, K. R. 1989. The origin and history of the A + B - C payment system. Pages 9-11 *in* Milk Payment and Quality, Animal Industries Workshop. G. K. Barrell, ed. Lincoln Coll., Canterbury, New Zealand.

11 Rendel, J. M., and A. Robertson. 1950. Estimation of genetic gain in milk yield by selection in a closed herd of dairy cattle. J. Genet. 50:1-8.

12 Sellier, P. 1982. Selecting populations for use in crossbreeding. Proc. 2nd World Congr. Genet. Appl. Livest. Prod., Madrid, Spain VI:15-49.

13 Shannon, P. 1989. Increasing rates of genetic gain. Proc. Ruakura Farmers' Conf. 41:6-11.

14 Touchberry, R. W. 1992. Crossbreeding effects in dairy cattle: the Illinois experiment, 1949 to 1969. J. Dairy Sci. 75:640-667.

15 Wiles, P. G. 1987. Cost model comparing differences in returns for milk produced by Friesian and Jersey type herds. N. Z. J. Dairy Sci. Technol. 22:221-240.

Chapter 2

A review of crossbreeding parameters

ABSTRACT

A comprehensive breeding programme for the genetic improvement of dairy cattle must consider genetic variability within and between breeds. Estimates of heterotic effects are required to predict the level of performance of straightbred and crossbred animals in later generations. The objective of this study was to review estimates of heterosis in crosses between breeds of dairy cattle in temperate climates. Estimates of heterotic effects are low for traits of reproductive efficiency and for contents of solids nonfat, fat and protein in milk. There is evidence of heterosis for yields of milk, fat and protein, and for growth and fitness (survival and resistance to infections) traits even though the estimates are generally less than 10%. Estimates of heterosis for lifetime production of milk and its components are in the range of 16 to 20%. When the heterosis effects of individual traits are combined, crossbred cows have higher profitability ($/cow) than straightbred cows. Values of heterosis for traits of economic efficiency ranged from 6 to 20%. A conclusion of this review was that crossbreeding will likely increase the net income of a dairy farm but further studies are required to quantify the actual benefit, specifically under grazing conditions.

(**Key words:** review, crossbreeding, heterosis, dairy cattle)

INTRODUCTION

In most countries that have significant populations of dairy cattle, within breed selection has been used as the primary tool for genetic improvement of the animals. This is largely because milk and fat yields for crossbred animals are lower than for the genetically superior breeds (mainly Holstein strains), and because milk and fat yields have been the main traits determining income for the dairy enterprise.

In several countries, including Canada, the United States, New Zealand and Australia, the proportion of Holstein (or Holstein-Friesian) cows has been increased at the expense of Ayrshire, Guernsey, Jersey, Brown Swiss and Milking Shorthorn cows (7, 74, 52). The “Holsteinisation” phenomenon (74) is also present to varying degrees in the dairy cattle populations of European countries such as France (10), the Netherlands (110), Sweden (89) and the United Kingdom (3).

More recently, some countries have changed their selection objective and criteria. Selection of animals is now based on economic indexes that either do not include milk volume or do consider milk volume, but with a negative economic value. Moreover, some indexes also consider other traits related to fitness (disease resistance), type, management (temperament) and reproductive performance (65). Under these conditions, crossbred cows might generate higher net income than straightbred Holstein cows, suggesting farmers should consider crossbreeding in their breeding programmes.

In the evaluation of a crossbreeding programme, prediction of the level of performance of later generations of crossbred animals from earlier generations of crosses is highly desirable in order to define the most efficient system. Therefore, estimates of heterotic effects are required. The objective of this study was to review estimates of heterosis effects for traits of economic importance for breeds of dairy cattle in temperate climates.

THE VALUE OF CROSSBREEDING

Crossbreeding is the mating of animals from different breeds (11, 33). The utilisation of crossbreeding as a method of genetic improvement has been discussed by several authors including Dickerson (21, 22), Fewson (34), Jakubec and Hyánek (53), Kinghorn (58), Moav (83), Robertson (97), and Swan and Kinghorn (106).

Heterosis

One reason for utilising crossbreeding is to take advantage of heterosis (h), or hybrid vigour, which may make the crossbreds more productive than either of the parental breeds. In animal breeding, heterosis is defined as the amount by which the phenotypic performance (Y) of the first generation cross (F_1) exceeds the mid parent performance (21, 22):

$$h = Y_{F_1} - [(Y_i + Y_{i'})/2]$$

where i and i' are the two parental breeds. Under this definition, heterosis can be measured at three levels: (a) individual (h^I), which is the improvement in performance of the individual crossbred animal relative to the mean of its parents; (b) maternal (h^M), which refers to the improvement on the crossbred progeny attributable to using crossbred instead of purebred dams; and (c) paternal (h^P), which refers to any advantage in using crossbred instead of straightbred sires on the performance of the progeny.

The genetic basis of heterosis requires expression of nonadditive gene action, including dominance (interactions within loci) and epistasis (interactions between loci), but there is no totally satisfactory explanation (20). Experimental evidence is supportive of the dominance model to explain heterosis (20) but, in some cases, models including epistatic effects offer partial explanations of heterosis (20, 56, 57, 59, 101).

Assuming a linear relationship between heterosis and heterozygosity (the dominance model), Falconer (33) showed that heterosis in the F_1 depends on the difference in gene frequencies in the parental lines and on the degree of dominance. Under this model, therefore, the second generation cross (F_2) is expected to retain half of the heterosis shown by the F_1 cross. However, some discrepancies have been observed between the actual and the expected heterosis from a genetic model including only additive and dominance effects. The genetic explanation of this difference was given by several authors (21, 22, 56, 59, 101). Long-term selection in some breeds seems to have fixed certain alleles, forming blocks of loci containing favourable epistatic combinations. Crossbreeding introduces new alleles, causing the blocks to break up gradually over a number of generations. The loss in value from these gene combinations caused by recombination in crossbred animals is called recombination loss (r) (21, 22) and is defined as the average fraction of independently segregating pairs of loci in gametes from both parents breeds which are expected to be non-parental combinations:

$$r = 2Y_{F_2} - [Y_{F_1} + (Y_i + Y_{i'})/2]$$

Like heterosis, r can be measured at the individual (r^I), maternal (r^M) or paternal level (r^P).

Breed Complementarity

Another reason for crossbreeding is to combine favourable qualities of two or more breeds of different type in a complementarity fashion. Breed complementarity refers to the production of a more desirable offspring by crossing breeds that are genetically different from each other, but that have complementarity attributes (11, 16).

Smith (103) compared the genetic improvement achieved by selecting in a single population line for overall merit with the progress achieved by selecting and crossing specialised sire and dam lines assuming that the effects of heterosis were nil. The sire line was selected for growth and carcass traits, and the dam line was selected for number of offspring produced. The overall rate of improvement through specialised lines was never less than in a single population line.

Moav (83) used the approach of Smith (103) and showed that in the absence of heterosis, an appropriate cross (i.e., using the line with the higher reproductive performance as the dam line) ranks better in profitability than the average of the two parental lines, and better than the reciprocal cross. This phenomenon was called profit heterosis by Moav (83). Although profit heterosis can be estimated for composite characteristics such as average daily gain, the term is probably most useful for some measure of efficiency of production, such as return per unit of investment and net income per hectare (17, 53).

Breed Differences

Implementation of a crossbreeding system provides the opportunity to exploit breed differences. This can give greater flexibility to adjust the breeding programme to changes in farm practices and market conditions. In several countries, local breeds have been upgraded to Holstein because the merits for milk and beef production of the Holsteins were higher than for any other single breed or crossbreds (74).

In Germany, after the second World War, Black and White cows were crossed with Danish Jersey bulls on the expectation that crossbred cows would produce higher yields of fat when fed rations containing high levels of forage. This was instigated by a very high demand for butter and a shortage of concentrates for feeding (12). In the sixties this programme was modified, and F_1 Jersey × Black and White cows were mated to Holstein-Friesian bulls. This three-breed combination was then inter-se mated to create a synthetic breed called the German Black Pied Dairy Cattle (SMR) (12, 40, 104). This illustrates that crossbreeding could be used to exploit breed differences and to combine positive characteristics between the initial breeds with the positive characteristics of the Holstein-Friesians under different feeding and market situations. The SMR was created to provide superior animals with respect to milk yield, fat content (4.5 to 5%), udder quality, milkability, growth rate and feed efficiency (40). Moreover, some heterotic effects for productive and reproductive traits were also exploited (104).

GENETIC MODELS FOR CROSSBREEDING

Several genetic models have been suggested for the analysis of diallel experiments dealing with the estimation of heterosis (27, 28, 36, 39, 67, 46). Models considering later generations of crossbreeding include that of Hill (48), Kinghorn (56, 57, 59), Mather and Jinks (73), and Sheridan (101). The model of Mather and Jinks (73) was developed originally for crosses with inbred lines in plant breeding, but it was applied in animal breeding by Jakubec and Hyánek (53).

One of the most widely used models to represent genetic effects for crossbreeding in animals is that suggested by Dickerson (21, 22). The genetic model is as follows:

$$\begin{aligned} Y_m = \mu &+ \Sigma f_i^I g_i^I + \Sigma k_{ii'}^I h_{ii'}^I + \Sigma f_i^M g_i^M + \Sigma k_{ii'}^M h_{ii'}^M + \Sigma k_{ii'}^P h_{ii'}^P \\ &+ \Sigma t_{ii'}^I r_{ii'}^I + \Sigma t_{ii'}^M r_{ii'}^M + \Sigma t_{ii'}^P r_{ii'}^P + e_m \end{aligned} \qquad [1]$$

where Y_m is the phenotypic performance of individual m; μ is the mean of the population; f_i^I and f_i^M are the proportions of genes contributed by breed i (i = 1, 2, ..., b) measured in the individual and its dam ($\Sigma k_i^I = \Sigma k_i^M = 1$); g_i^I and g_i^M are the direct and maternal effect of breed i; $k_{ii'}^I$, $k_{ii'}^M$ and $k_{ii'}^P$ are coefficients of individual, maternal and paternal heterosis between breeds i and i' ($i \neq i'$); $t_{ii'}^I$, $t_{ii'}^M$ and $t_{ii'}^P$ are the coefficients of individual, maternal and paternal recombination loss between breeds i and i' ($i \neq i'$); and e_m is a random error generally assumed to be normally and independently distributed, with mean zero and variance σ_e^2.

Wolf et al. (114) showed that almost all of the genetic models for crossbreeding reported in the literature can be derived from a general model based on the factorial model of gene effects as developed by Kempthorne (55) and Cockerham (19). Considering only effects at the level of the individual, this general model can be represented as follows (114):

$$\begin{aligned} Y_m = \mu &+ \sum_{i=1}^{b} \alpha_i^I A_i^I + \sum_{i=1}^{b} \sum_{j\geq i}^{b} \delta_{ij}^I D_{ij}^I + \sum_{i=1}^{b} \alpha_i^{I^2} AA_{ii}^I + 2\sum_{i=1}^{b-1} \sum_{j\geq i}^{b} \alpha_i^I \alpha_j^I AA_{ij}^I \\ &+ \sum_{i=1}^{b} \sum_{j=1}^{b} \sum_{k\geq 1}^{b} \alpha_i^I \delta_{ik}^I AD_{i(jk)}^I + \sum_{i=1}^{b} \sum_{j\geq i}^{b} \delta_{ij}^{I^2} DD_{(ij)(ij)}^I \\ &+ 2 \underset{(i\neq k)\ \text{or}\ (i\neq l)}{\sum_{i=1}^{b} \sum_{j\geq 1}^{b} \sum_{k=1}^{b} \sum_{l\geq k}^{b}} \delta_{ij}^I \delta_{kl}^I DD_{(ij)(kl)}^I + e_m \end{aligned} \qquad [2]$$

where Y_m, μ and e_m are as defined above; A_i^I is the additive effect of breed i (i = 1, 2, ..., b); α_i^I is the proportion of genes in the individual from the breed i, with $\sum_{i=1}^{b} \alpha_i^I = 1$; D_{ij}^I

is the dominance effect between breed i and breed j; δ^I_{ij} is the probability that at a randomly chosen locus in the individual, one allele is from the breed i and the other allele is from the breed j, with $\sum\limits_{i \le j}^{b} \delta^I_{ij} = 1$; AA^I_{ii} is the additive × additive effect; $AD^I_{i(jk)}$ is the additive × dominance effect; and $DD^I_{(ij)(kl)}$ is the dominance × dominance effect.

Equation [2] represents only individual effects but the inclusion of maternal, paternal and grandmaternal effects is straightforward (114). Several authors (40, 60, 114) have used this general model to estimate effects of breed and heterosis (split into dominance and epistasis) in later generations of crossbreeding.

Using the general model (equation [2]), Wolf et al. (114) showed, for example, that the model of Dickerson (22) (equation [1]) considering only individual effects can be expressed as:

$$Y_m = \mu + \sum_{i=1}^{b} \alpha_i A_i + \sum_{i=1}^{b} \sum_{j \ge i}^{b} k^I_{ij} h^I_{ij} + \sum_{i=1}^{b} \sum_{j \ge i}^{b} t^I_{ij} r^I_{ij} + e_m$$

where the coefficients of individual heterosis (k^I_{ij}) and recombination loss (t^I_{ij}) can be obtained as follows:

$$k^I_{ij} = \delta^I_{ij} \text{ and } t^I_{ij} = 4\alpha^I_i \alpha^I_j - \delta^I_{ij}.$$

Komender (61) developed a general method to calculate transformation matrices to find the linear dependencies between parameters of two different models used for the analysis of the same experiment or data set.

ESTIMATION OF CROSSBREEDING PARAMETERS

Crossbreeding parameters for productive and reproductive traits in dairy cattle have commonly been estimated by least squares techniques. A linear model in matrix notation describing the crossbreeding information can be represented as follows:

$$\mathbf{y} = \mathbf{X}\beta + \mathbf{e} \qquad [3]$$

where $\mathbf{y}$ is the vector of phenotypic observations, β is the vector of crossbreeding effects, $\mathbf{X}$ is a matrix relating the observations in $\mathbf{y}$ with the parameters in β, and $\mathbf{e}$ is the vector of errors.

Estimation of crossbreeding parameters can be obtained directly by fitting a genetic model (e.g., model of equation [1]) in the matrix $\mathbf{X}$ or, alternatively, breed groups can be fitted as main effects in the matrix $\mathbf{X}$ and estimates of breed groups are used to fit the genetic model (62).

The generalised least squares estimator of β is

$$\hat{\beta} = (\mathbf{X}'\mathbf{V}^{-1}\mathbf{X})^{-1}\mathbf{X}'\mathbf{V}^{-1}\mathbf{y} \qquad [4]$$

with variance of $\hat{\beta} = (\mathbf{X}'\mathbf{V}^{-1}\mathbf{X})^{-1}$ where $\mathbf{V}$ is the phenotypic covariance matrix between the observations. In most of the cases, $\mathbf{X}$ is not of full rank, therefore pertinent restrictions must be used (61). If the phenotypic variance within breed groups (σ_y^2) is assumed equal across all breed groups then, $\mathbf{V} = \mathbf{I}\sigma_y^2$, where $\mathbf{I}$ is identity matrix. In this case, the solution for $\hat{\beta}$ in equation [4] simplifies to ordinary least squares, i.e.,

$$\hat{\beta} = (\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}'\mathbf{y}$$

Komender and Hoeschele (62) showed that ordinary least squares result in an underestimation of standard errors for the estimates of crossbreeding effects. A more appropriate structure of **V** might be $\mathbf{V} = (\mathbf{R} + \mathbf{G})$ where **R** is the matrix of covariance between the residuals and **G** is the genetic covariance matrix. Swan (105) showed that using the inverse of **V** to obtain the generalised least squares solution for $\hat{\beta}$ is computationally difficult, and therefore the ordinary least squares approach is preferred.

To overcome the problems of the least squares procedures, some authors (40, 75, 92, 106, 110, 116) have considered mixed model methodology (45) as a tool for estimating crossbreeding parameters. Moreover, mixed model procedures remove biases caused by selection (62).

A mixed model to obtain estimates of crossbreeding effects and breeding values can be represented as:

$$\mathbf{y} = \mathbf{X}\beta + \mathbf{Z}\mathbf{u} + \mathbf{e} \qquad [5]$$

where **y**, **X**, β and **e** are as defined above, **u** is a vector of random additive genetic effects and **Z** is a matrix relating the observations in **y** with **u**. The expectations of **y**, **u** and **e** are assumed to be (94):

$$E\begin{bmatrix}\mathbf{y}\\ \mathbf{u}\\ \mathbf{e}\end{bmatrix} = \begin{bmatrix}\mathbf{X}\beta\\ \mathbf{0}\\ \mathbf{0}\end{bmatrix}$$

with variance-covariances matrices

$$\text{var}\begin{bmatrix}\mathbf{u}\\ \mathbf{e}\end{bmatrix} = \begin{bmatrix}\mathbf{G} & \mathbf{0}\\ \mathbf{0} & \mathbf{R}\end{bmatrix} \text{ and } \text{var}(\mathbf{y}) = \mathbf{V} = \mathbf{ZGZ'} + \mathbf{R}.$$

The estimator of β is $\hat{\beta} = (\mathbf{X'V^{-1}X})^{-1}\mathbf{X'V^{-1}y}$, as in the case of the linear model of equation [1], and the estimator of **u** is $\hat{\mathbf{u}} = \mathbf{GZ'V^{-1}}(\mathbf{y} - \mathbf{X}\hat{\beta})$.

Henderson (45) showed that $\hat{\beta}$ and $\hat{\mathbf{u}}$ can be obtained simultaneously without the need to compute $\mathbf{V}^{-1}$. This is done by solving the mixed model equations:

$$\begin{bmatrix} \mathbf{X'R^{-1}X} & \mathbf{X'R^{-1}Z} \\ \mathbf{Z'R^{-1}X} & \mathbf{Z'R^{-1}Z+G^{-1}} \end{bmatrix} \begin{bmatrix} \hat{\beta} \\ \hat{\mathbf{u}} \end{bmatrix} = \begin{bmatrix} \mathbf{X'R^{-1}y} \\ \mathbf{Z'R^{-1}y} \end{bmatrix}.$$

Solutions for $\hat{\beta}$ and $\hat{\mathbf{u}}$ can be greatly simplified if the matrices **R** and **G** are assumed to be $\mathbf{R} = \mathbf{I}\sigma^2_e$ and $\mathbf{G} = \mathbf{A}\sigma^2_a$, where **A** is the numerator relationship matrix for the animals to be evaluated. Alternatively, **G** (and $\mathbf{G}^{-1}$) can be constructed with heterogeneous variances across breed genotypes using the procedures of Elzo (29, 30) and Elzo and Wakeman (31).

If breed groups were fitted in the linear model of equations [3] and [5] then the vector $\hat{\beta}$ (obtained by either least squares or mixed model procedures), can be used to calculate estimates of crossbreeding parameters fitting a genetic model. A general linear model for crossbreeding parameters can be represented as:

$$\hat{\beta} = \mathbf{Kp} + \mathbf{e}$$

where $\hat{\beta}$ contains the estimates of b breed groups, **p** is a vector of p crossbreeding parameters to be estimated, **K** is a (b × p) matrix relating crossbreeding parameters to group means, and **e** is a vector of random errors. A least squares procedure can be used to solve for **p** (35). With **K** of full column rank, the estimator of **p** is (100):

$$\hat{\mathbf{p}} = (\mathbf{K'C^{-1}K})^{-1}\mathbf{K'C^{-1}}\hat{\beta} \text{ with } \mathrm{var}(\hat{\mathbf{p}}) = (\mathbf{K'C^{-1}K})^{-1}\sigma^2_e$$

where **C** is the covariance matrix between the estimates of breed groups. Approximate estimates and measures of accuracy can be easily obtained assuming the matrix **C** to be a diagonal matrix, with $c_i = \sigma_e^2 / n_i$ where n_i is the number of observations for the i breed group. This simplification of matrix **C** gives the weighted least squares solution of **p**.

When the number of crossbreeding parameters to be estimated exceeds the number of crossbreeding groups, or when dependencies exist among the parameters such that **K** is not of full rank, restrictions must be imposed on the elements of **p** (100).

REVIEW OF ESTIMATES OF CROSSBREEDING PARAMETERS

The literature on crossbreeding in dairy cattle is extensive. However, many of the estimates have been obtained from crossbreeding experiments in the tropics. Results from crossbreeding experiments in temperate climates have been discussed and summarised by several authors (74, 76, 90, 96, 101, 108, 109). In this review, those estimates are summarised, together with values generated from analysis of field data.

Table 1 shows the average and range of estimates of heterosis for several traits of economic importance for dairy cattle. Estimates of heterosis for specific crosses are shown in Tables A.1 to A.8 of the Appendix. Heterosis was defined as the deviation between the mean performance of first reciprocal crosses from the mean of the parental breeds, and was expressed as a percentage of the mean of the parental breeds.

In several studies, only one of the two reciprocal crosses was available, therefore heterosis was calculated as the deviation of this first cross from the mean of the parental breeds. Other studies estimated heterosis by a regression approach using least squares or mixed model procedures. In this case, the coefficient of regression for heterosis was expressed as the percentage of the parental mean if they were estimable.

TABLE 1. Average values for heterosis[1] and ranges, for crosses among dairy breeds in temperate climates.

Trait	No. of estimates	Heterosis Average	Heterosis Range
		(%)	(%)
Yields			
Milk, kg/lactation	34	4.7	–0.7 to 12.0
Solids corrected milk, kg/lactation	3	5.7	3.6 to 6.9
Fat corrected milk, kg/lactation	14	4.7	–1.7 to 9.3
Total solids, kg/lactation	6	5.6	1.3 to 8.6
Solids nonfat, kg/lactation	8	5.3	–0.6 to 10.4
Fat, kg/lactation	30	5.6	–0.1 to 12.8
Protein, kg/lactation	12	4.7	–1.7 to 10.5
Lifetime milk, kg	1	16.5	
Lifetime fat, kg	1	20.0	
Lifetime protein, kg	1	17.2	
Lifetime lactose, kg	1	16.6	
Milk composition			
Solids nonfat, %	10	0.4	–0.2 to 1.2
Fat, %	21	0.2	–2.6 to 2.8
Protein, %	5	–0.3	–3.3 to 1.0
Lactation characteristics			
Milk yield first day of lactation, kg	3	6.1	1.0 to 14.4
Milk yield in peak of lactation, kg	3	6.8	4.4 to 8.1
Milk yield in 300-d of lactation, kg	3	17.7	14.4 to 20.0
Day of peak of lactation	3	2.1	–3.3 to 11.6
Number of days in peak of lactation	3	4.3	–34.6 to 32.0
Lactation length, d	7	0.1	–2.5 to 1.9
Persistence, %	8	–0.7	–10.0 to 4.1
Milking speed, kg/min	4	5.8	4.1 to 7.7

(continued)

TABLE 1. (continued) Average values for heterosis[1] and ranges, for crosses among dairy breeds in temperate climates.

Trait	No. of estimates	Heterosis Average (%)	Range (%)		
Biological efficiency					
kg live weight gain[2]/kg TDN[3]	1	0.0			
Mcal milk/Mcal intake	3	1.1	0.0	to	2.5
kg fat corrected milk/Mcal intake	3	1.4	0.5	to	3.1
kg solids corrected milk/Mcal intake	3	1.3	0.6	to	1.9
kg milk/kg 18-mo live weight	3	1.8	−3.5	to	7.9
kg total solids/kg 18-mo live weight	3	1.7	−3.3	to	8.2
kg milk/kg mature live weight	1	−0.5			
Live weight at					
birth, kg	13	2.4	−0.5	to	6.2
3 mo, kg	7	3.4	1.1	to	7.2
6 mo, kg	11	3.3	−0.6	to	7.1
12 mo, kg	10	3.9	0.7	to	6.3
24 mo, kg	5	4.5	3.3	to	7.0
48 mo, kg	2	3.2	1.0	to	5.3
Mature live weight, kg	1	3.0			
Live weight gain					
before 9 mo, kg/d	4	2.3	0	to	4.5
during lactation, kg/d	3	−1.0	−8.2	to	7.0
Skeletal dimensions					
Withers height					
6 mo, cm	8	0.7	0.0	to	1.7
12 mo, cm	8	1.0	0.4	to	1.7
18 mo, cm	8	0.9	0.0	to	1.7
Heart girth					
6 mo, cm	5	1.0	0.0	to	1.9
12 mo, cm	5	1.6	0.5	to	2.0
18 mo, cm	5	1.5	1.0	to	2.4

(continued)

TABLE 1. (continued) Average values for heterosis[1] and ranges, for crosses among dairy breeds in temperate climates.

Trait	No. of estimates	Heterosis	
		Average	Range
		(%)	
Breeding efficiency			
Age at first service, d	1	−2.1	
Age at first calving, d	6	1.1	−1.2 to 2.7
Days from calving to first heat	3	3.8	−0.8 to 9.1
Days open	11	−5.8	−21.7 to 9.4
Services per conception	2	9.4	5.9 to 12.8
Calving interval, d	7	−0.8	−3.7 to 3.3
Gestation length, d	3	−0.7	−2.3 to 0.5
Days of dry period	1	12.7	
Viability and stayability			
Calving difficulty (scale 1 = very easy to 5 = caesarian)	2	6.3	3.1 to 9.4
Incidence rate of calving difficulty	4	−2.3	−68.7 to 61.9
Perinatal survival, %	5	4.4	−2.8 to 15.5
Survival rate from birth to			
3 mo	1	3.2	
6 mo	1	4.1	
12 mo	1	5.2	
first calving	5	19.7	10.1 to 40.7
end of first lactation	1	6.0	
second calving	1	12.5	
Median herd life, d	1	9.8	
Infection rate from birth to first calving	3	−25.8	−40.7 to −15.8
Infection rate during first lactation	3	34.7	18.8 to 46.7
Incidence rate of mastitis	3	15.7	−6.9 to 47.0

(continued)

TABLE 1. (continued) Average values for heterosis[1] and ranges, for crosses among dairy breeds in temperate climates.

Trait	No. of estimates	Heterosis Average	Range		
		(%)			
Economic efficiency per cow					
Value of milk per year, $	1	6.1			
Total income per year, $	1	11.4			
Total income over feed cost per lactation, $	3	8.5	–0.5	to	14.2
Economic worth per lactation[4], $	3	11.8	–6.9	to	28.9
Lifetime milk value, $	1	17.9			
Annualised discounted net return, $	1	20.6			

[1] Heterosis was calculated as [(mean performance of first reciprocal crosses – mean of the parental breeds)/mean of the parental breeds] × 100.

[2] Live weight gain from 26 to 34 weeks of age.

[3] Total digestible nutrients.

[4] Total income minus costs of feeds, veterinary treatment, dry cow maintenance and unrealised returns due to mortality.

Milk Traits

Crosses between breeds. There is a tendency towards a moderate level of heterosis for lactation yields of milk, solids-corrected milk, fat-corrected milk, total solids, solids nonfat, fat and protein (Table 1). Values range from –1.7 to 12.0%. There is no clear evidence of a relationship between heterosis and lactation number (Table A.1). Some studies (24, 71, 108) found that crossbred cows showed higher heterosis for second than for first lactation yields of milk and fat. However, opposite trends were reported by McAllister (74).

Evidence of heterosis for milk composition traits is absent (Tables 1 and A.1). This implies that the phenotypic expression of these traits is more under the control of additive than dominance genetic effects. This is consistent with the typically high heritabilities for fat and protein percentage (72).

By fitting an incomplete gamma function (115), Grossman et al. (41) concluded that there is some evidence of nonadditive genetic variation associated with coefficients of the lactation curve. Average estimates of heterosis for several characteristics associated with the lactation curve of crossbred and straightbred cows are shown in Table 1. Specific values of heterosis are in Table A.2. In summary, crossbred cows, compared to the average of parental breeds, have higher daily milk yield at the start of lactation, peak and 300-d of lactation, reach the peak yield later, but have similar lactation length and persistence. There is also evidence of heterosis for milking speed (values range from 4.1 to 7.7%; Table A.2).

Lifetime yields of milk and its components are key determinants of farm income. Conceptually, lifetime production consists of average yield per lactation and the number of lactations during herd life. Nagai and McAllister (84) illustrated that moderate levels of heterosis for lactation milk yield (6%) and number of lactations per herd life (12%) combine to result in high levels of heterosis (19%) for lifetime milk production. Only one study was found reporting heterosis for lifetime yields. McAllister et al. (75) estimated Holstein x Ayrshire heterosis for lifetime yields of milk, fat, protein and lactose at 17, 20, 17 and 16 %, respectively (Table 1).

Crosses between strains. Several studies involving crosses between strains of Holstein-Friesian (3, 10, 110, 116) and Jersey (82) have reported estimates of heterosis for yields of milk, fat and protein. Most of the estimates are shown in Table A.3 of the Appendix.

In the Polish crossbreeding trial, Holstein and Friesians bulls from nine countries were crossed with the Polish Black and White cows (116). Ranges of heterosis for yields of milk and fat were –1.9 to 10.7% and –1.6 to 10.4%, respectively. Estimates of heterosis for yields of milk, fat and protein ranged from 1.8 to 3.0% for crosses between

North American Holstein and European Friesian cattle (3), North American Holstein and French Black and White cattle (10), Dutch-Friesian and Holstein-Friesian cattle (110), and US and Danish Jersey cattle (82).

Estimates of heterosis for contents of fat and protein were zero between crosses of North American Holstein and French Black and White cattle (10) and Dutch-Friesian and Holstein-Friesian cattle (110). In contrast, estimates of heterosis for content of fat ranged from 0.4 to 5.6% from crosses of the Polish crossbreeding trial (116).

One of the objectives for estimating crossbreeding parameters between strains of the same breed was to detect bias in the genetic evaluation (3, 10, 110). The consequences for genetic evaluation were studied by comparison of results from two analyses, with and without nonadditive effects included in the model. When the nonadditive effects were not accounted for, estimated breeding values were overestimated for some sires if they had large numbers of crossbred daughters.

Nonadditive effects from crossbreeding are often considered as nuisance effects which have to be taken into account when estimating breeding values (110). This can be done simply by including heterosis and recombination as covariables in the model (10, 110).

Estimates of recombination loss. There is evidence of recombination loss for milk traits between crosses of strains (3, 10, 110) and breeds (12, 32, 40, 91). Estimates are summarised in Table A.3.

Estimates of recombination loss for contents of fat and protein are low and not significant for most of the crosses. Estimates of recombination losses for yield traits are surprisingly large and negative, reaching about 80% of the heterosis in most of the studies, except in the studies of Akbas et al. (3) and Pedersen and Christensen (91), where estimates of recombination loss were higher than the estimates of heterosis. Grosshans et al. (40) indicated that because Holstein-Friesians have been selected for decades with the objective to increase milk yield per cow, favourable epistatic interactions between genes on different loci within gametes may have been enriched in addition to positively acting additive genes. By crossing this breed it may be expected that the favourable epistatic interactions are being lost due to recombination during meiosis. These estimates of recombination loss suggest that first cross heterosis for yields of milk, fat and protein may be eroded in advanced generations of two- and three-breed rotational crossbreeding.

Others studies have reported that estimates of recombination loss (71, 74) or epistasis (99) were not significant for lactation yields of milk and fat.

Biological Efficiency

Biomass efficiency of dairy cattle was defined by Blake (8) as the rate of converting living matter into milk. This biomass efficiency depends on diet and other environmental factors, and on the genetic ability of the cow to utilise these inputs to produce milk (9). Among domestic livestock, dairy cattle have a comparative advantage in producing food protein and energy from livestock feeds (54). Genetic improvement for milk yield has been a determining factor in the improvement of biomass efficiency (93).

Experimental results show that feed efficiency per cow (energy produced in milk as a proportion of metabolisable energy consumed) for Jerseys is higher than Holstein-Friesians (70), Holstein (38), or a group of Friesians (87, 88). The greater feed efficiency exhibited by Jersey cows may reflect: 1) a greater efficiency of utilisation of metabolisable energy for milk and tissue deposition as a consequence of a lower heat increment (63); 2) a greater ability to consume more feed per kg live weight than Friesian cows (107), which may be a function or larger reticulo-rumen volumes as a proportion of live weight (12); and 3) a lower proportion of the total energy used for maintenance and, consequently, a higher proportion of total energy used for milk production (87, 88).

Estimates of heterosis effects for feed efficiency are scarce (Tables 1 and A.4). Only one report (77) was found in the literature. Daily feed intakes during first lactation of Holstein, Ayrshire and Brown Swiss and their crosses were used to estimate heterosis for feed efficiency using three estimates: 1) calculated total Mcal of milk energy for lactation per Mcal estimated net energy (ENE) consumed; 2) kg of lactation fat-corrected milk yield per Mcal ENE consumed; and 3) kg of lactation solids-corrected milk yield per Mcal ENE consumed (Table A.4). The estimates of heterosis were variable, ranging from 0 to 3.1%. The general conclusion of that study was that both additive and heterotic effects may occur in feed utilisation. However, McDowell (76) pointed out that the measurements of efficiency were referred to as gross efficiency and had the inherent inaccuracy of measures of feed efficiency that do not account for the contribution of energy catabolised from tissues to subsidise nutrient intake.

Some studies have reported heterosis for lactation milk and total solids yields in relation to live weight (12, 24). Averages of estimates of heterosis for these proportions are shown in Table 1. Values were negative for the Holstein-Friesian × Jersey (–3.5 and –3.3%) but high and positive for the cross Holstein-Friesian × Ayrshire (7.9 and 8.2%) (Table A.4).

Growth Traits

In some European countries, beef production is an important component of the gross income for the dairy farm (66). In New Zealand, income from beef accounts for only 6% of the gross farm income (69).

Mature live weight of lactating animals affects the efficiency with which cows convert feed into milk, fat and protein. Heavy cows have to produce more milk than smaller cows to achieve an equivalent efficiency, to offset the effect of a larger energy requirement for maintenance (51, 112). The New Zealand breeding programme for dairy cattle includes live weight in the selection objective with a negative economic value (44).

This negative economic value reflects the fact that extra income from culling larger cows does not overcome the extra costs of maintenance of the larger animals.

Estimates of heterosis for live weights and body measurements at different ages are shown in Table 1. Heterosis for live weights appear to increase up to 24 mo of age and decrease afterwards. Average values for heterosis for body measurements were generally 1 to 2% with no trends for age. Estimated values of heterosis for specific crosses are shown in Tables A.5 and A.6.

Heterosis for live weight gain and feed efficiency (kg live weight gain/kg total digestible nutrient) from 26 to 34 weeks of age were close to zero in Holstein × Ayrshire crossbred heifers (64). Heterosis in Holstein × Ayrshire, Holstein × Brown Swiss and Ayrshire × Brown Swiss first crosses were 1.3, 4.5 and 3.4%, respectively, for average daily gain from birth to 270 d of age (76) and –8.2, –1.8 and 7.0%, respectively, for live weight gain during lactation (77). Heterosis in Holstein × Ayrshire crosses for asymptotic mature weight was estimated to be 3.0% (92). These results suggest that heterosis affects the growth of dairy cattle. Crossbred animals grow faster and have higher mature weight than the average of the parental breeds.

Estimates of heterosis for live weight gain during lactation is not consistent. In the crossbreeding experiment reported by McDowell and McDaniel (77), heterosis for Holstein × Ayrshire was positive whereas heterosis for the Ayrshire × Brown Swiss was negative. The authors suggested that Holstein × Ayrshire crossbred cows used more body reserves for milk production than Ayrshire × Brown Swiss crossbred cows.

Reproduction Traits

Failure in reproduction can account for 16 to 32% of all disposals, and ranks second to low production as the major reason for cows leaving the herd (4, 14, 42, 85). Reproductive performance affects the total profitability of a dairy herd. For countries where calvings are spread through the year, age at first calving and length of the intercalving interval have major effects on income per cow per year from both milk and sale of cull animals (108).

Heterosis values for age at first calving are low, averaging 1.1 % (Table 1). The effect of heterosis indicates that crossbred heifers may have their first calving at an age of 8 d older than the average of straightbred heifers (considering age at first calving equal to 730 d).

The average of estimates of heterosis for open days is –5.8% (Table 1), suggesting that crossbred cows have shorter periods from calving to conception than the average of parental breeds. Donald and Russell (25) indicated that these heterotic effects would also mean that crossbred females are about 10% more likely to conceive than straightbreds. Heterosis values for calving interval and gestation length are in general favourable (negative) but low (Tables 1 and A.7).

The possible advantages of crossbreds among dairy breeds in comparison to straightbreds seem to be primarily in fewer days open during lactation and a greater proportion of cows which conceive during the breeding period.

Viability and Stayability

Fitness traits such as health and survival rates are becoming more crucial for the dairy industry because production and management systems are becoming more intensive. Averages of estimates of heterosis for fitness traits are shown in Table 1 and estimated values for specific crosses are shown in Table A.8.

Breed of sire has a significant effect on the incidence of calving difficulty (1, 23), however, crossbred cows show a lower incidence of dystocia than straightbred cows, with an average heterosis of –2.3%. However, these results contradict the estimates of heterosis for calving difficulty reported by Christensen et al. (18).

Effects of maternal and individual heterosis for perinatal survival generally are confounded. Donald (23) found that perinatal survival was higher for crossbred than straightbred calves born out of mature cows but not for calves born out of heifers. Similarly, Vesely et al. (111) reported lower perinatal mortality of crossbred Holstein × Ayrshire calves (6.6%) compared with straightbred calves (7.2%) all born to straightbred dams, as well as lower perinatal mortality of crossbred calves (7.7%) against straightbred calves (10.4%) born of contemporary crossbred and straightbred dams, respectively. In contrast, Christensen et al. (18) found higher perinatal mortality for crossbred than straightbred calves.

In general, there is heterosis for survival at different ages (Table 1). McDowell and McDaniel (78) found a tendency for superior disease resistance in crossbred calves as compared to straightbreds, although this fluctuated among specific crosses. However, they did not find any evidence that crossbred cows had superior resistance to health problems of first lactation cows, such as mastitis.

Herd life usually refers to the average age of cows at disposal. Longer herd life reduces replacement costs and land requirements (37). Hocking et al. (50) found that crossbred Holstein x Ayrshire females had longer median herd life than the average of the straightbreds. Heterosis for this trait was estimated at 9.8%. In contrast, McDowell (76) concluded that in most situations crossbreeding will not extend herd life.

Profitability

The critical and practical question is whether crossbreeding will result in sufficient heterosis to provide greater economic returns than the best of existing breeds. One criterion to evaluate the breeding programme is net profit per unit of production (cow, hectare or dairy farm), where net profit would be the total income minus the production costs including investments and direct expenses.

Touchberry (108) estimated heterosis levels of 9.4, 39.6 and 12.6% for value of milk, value of animals sold and total value per cow per lactation, respectively. Respective values per cow per year were 6.1, 35.4 and 11.4%. Heterosis for income per cow per lactation over feed costs and death losses was 21.7%

McDowell and McDaniel (79) compared two breed crosses among Holstein, Ayrshire and Brown Swiss to contemporary straightbred cows for first lactation income over feed cost, under different milk price-feed cost combinations. By obtaining an average of all combinations of prices, heterosis values were 11.8, 14.2 and –0.5% for Holstein x Ayrshire, Holstein x Brown Swiss and Ayrshire x Brown Swiss, respectively. When costs of veterinary treatment, dry cow maintenance and unrealised returns due to mortality were added to income over feeds costs, respective heterosis values for economic worth per lactation were 13.3, 28.9 and –6.9% (Table 1).

Lifetime milk value and annualised discounted net returns of Holstein, Ayrshire and crossbred cows were analysed by McAllister et al. (75). Heterosis for lifetime milk value and annualised discounted net returns per cow were estimated to be 17.9 and 20.6%, respectively (Table 1).

In general, the above studies agree that the value of crossbreeding must be judged on net profit which includes a number of traits such as viability, reproductive performance, lactation yields of milk and its constituents and production costs.

In the New Zealand dairy industry, cows can be compared across breeds in terms of production worth which is a measure of net income per cow per 4500 kg pasture. Production worth is calculated as the sum of production values (breeding value plus permanent environment effect plus average heterosis effect) for fat, protein, milk and live weight each weighted by their corresponding economic value (44). Results from the genetic evaluation indicate that average production worths for crossbred Holstein-Friesian × Jersey cows are higher than those for straightbred Holstein-Friesian and Jersey cows (44). This supports the experimental evidence that the joint effects of heterosis for individual traits result in heterosis for net profit. However, further studies are required, particularly under grazing conditions where pasture, animals and dairy farmers are important factors determining profit per hectare instead of profit per cow.

CONCLUSIONS

Crossbreeding can take advantage of heterosis, breed complementarity and breed differences. This review demonstrated that heterosis for traits of economic importance exists in breeds of dairy cattle farmed in temperate climates. Considered individually, few of the heterosis values are large but all tended to favour net profit, which must be the general objective of a breeding programme. The data suggest that systematic crossbreeding can therefore be used by dairy farmers to increase farm net income, but further studies are required.

APPENDIX

TABLE A.1. Estimates of heterosis[1] for milk traits of dairy breeds[2] in temperate climates.

Reference	Country	Breeds crossed	Lactation	Lactation yield (kg)							Content (%)		
				Milk	SCM[3]	FCM[4]	TS[5]	SNF[6]	Fat	Protein	SNF	Fat	Protein
Ahlborn-Breier and Hohenboken, 1991 (2)	New Zealand	F × J	1	6.1					7.2			0.0	
Harris, 1994 (43)	New Zealand		All	5.9					6.9	6.3			
Donald et al., 1977 (24)	England		1	3.6			5.2				1.1	1.3	
			2	5.7			6.5				0.8	0.4	
McDowell, 1982 (76)	USA		1	6.6		9.3			11.0			0.2	
Okumu and Berry, 1966 (86)	Canada		All			3.2							
Brade, 1992 (12)	Germany		1						7.6				
Grosshans et al., 1994 (40)	Germany		1	2.6					6.3			–0.5	
McDowell and McDaniel, 1968 (77)	USA	F × A	1	8.1				7.5	7.9	5.3			
Rincon et al., 1982 (95)	USA		1	7.2	6.5	7.0		6.1		3.5	1.2	–0.7	–3.3
Donald et al., 1977 (24)	England		1	8.2			8.6				0.7	0.0	
			2	0.7			1.3				0.6	1.3	
McAllister, 1986 (74)	Canada		1	3.7					3.9	4.0			
			2	3.4					1.5				
			3	0.8					0.7				
			4 and +	2.6					1.6				
Harris, 1994 (43)	New Zealand		All	3.1					2.8	3.0			
Okumu and Berry, 1966 (86)	Canada		All			–1.7							
Touchberry, 1992 (108)	USA	F × G	1	4.3					4.1				
			2	12.0					12.8				
			1 and 2	8.0				1.9	8.5	4.7			
Okumu and Berry, 1966 (86)	Canada		All			1.9							

(continued)

TABLE A.1. (continued) Estimates of heterosis[1] for milk traits of dairy breeds[2] in temperate climates.

		Breeds		Lactation yield (kg)							Content (%)		
Reference	Country	crossed	Lactation	Milk	SCM[3]	FCM[4]	TS[5]	SNF[6]	Fat	Protein	SNF	Fat	Protein
McDowell and McDaniel, 1968 (77)	USA	F × S	1	9.9				10.4	10.4	10.5			
Rincon et al., 1982 (95)	USA		1	7.1	6.9	6.6		7.4	6.5	7.5	0.2	–2.1	0.7
Brandt et al., 1974 (13)	USA		1	5.8		6.3		5.6	6.6	5.4	–0.2	0.7	–0.1
McDowell, 1982 (76)	USA		1	–0.3		1.4			2.7			1.5	
Brade, 1992 (12)	Germany	F × Gbw	1						2.2				
Grosshans et al., 1994 (40)	Germany		1	–0.6					1.4			1.3	
Donald et al., 1977 (24)	England	J × A	1	7.5			7.4				–0.1	0.2	
			2	4.9			4.7				–0.2	–0.2	
Harris, 1994 (43)	New Zealand		All	5.7					6.4	6.1			
Okumu and Berry, 1966 (86)	Canada		All			5.9							
Okumu and Berry, 1966 (86)	Canada	J × G	All			2.4							
McDowell, 1982 (76)	USA	J × S	1	5.6		8.5			10.1			2.8	
Ellinger, 1923 cited by Touchberry, 1992 (108)	Denmark	J × D	1	3.6					4.2			0.0	
Lenschow et al., 1963 cited by Brade, 1992 (12)	Germany	J × Gbw	1	3.9					8.4			0.6	
Witt et al. 1973 cited by Brade, 1992 (12)	Germany		1	3.3					5.6			–2.6	
Brade, 1992 (12)	Germany		1						7.6				
Grosshans et al., 1994 (40)	Germany		1	6.6					8.8			0.7	
Okumu and Berry, 1966 (86)	Canada	A × G	All			8.8							
McDowell and McDaniel, 1968 (77)	USA	A × S	1	–0.7				–0.6	–0.1	–1.7			
Rincon et al., 1982 (95)	USA		1	4.1	3.6	3.7		3.9	3.4	1.7	0.2	–0.6	1.0
Ericson et al., 1988 (32)	Sweden	Sf × Srw	1	1.9		1.9			1.8			0.1	0.1

[1] Heterosis was calculated as [(mean performance of first reciprocal crosses – mean of the parental breeds)/mean of the parental breeds] × 100.

[2] Symbols for breeds are F = Holstein/Friesian, J = Jersey, A = Ayrshire, G = Guernsey, S = Brown Swiss, D = Red Danish, Sf = Swedish Friesian, Srw = Swedish Red and White, and Gbw = German Black and White.

[3] Solids corrected milk, [4] Fat corrected milk, [5] Total solids, [6] Solids nonfat.

TABLE A.2. Estimates of heterosis[1] for lactation characteristics of dairy breeds[2] in temperate climates.

Reference	Country	Breeds crossed	Milk yield (kg) 1st d lactation	Milk yield (kg) Peak daily	Milk yield (kg) 300-d lactation	Peak yield Day	Peak yield No. of days[3]	Persistence (%)	Lactation length (d)	Milking speed[4]
Donald et al., 1977 (24)	England	F × J							–2.5	
Arave et al., 1987 (5)	New Zealand									4.1
McDowell and McDaniel, 1968 (77)	USA	F × A						0.8[a]	–0.1	4.8
Donald et al., 1977 (24)	England								1.2	
Cady and McDowell, 1980 (15)	USA		14.4	8.1	14.4	–3.3	–34.6	0.0[b]		
McDowell and McDaniel, 1968 (77)	USA	F × S						4.1[a]	1.9	6.6
Brandt et al., 1974 (13)	USA							2.2[a]	0.0	
Cady and McDowell, 1980 (15)	USA		2.9	7.8	18.8	11.6	32.0	–6.5[b]		
Donald et al., 1977 (24)	England	J × A							1.3	
McDowell, 1982 (76)	USA	J × S								7.7
McDowell and McDaniel, 1968 (77)	USA	A × S						3.9[a]	–1.4	
Cady and McDowell, 1980 (15)	USA		1.0	4.4	20.0	–2.1	15.4	–10.0[b]		
Ericson et al., 1988 (32)	Sweden	Sf × Srw						0.0[c]		

[1] Heterosis was calculated as [(mean performance of first reciprocal crosses – mean of the parental breeds)/mean of the parental breeds] × 100.

[2] Symbols for breeds are F = Holstein/Friesian, J = Jersey, A = Ayrshire, S = Brown Swiss, Sf = Swedish Friesian, and Srw = Swedish Red and White.

[3] Number days maximum daily deviated ± 1% maximum daily yield.

[4] kg milk/minute for the total period.

[a] Persistency (%) = (milk yield second 150 d)/(milk yield first 150 d) x 100.

[b] Slope of the lactation curve from day 40 to day 300 as estimated from least squares using 10-d weights.

[c] Persistency (%) = (milk yield second 100 d)/(milk yield first 100 d) x 100.

TABLE A.3. Estimates of heterosis[1] (h) and recombination loss[1] (r) for milk traits of crosses between strains and breeds of dairy cattle[2] in temperate climates.

			Lactation yield (kg)						Content (%)			
		Breed	Milk		Fat		Protein		Fat		Protein	
Reference	Country	crossed	h	r	h	r	h	r	h	r	h	r
Boichard et al., 1993 (10)	France	F × Fbw	135	−94	5.6	−4.8	4.3	−1.74	0.12	0.22	0.01	0.16
Akbas et al., 1993 (3)	England	F × Ef	104	−135	4.3	−2.6	2.9	−3.7				
Van der Werf and de Boer, 1989 (110)	The Netherlands	F × Df	123	−101	6.0	−1.3	4.4	−3.5	0.01	0.06	0.00	−0.01
Pedersen and Christensen, 1989 (91)	Denmark	F × A	820	−3208	24.0	−97.0	30.0	−113.0				
Pedersen and Christensen, 1989 (91)	Denmark	F × D	210	−2382	10.0	−77.0	7.0	−83.0				
Pedersen and Christensen, 1989 (91)	Denmark	A × D	486	−1515	22.0	−33.0	20.0	−54.0				
Ericson et al., 1988 (32)	SBP, Sweden	Sf × Srw	105	−25	3.7	−1.0			0.00	0.00	0.02	0.00
Grosshans et al., 1994 (40)	Germany	F × Gbw	−22	−174	2.1	−3.4			0.05	0.06		
Grosshans et al., 1994 (40)	Germany	F × J	93	−179	9.7	−10.1			−0.02	−0.22		
Grosshans et al., 1994 (40)	Germany	J × Gbw	201	144	12.1	−2.8			0.03	−0.25		

[1] Units of estimates of heterosis and recombination loss are in the same units in that the traits are measured.

[2] Symbols for breeds are F = Holstein/Friesian, J = Jersey, A = Ayrshire, D = Red Danish, Sf = Swedish Friesian, Srw = Swedish Red and White, Gbw = German Black and White, Fbw = French Black and White, Ef = European Friesian, and Df = Dutch Friesian.

TABLE A.4. Estimates of heterosis[1] for measurements of biological efficiency of dairy breeds[2] in temperate climates.

Reference	Country	Breeds crossed	Per Mcal ENE intake			Per kg 18-mo LW[3]		Per kg LW
			Mcal milk	kg FCM[4]	SCM[5]	kg milk	kg TS[6]	kg milk
Donald et al., 1977 (24)	England	F × J				–3.5	–3.3	
McDowell, 1982 (76)	USA	F × A	2.5	3.1	1.9			
Donald et al., 1977 (24)	England					7.9	8.2	
McDowell, 1982 (76)	USA	F × S	0.8	0.6	1.3			
Donald et al., 1977 (24)	England	J × A				0.9	0.3	
McDowell and McDaniel, 1968 (77)	USA	A × S	0.0	0.5	0.6			
Witt et al., 1974 (113)	Germany	J × Gbw						–0.5

[1] Heterosis was calculated as [(mean performance of first reciprocal crosses – mean of the parental breeds)/mean of the parental breeds] × 100.

[2] Symbols for breeds are F = Holstein/Friesian, J = Jersey, A = Ayrshire, S = Brown Swiss, and Gbw = German Black and White.

[3] Live weight.

[4] Fat-corrected milk.

[5] Solids-corrected milk.

[6] Total solids.

TABLE A.5. Estimates of heterosis[1] for live weight of dairy breeds[2] in temperate climates.

Reference	Country	Breeds crossed	Live weight (kg) at								Mature
			birth	3-mo	6-mo	12-mo	18-mo	24-mo	30-mo	48-mo	weight (kg)
Donald et al., 1962 (26)	England	F × J	−0.5								
Donald et al., 1977 (24)	England						4.8				
Hilder and Fohrman, 1949 (47)	USA		0.0	2.5	3.3						
Batra et al., 1983 (6)	Canada	F × A	6.0		7.1	5.6	2.7				
Donald et al., 1962 (26)	England		0.3								
Donald et al., 1977 (24)	England						−0.1				
Robison et al., 1980 (98)	USA				3.6	3.1	5.2		4.4		
Lee et al., 1988 (64)	Canada		0.6								
Perotto et al., 1994 (92)	Canada										3.0
McDowell et al., 1969 (80)	USA			1.1	1.2	0.7	4.3	3.7			
McDowell, 1982 (76)	USA		4.3								
Touchberry, 1992 (108)	USA	F × G					5.0	7.0	4.4	5.3	
Shreffler and Touchberry, 1959 (102)	USA			7.2	1.4	4.4	5.4	5.0	3.7	1.0	
Robison et al., 1980 (98)	USA	F × S			1.1	6.3	4.4		2.9		
McDowell et al., 1969 (80)	USA			2.7	4.0	1.8	4.2	3.3			
McDowell, 1982 (76)	USA		1.1								
Christensen et al., 1984 (18)	Denmark	F × D	2.7								
Hilder and Fohrman, 1949 (47)	USA		6.2	2.7	−0.6	3.4	1.0				
Donald et al., 1962 (26)	England	J × A	0.9								
Donald et al., 1977 (24)	England						4.7				
Hilder and Fohrman, 1949 (47)	USA	J × D	3.2	6.0	5.6	5.3	3.4				
Robison et al., 1980 (98)	USA	A × S			4.4	4.5	5.4		3.1		
McDowell et al., 1969 (80)	USA			1.8	4.6	3.9	4.8	3.3			
McDowell, 1982 (76)	USA		3.9								
Christensen et al., 1984 (18)	Denmark	A × D	2.6								

[1] Heterosis was calculated as [(mean performance of first reciprocal crosses – mean of the parental breeds)/mean of the parental breeds] × 100.

[1] Symbols for breeds are F = Holstein/Friesian, J = Jersey, A = Ayrshire, G = Guernsey, S = Brown Swiss, and D = Red Danish.

TABLE A.6. Estimates of heterosis[1] for body measurements of dairy breeds[2] in temperate climates.

Reference	Country	Breeds crossed	Heart girth (cm)			Withers height (cm)			Chest depth (cm)			Withers to pins (cm)		
			6-mo	12-mo	18-mo	6-mo	12-mo	18-mo	6-mo	12-mo	18-mo	6-mo	12-mo	18-mo
Hilder and Fohrman, 1949 (47)	USA	F × J				0.5	0.4	0.8	2.2	0.0	–0.8	3.4	1.8	1.3
Batra et al., 1983 (6)	Canada	F × A	1.9	2.0	1.0	1.3	1.3	1.3		1.4	1.7			
Robison et al., 1980 (98)	USA		1.6	1.3	1.1	0.5	1.6	1.6	1.5	0.5	1.2	1.3	0.7	2.2
Shreffler and Touchberry, 1959 (102)	USA	F × G	0.0	2.0	2.4	0.0	0.9	0.4	0.0	0.9	0.8	0.5	0.0	1.5
Robison et al., 1980 (98)	USA	F × S	0.5	2.0	1.4	0.3	1.7	1.7	0.3	1.9	1.6	0.8	1.3	1.1
Hilder and Fohrman, 1949 (47)	USA	F × D				1.0	0.4	0.4	1.1	0.0	–0.8	2.2	0.9	0.8
Hilder and Fohrman, 1949 (47)	USA	J × D				0.0	0.5	0.0	2.2	0.9	0.8	1.7	1.4	0.9
Robison et al., 1980 (98)	USA	A × S	1.2	0.5	1.5	1.7	1.2	1.2	1.1	1.0	1.5	1.5	0.4	1.8

[1] Heterosis was calculated as [(mean performance of first reciprocal crosses – mean of the parental breeds)/mean of the parental breeds] × 100.

[2] Symbols for breeds are F = Holstein/Friesian, J = Jersey, A = Ayrshire, G = Guernsey, S = Brown Swiss, and D = Red Danish.

TABLE A.7. Estimates of heterosis[1] for reproduction traits of dairy breeds[2] in temperate climates.

Reference	Country	Breeds crossed	Age (d) at			Days from calving to			Services per concep	Calving interval (d)	Gestation length (d)	Dry period (d)
			service	concep[3]	calving	first heat	first service	concep				
Donald et al., 1977 (24)	England	F × J								–3.7		
McDowell and McDaniel, 1968 (77)	USA	F × A			2.7			–15.0				
Donald et al., 1977 (24)	England									–1.6		
Vesely et al., 1986 (111)	Canada						–1.3		5.9	–0.9	–0.2	
McDowell et al., 1970 (81)	USA					3.1		–5.9				
Touchberry, 1992 (108)	USA	F × G	–2.1	1.7	1.1		1.0	9.4	12.8	3.3		12.7
McDowell and McDaniel, 1968 (77)	USA	F × S			2.7			–11.6				
Brandt et al., 1974 (13)	USA				–1.2			–21.7				
McDowell et al., 1970 (81)	USA					–0.8		–9.4				
Christensen et al., 1984 (18)	Denmark	F × D						0.0		0.1	0.5	
Donald et al., 1977 (24)	England	J × A								–1.7		
McDowell and McDaniel, 1968 (77)	USA	A × S			0.4			–4.2				
McDowell et al., 1970 (81)	USA					9.1		0.4				
Christensen et al., 1984 (18)	Denmark	A × D						–7.2		–1.3	–2.3	
Ericson et al., 1988 (32)	Sweden	Sf × Srw			1.1			1.2				

[1] Heterosis was calculated as [(mean performance of first reciprocal crosses – mean of the parental breeds)/mean of the parental breeds] × 100.

[2] Symbols for breeds are F = Holstein/Friesian, J = Jersey, A = Ayrshire, G = Guernsey, S = Brown Swiss, D = Red Danish, Sf = Swedish Friesian, and Srw = Swedish Red and White.

[3] Conception.

TABLE A.8. Estimates of heterosis[1] for fitness traits of dairy breeds[2] in temperate climates.

Trait	Breeds crossed								Reference	Country
	F × J	F × A	F × G	F × S	F × D	J × A	A × S	A × D		
Calving difficulty (scale 1=easy to5=difficult)					9.4			3.1	Christensen et al., 1984 (18)	Denmark
Incidence rate of dystocia		11.5		–68.7			61.9		McDowell and McDaniel, 1968 (78)	USA
	–13.7								Ahlborn-Breier, 1989 (1)	New Zealand
Perinatal survival, %	15.5	8.2				2.7			Donald, 1963 (23)	England
					–2.8			–1.4	Christensen et al., 1984 (18)	Denmark
Survival rate from birth to										
1 wk		0.8							Lin et al., 1982 (68)	Canada
9 wk		3.1							Lin et al., 1982 (68)	Canada
3 mo		3.2							Lin et al., 1982 (68)	Canada
6 mo		4.1							Lin et al., 1982 (68)	Canada
12 mo		5.2							Lin et al., 1982 (68)	Canada
first calving		10.1							Lin et al., 1982 (68)	Canada
			15.6						Touchberry, 1992 (108)	USA
		15.8		40.7			16.2		McDowell and McDaniel, 1968 (78)	USA
end of first lactation		6.0							Hocking et al., 1988 (49)	Canada
second calving		12.5							Hocking et al., 1988 (49)	Canada
Percentage of cows that										
calved once			18.4						Touchberry, 1992 (108)	USA
calved twice			24.5						Touchberry, 1992 (108)	USA
Median herd life, d		9.8							Hocking et al., 1988 (50)	Canada
Infection rate from birth to first calving		–15.8		–40.7			–20.8		McDowell and McDaniel, 1968 (78)	USA
Incidence rate of mastitis		7.0		47.0			–6.9		McDowell and McDaniel, 1968 (78)	USA
Infection rate during first lactation		46.7		38.5			18.8		McDowell and McDaniel, 1968 (78)	USA

[1] Heterosis was calculated as [(mean performance of first reciprocal crosses – mean of the parental breeds)/mean of the parental breeds] × 100.

[2] Symbols for breeds are F = Holstein/Friesian, J = Jersey, A = Ayrshire, G = Guernsey, S = Brown Swiss, and D = Red Danish.

REFERENCES

1 Ahlborn-Breier, G. 1989. Crossbreeding - an opportunity to increase farm income. Dairyfarm. Annu., Massey Univ. 41:23-43.

2 Ahlborn-Breier, G., and W. D. Hohenboken. 1991. Additive and nonadditive genetic effects on milk production in dairy cattle: evidence for major individual heterosis. J. Dairy Sci. 74:592-602.

3 Akbas, Y., S. Brotherstone, and W. G. Hill. 1993. Animal model estimation of non additive genetic parameters in dairy cattle, and their effect on heritability estimation and breeding value prediction. J. Anim. Breed. Genet. 110:105-113.

4 Allaire, F. R., H. E. Sterwerf, and T. M. Ludwick. 1977. Variations in removal reasons and culling rates with age for dairy females. J. Dairy Sci. 60:254-267.

5 Arave, C. W., K. L. Macmillan, and R. Kilgour. 1987. Milking characteristics of Friesian, Jersey, and Friesian-Jersey crossbreds in eleven New Zealand dairy herds. N. Z. J. Exp. Agric. 15:33-37.

6 Batra, T. R., A. J. McAllister, A. J. Lee, C. Y. Lin, G. L. Roy, J. A. Vesely, J. Wauthy, and K. A. Winter. 1983. Body weights and dimensions of pureline and crossline heifers of the Canadian dairy cattle breeding project. Can. J. Anim. Sci. 63:511-522.

7 Black, N. 1981. Design of selection programs for dairy cattle. Proc. Aust. Assoc. Anim. Breed. Genet. 2:78-81.

8 Blake, R. W. 1979. Research needs to supply milk protein in the human diet. J. Dairy Sci. 62:1963-1977.

9 Blake, R. W., and A. A. Custodio. 1984. Feed efficiency: a composite trait of dairy cattle. J. Dairy Sci. 67:2075-2083.

10 Boichard, D., B. Bonaiti, and A. Barbat. 1993. Effect of Holstein crossbreeding in the French Black and White cattle population. J. Dairy Sci. 76:1157-1162.

11 Bourdon, R. M. 1997. Understanding Animal Breeding. Prentice Hall, Upper Saddle River, NJ.

12 Brade, W. 1992. Crossbreeding effects in the development of the synthetic black and white (SMR) dairy cattle in East Germany. Livest. Prod. Sci. 32:203-218.

13 Brandt, G. W., C. C. Brannon, and W. E. Johnston. 1974. Production of milk and milk constituents by Brown Swiss, Holstein and their crossbreds. J. Dairy Sci. 57:1388-1393.

14 Burnside, E. B., S. K. Kowalchuk, D. B. Lambroughton, and N. M. MacLeod. 1971. Canadian dairy cows disposal. I. Difference between breeds, lactation numbers, and seasons. Can. J. Anim. Sci. 51:75-83.

15 Cady, R. A., and R. E. McDowell. 1980. Persistency and other lactation parameters in crossbred dairy cattle. J. Dairy Sci. 63(Suppl. 1):111.(Abstr.)

16 Cartwright, T. C. 1970. Selection criteria for beef cattle for the future. J. Anim. Sci. 30:706-711.

17 Cartwright, T. C. 1974. Net effects of genetic variability on beef production systems. Genetics 78:541-561.

18 Christensen, L. G., R. Barlow, and A. Neiman-Sørensen, A. 1984. Crossbreeding Red Danish, Holstein-Friesian and Finnish Ayrshire cattle. Acta Agric. Scand. 34:463-479.

19 Cockerham, C. C. 1980. Random and fixed effects in plant genetics. Theor. Appl. Genet. 56:119-131.

20 Cunningham, E. P. 1982. The genetic basis of heterosis. Proc. 2nd World Congr. Genet. Appl. Livest. Prod., Madrid, Spain VI:190-205.

21 Dickerson, G. E. 1969. Experimental approaches in utilising breed resources. Anim. Breed. Abstr. 37:191-202.

22 Dickerson, G. E. 1973. Inbreeding and heterosis in animals. Pages 54-77 *in* Proc. Anim. Breeding Genet. Symp. in Honor of Dr. J. L. Lush, Am. Soc. Anim. Sci., Am. Dairy Sci. Assoc., Champaign, IL.

23 Donald, H. P. 1963. Perinatal deaths among calves in a crossbred dairy herd. Anim. Prod. 5:87-95.

24 Donald, H. P., D. Gibson, and W. S. Russell. 1977. Estimations of heterosis in crossbred dairy cattle. Anim. Prod. 25:193-208.

25 Donald, H. P., and W. S. Russell. 1968. Some aspects of fertility in purebred and crossbred dairy cattle. Anim. Prod. 10:465-471.

26 Donald, H. P., W. S. Russell, and St. C. S. Taylor. 1962. Birth weights of reciprocally cross-bred calves. J. Agric. Sci. 58:405-412.

27 Eberhart, S. A., and C. O. Gardner. 1966. A general model for genetic effects. Biometrics 22:864-881.

28 Eisen, E. J., G. Hörrstgen-Schwark, A. M. Saxton, and T. R. Bandy. 1983. Genetic interpretation and analysis of diallel crosses with animals. Theor. Appl. Genet. 65:17-23.

29 Elzo, M. A. 1986. Inverse of single trait additive genetic covariance matrix with unequal variances across additive genetic groups. J. Dairy Sci. 69:569-574.

30 Elzo, M. A. 1990. Covariances among sire by breed group of dam interaction effects in multibreed sire evaluation procedures. J. Anim. Sci. 68:4079-4099.

31 Elzo, M. A., and D. L. Wakeman. 1998. Covariance components and prediction for additive and nonadditive preweaning growth genetic effects in an Angus-Brahman multibreed herd. J. Anim. Sci. 76:1290-1302.

32 Ericson, K., B. Danell, and J. Rendel. 1988. Crossbreeding effects between two Swedish dairy breeds for production traits. Livest. Prod. Sci. 20:175-192.

33 Falconer, D. S. 1989. Introduction to Quantitative Genetics. Longman, Harlow, U.K.

34 Fewson, D. 1974. Crossbreeding in farm animals. Pages 107-126 *in* Proc. Working Symp. on Breed Evaluation and Crossing Experiments with Farm Animals, Zeist, The Netherlands.

35 Fimland, E. A. 1975. Estimation of sire's breeding value. II. Procedure for estimation of crossbreeding parameters in regular A.I. breeding scheme. Z. Tierz. Zuechtungsbiol. 92:1-9.

36 Gardner, C. O., and S. A. Eberhart. 1966. Analysis and interpretation of the variety crossdiallel and related populations. Biometrics 22:439-452.

37 Gartner, J. A. 1982. Replacement policy in dairy herds on farms where heifers compete with the cow for grassland- part 3: a revised hypothesis. Agric. Syst. 8:249-272.

38 Gibson, J. P. 1986. Efficiency and performance of genetically high and low milk-producing British Friesian and Jersey cattle. Anim. Prod. 42:161-182.

39 Griffing, B. 1956. Concept of general and specific combining ability in relation to diallel crossing systems. Aust. J. Biol. Sci. 9:463-493.

40 Grosshans, T., O. Distl, G. Seeland, and J. Wolf. 1994. Estimation of individual cross-breeding effects on milk production traits of the German Black Pied dairy cattle using different genetic models. J. Anim. Breed. Genet. 111:472-492.

41 Grossman, M., A. L. Kuck, and H. W. Norton. 1986. Lactation curves of purebred and crossbred dairy cattle. J. Dairy Sci. 69:195-203.

42 Harris, B. L. 1989. New Zealand dairy cow removal reasons and survival rate. N. Z. J. Agric. Res. 32:355-358.

43 Harris, B. L. 1994. Hybrid vigour effect in first cross. N. Z. Dairy Exp. 69:27.

44 Harris, B. L., J. M. Clark, and R. G. Jackson. 1996. Across breed evaluation of dairy cattle. Proc. N. Z. Soc. Anim. Prod. 56:12-15.

45 Henderson, C. R. 1973. Sire evaluation and genetic trends. Pages 10-41 *in* Proc. Anim. Breeding Genet. Symp. in Honor of Dr. J. L. Lush, Am. Soc. Anim. Sci., Am. Dairy Sci. Assoc., Champaign, IL.

46 Henderson, C. R. 1977. Prediction of the merits of single crosses. Theor. Appl. Genet. 49:273-282.

47 Hilder, R. A., and M. H. Fohrman. 1949. Growth of first-generation crossbred dairy calves. J. Agric. Res. 78:457-469.

48 Hill, W. G. 1982. Dominance and epistasis as components of heterosis. Z. Tierz. Zuechtungsbiol. 99:161-168.

49 Hocking, P. M., A. J. McAllister, M. S. Wolynetz, T. R. Batra, A. J. Lee, C. Y. Lin, G. L. Roy, J. A. Vesely, J. M. Wauthy, and K. A. Winter. 1988. Factors affecting culling and survival during rearing and first lactation in purebred and crossbred dairy cattle. Anim. Prod. 46:1-12.

50 Hocking, P. M., A. J. McAllister, M. S. Wolynetz, T. R. Batra, A. J. Lee, C. Y. Lin, G. L. Roy, J. A. Vesely, J. M. Wauthy, and K. A. Winter. 1988. Factors affecting length of herdlife in purebred and crossbred dairy cattle. J. Dairy Sci. 71:1011-1024.

51 Holmes, C. W., G. F. Wilson, W. Kuperus, S. Buvaneshwa, and B. W. Wickham. 1993. Liveweight, feed intake and feed conversion efficiency of lactating dairy cows. Proc. N. Z. Soc. Anim. Prod. 53:95-99.

52 Holmes, C. W., G. F. Wilson, D. D. S. MacKenzie, D. S. Flux, I. M. Brookes, and A. W. F. Davey. 1987. Milk Production from Pasture. Butterworth Agric. Books, Wellington, New Zealand.

53 Jakubec, V., and J. Hyánek. 1982. Quantitative analysis of components of hybridization. Livest. Prod. Sci. 9:639-651.

54 Janick, J., C. H. Noller, and C. L. Rhykerd. 1976. The cycles of plant and animal nutrition. Sci. Amer. 235(3):75-86.

55 Kempthorne, O. 1957. An introduction to genetic statistic. John Wiley, New York, NY.

56 Kinghorn, B. P. 1980. The expression of "Recombination loss" in quantitative traits. Z. Tierz. Zuechtungsbiol. 97:138-143.

57 Kinghorn, B. P. 1982. Genetic effects in crossbreeding. I. Models of merit. Z. Tierz. Zuechtungsbiol. 99:59-68.

58 Kinghorn, B. P. 1982. Genetic effects in crossbreeding. II. Multibreed selection indices. Z. Tierz. Zuechtungsbiol. 99:315-320.

59 Kinghorn, B. P. 1987. The nature of 2-locus epistatic interaction in animals: evidence from Sewall Wright's Guinea pig data. Theor. Appl. Genet. 73:595-604.

60 Koch, R. M., G. E. Dickerson, L. V. Cundiff, and K. E. Gregory. 1985. Heterosis retained in advanced generations of crosses among Angus and Hereford cattle. J. Anim. Sci. 60:1117-1132.

61 Komender, P. 1988. Crossbreeding in farm animals. III. A general method of comparing models to estimate crossbreeding parameters with an application to diallel crossbreeding experiments. J. Anim. Breed. Genet. 105:362-371.

62 Komender, P., and I. Hoeschele. 1989. Use of mixed-model methodology to improve estimation of crossbreeding parameters. Livest. Prod. Sci. 21:101-113.

63 L'Huillier, P. J., C. R. Parr, and A. M. Bryant. 1988. Comparative performance and energy metabolism of Jersey and Friesian in early-mid lactation. Proc. N. Z. Soc. Anim. Prod. 38:321:325.

64 Lee, A. J., C. Y. Lin, A. J. McAllister, K. A. Winter, G. L. Roy, J. A. Vesely, J. M. Wauthy, T. R. Batra, and A. S. Atwal. 1988. Growth and feed efficiency of pureline and crossline dairy heifers. J. Dairy Sci. 71:1000-1010.

65 Leitch, H. W. 1994. Comparison of international selection indices for dairy cattle. in Proc. INTERBULL Annu. Mtg., Ottawa, Canada. Bull. No. 10. INTERBULL, Uppsala, Sweden.

66 Liinamo, A. -E., and J. A. M. Van Arendonk. 1998. Combining selection for carcass quality and milk traits in dairy cattle. Proc. 6th World Congr. Genet. Appl. Livest. Prod., Armidale, Australia 25:387-390.

67 Lin, C. 1972. Analysis of diallel crosses between two groups where parental lines are included. Biometrics 28:612-618.

68 Lin, C. Y., A. J. McAllister, T. R. Batra, A. J. Lee, G. L. Roy, J. A. Vesely, and K. A. Winter. 1982. Comparison of purebred and crossbred heifer reproduction and disposal. J. Dairy Sci. 65(Suppl. 2):91.(Abstr.)

69 Livestock Improvement. 1997. Economic Survey of Factory Supply Dairy Farmers 1996-1997. Livestock Imp. Corp. Ltd., Hamilton, New Zealand.

70 Mackle, T. R., C. R. Parr, G. K. Stakelum, A. M. Bryant, and K. L. Macmillan. 1996. Feed conversion efficiency, daily pasture intake, and milk production of primiparous Friesian and Jersey cows calved at two different liveweights. N. Z. J. Agric. Res. 39:357-370.

71 Madgwick, P. A., and M. E. Goddard. 1989. Comparison of purebred and crossbred dairy cattle for Victoria: estimation of genetic effects for yield. Aust. J. Exp. Agric. 29:1-7.

72 Maijala, K., and M. Hanna. 1974. Reliable phenotypic and genetic parameters in dairy cattle. Proc. 1st World Congr. Genet. Appl. Livest. Prod., Madrid, Spain 1:541-563.

73 Mather, K., and J. L. Jinks. 1971. Biometrical Genetics. Chapman and Hall, London, U. K.

74 McAllister, A. J. 1986. The role of crossbreeding in breeding programs for intensive milk production in temperate climates. Proc. 3rd World Congr. Genet. Appl. Livest. Prod., Lincoln, NE IX:47-61.

75 McAllister, A. J., A. J. Lee, T. R. Batra, C. Y. Lin, G. L. Roy, J. A. Vesely, J. M. Wauthy, and K. A. Winter. 1994. The influence of additive and nonadditive gene action on lifetime yields and profitability of dairy cattle. J. Dairy Sci. 77:2400-2414.

76 McDowell, R. E. 1982. Crossbreeding as a System of Mating for Dairy Production. Bull. No. 259, Southern Coop. Ser. Baton Rouge, LA.

77 McDowell, R. E., and B. T. McDaniel. 1968. Interbreed matings in dairy cattle. I. Yield traits, feed efficiency, type and rate of milking. J. Dairy Sci. 51:767-777.

78 McDowell, R. E., and B. T. McDaniel. 1968. Interbreed matings in dairy cattle. II. Herd health and viability. J. Dairy Sci. 51:1275-1283.

79 McDowell, R. E., and B. T. McDaniel. 1968. Interbreed matings in dairy cattle. III. Economic aspects. J. Dairy Sci. 51:1649-1648.

80 McDowell, R. E., G. V. Richardson, R. P. Lehmann, and B. T. McDaniel. 1969. Interbreed matings in dairy cattle. IV. Growth rate of two-breed crosses. J. Dairy Sci. 52:1624-1632.

81 McDowell, R. E., G. V. Richardson, B. E. Mackey, and B. T. McDaniel. 1970. Interbreed matings in dairy cattle. V. Reproductive performance. J. Dairy Sci. 53:757-763.

82 Metzger, J. S., L. B. Hansen, H. D. Norman, C. W. Wolfe, and J. Pedersen. 1994. Comparison of United States and Danish strains of Jersey for yield traits. J. Dairy Sci. 77:1457-1465.

83 Moav, R. 1966. Specialised sire and dam lines. I. Economic evaluation of crossbreds. Anim. Prod. 8:193-202.

84 Nagai, J., and A. J. McAllister. 1982. Expected performance under repeated hybrid male cross and crisscross mating systems. Theor. Appl. Genet. 61:177-182.

85 O'Bleness, G. V., and L. D. Van Vleck. 1962. Reasons for disposal of dairy cows from New York herds. J. Dairy Sci. 45:1087-1093.

86 Okumu, C., and J. C. Berry. 1966. Studies of milk production in crossbred dairy cattle. East Afr. Agric. For. J. 32:163-174.

87 Oldenbroek, J. K. 1986. The performance of Jersey heifers and heifers of larger dairy breeds on two complete diets with different roughage contents. Livest. Prod. Sci. 14:1-14.

88 Oldenbroek, J. K. 1988. The performance of Jersey cows and cows of larger dairy breeds on two complete diets with different roughage contents. Livest. Prod. Sci. 18:1-17.

89 Oltenacu, P. A., A. Frick, and B. Lindhé. 1990. Evaluation of production, fertility and health traits in progeny of Swedish Friesian, North American Holstein and FriesianxHolstein crossbred sires. Proc. 4th World Congr. Genet. Appl. Livest. Prod., Edinburgh, Scotland 14:95-98.

90 Pearson, L., and R. E. McDowell. 1968. Crossbreeding of dairy cattle in temperate zones: a review of recent studies. Anim. Breed. Abstr. 36:1-15.

91 Pedersen, J., and L. G. Christensen. 1989. Heterosis for milk production traits by crossing Red Danish, Finnish Ayrshire and Holstein Friesian cattle. Livest. Prod. Sci. 23:253-266.

92 Perotto, D., R. I. Cue, A. J. Lee, A. J. McAllister, T. R. Batra, C. Y. Lin, G. L. Roy, and J. M. Wauthy. 1994. Additive and non additive genetic effects of growth curve parameters of Holstein Ayrshire and crossbred females. J. Anim. Sci. 74:401-409.

93 Powell, R. L., H. D. Norman, and F. N. Dickinson. 1977. Trends in breeding value and production. J. Dairy Sci. 60:1316-1326.

94 Quaas, R. L., R. D. Anderson, and A. R. Gilmour. 1984. BLUP School Handbook - Use of Mixed Models for Prediction and Estimation of (Co)Variance Components. Anim. Breed. Genet. Unit, Univ. New England, Australia.

95 Rincon, E. J., E. C. Shermerhorn, R. E. McDowell, and B. T. McDaniel. 1982. Estimation of genetic effects on milk yield and constituent traits in crossbred dairy cattle. J. Dairy Sci. 65:848-856.

96 Robertson, A. 1949. Crossbreeding experiments with dairy cattle. Anim. Breed. Abstr. 17:201-208.

97 Robertson, A. 1971. Optimum utilization of genetic material with special reference to crossbreeding in relation to other methods of genetic. Pages 57-67 *in* Proc. 10th Int. Congr. Anim. Prod., Paris and Versailles, France.

98 Robison, O. W., M. G. Kelly, B. T. McDaniel, and R. E. McDowell. 1980. Genetic parameters of body size in purebred and crossbred dairy cattle. J. Dairy Sci. 63:1887-1899.

99 Robison, O. W., B. T. McDaniel, and E. J. Rincon. 1981. Estimation of direct and maternal additive and heterotic effects from crossbreeding experiments in animals. J. Anim. Sci. 52:44-50.

100 Searle, S. R. 1971. Linear models. John Wiley and Sons, New York, NY.

101 Sheridan, A. K. 1981. Crossbreeding and heterosis. Anim. Breed. Abstr. 49:131-144.

102 Shreffler, D. C., and R. W. Touchberry. 1959. Effects of crossbreeding on rate of growth in dairy cattle. J. Dairy Sci. 42:607-620.

103 Smith, C. 1964. Use of specialised sire and dam lines in selection for meat production. Anim. Prod. 6:337-344.

104 Stenske, M., O. Distl, T. Grosshans, and G. Seeland. 1998. Effects of crossbreeding on production traits in German Black Pied dairy cattle. Proc. 6th World Congr. Genet. Appl. Livest. Prod., Armidale, Australia 23:395-398.

105 Swan, A. A. 1992. Multibreed evaluation procedures. Ph.D. Thesis, Univ. New England, Australia.

106 Swan, A. A., and B. P. Kinghorn. 1992. Evaluation and exploitation of crossbreeding in dairy cattle. J. Dairy Sci. 75:624-639.

107 Taylor, St. C. S., A. J. Moore, and R. B. Thiessen. 1986. Voluntary food intake in relation to body weight among British breeds of cattle. Anim. Prod. 42:11-18.

108 Touchberry, R. W. 1992. Crossbreeding effects in dairy cattle: the Illinois experiment, 1949 to 1969. J. Dairy Sci. 75:640-667.

109 Turton, J. D. 1981. Crossbreeding of dairy cattle-a selective review. Anim. Breed. Abstr. 49:293-300.

110 Van der Werf, J. H. J., and W. de Boer. 1989. Estimation of genetic parameters in a crossbred population of black and white dairy cattle. J. Dairy Sci. 72:2615-2623.

111 Vesely, J. A., A. J. McAllister, A. J. Lee, T. R. Batra, C. Y. Lin, G. L. Roy, J. M Wauthy, and K. A. Winter. 1986. Reproductive performance of crossbred and purebred dairy cows. J. Dairy Sci. 69:518-526.

112 Wallace, L. R. 1956. The relationship of size and yield to efficiency of cows. Proc. Ruakura Farmers' Conf. 8:177-186.

113 Witt, M., E. Werhahn, and U. E. Pfleiderer. 1974. Results of a long-term crossbreeding trial with German Black Pie and Jersey cattle. Part 2. Anim. Breed. Abstr. 42:6.(Abstr.)

114 Wolf, J., O. Distl, J. Hyanek, T. Grosshans, and G. Seeland. 1995. Crossbreeding in farm animals. V. Analysis of crossbreeding plans with secondary crossbred generations. J. Anim. Breed. Genet. 112:81-94.

115 Wood, P. D. P. 1967. Algebraic model of the lactation curve in cattle. Nature (Lond.) 216:164-165.

116 Zarnecki, A., H. D. Norman, M. Gierdziewicz, and J. Jamrozik. 1993. Heterosis for growth and yield traits from crosses of Friesian strains. J. Dairy Sci. 76:1661-1670.

Chapter 3

Profitabilities of some mating systems for dairy herds in New Zealand

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ABSTRACT

The aim of this study was to evaluate the profitability of dairy herds under three mating systems involving the Holstein-Friesian, Jersey and Ayrshire breeds. Mating systems were straightbreeding and rotational crossbreeding using two or three breeds. A deterministic model was developed to simulate the nutritional, biological and economic performances of dairy herds under New Zealand conditions. Expected performances per cow were obtained using estimates of breed group and heterotic effects, age effects and herd age distribution. Dry matter feed requirements per cow were estimated for maintenance, lactation, pregnancy and growth of the replacements. Stocking rate was calculated by assuming 12,000 kg dry matter annually utilised per hectare. Productivity per hectare was calculated as performance per cow multiplied by stocking rate. Profitability was the difference between income (sale of milk and salvage animals) and costs (related to the number of cows in the herd and the land area farmed). Under current market values for milk and meat, all the rotational crossbred herds showed superior profitability to the straightbred herds (Holstein-Friesian × Jersey, NZ$505/ha; Holstein-Friesian × Jersey × Ayrshire NZ$493/ha; Jersey × Ayrshire, NZ$466/ha; Holstein-Friesian × Ayrshire, NZ$430/ha; Jersey, NZ$430/ha; Holstein-Friesian, NZ$398/ha; Ayrshire, NZ$338/ha). Changes in the value for fat relative to protein affected profitability more significantly in herds using the Jersey breed, whereas changes in the value for meat affected profitability more significantly in herds using the Holstein-Friesian and Ayrshire breeds. Results suggest that, under New Zealand conditions, the use of rotational crossbreeding systems can increase profitability of dairy herds under the conceivable market conditions.

(**Key words:** dairy cattle, crossbreeding, profitability, heterosis)

Abbreviation key: **A** = Ayrshire, **APF** = age-production factor, **F** = Holstein-Friesian, **J** = Jersey, **LW** = live weight, **LWG** = LW gain, **ME** = metabolisable energy.

INTRODUCTION

The New Zealand dairy industry comprised 3.1 million cows distributed in 14,741 herds for the 1996-97 season. The breed structure of the national herd was 57% Holstein-Friesian (**F**), 16% Jersey (**J**), 18% crossbred F × J, 2% Ayrshire (**A**) and 7% other dairy breeds and their crosses (16). The average dairy farm was 86 ha with 208 lactating cows grazing on mainly ryegrass-clover pastures, at 2.42 cows/ha.

Reports on crossbreeding in New Zealand dairy cattle (3, 13) showed evidence of favourable heterosis for yields of milk, fat and protein, and for live weight (**LW**) and cow survival. Studies in other countries (7, 8, 11, 19, 21, 24, 30) have also reported favourable heterosis for viability, reproductive and productive performances of dairy cows.

Straightbred herds produce their own replacements from mating the cows to bulls of the same breed, whereas a first generation cross (F_1) is produced from the mating of a straightbred cow to a straightbred bull of another breed. The F_1 contains 50% of genes of the two parental breeds and expresses 100% of the individual heterosis. Ideally the entire herd should be composed of these F_1 animals, however, such a herd can not produce its own replacements.

One approach for exploiting heterosis in a self-replacing herd is by rotational crossbreeding. Straightbred bulls of different breeds are mated to crossbred cows from alternate generations. In a two-breed rotation with Holstein-Friesian and Jersey (**FJ**) starting with a J herd, cows are mated to F bulls to produce F_1 F × J cows. Half of the F_1 cows are mated to F bulls to produce 3/4 F 1/4 J cows and the other half are mated to J bulls to produce 1/4 F 3/4 J cows. Next, 3/4 F 1/4 J cows are mated to J bulls and 1/4 F 3/4 J cows are mated to F bulls. After three more generations, half of the herd will be 2/3 F 1/3 J and the other half will be 1/3 F 2/3 J. This strategy maintains 67% of the heterosis expressed by the F_1 (6). Similar approaches can be followed for two-breed rotation with Holstein-Friesian and Ayrshire (**FA**) and with Jersey and Ayrshire (**JA**).

In a three-breed rotation with Holstein-Friesian, Jersey and Ayrshire (**FJA**) starting with an A herd, cows are mated to J bulls to produce F_1 J × A cows. These F_1 cows are mated to F bulls to produce 2/4 F 1/4 J 1/4 A which will be mated to A bulls to produce 2/8 F 1/8 J 5/8 A and so on. After several generations the herd will be composed of three groups of animals: 4/7 F 2/7 J 1/7 A, 2/7 F 1/7 J 4/7 A and 1/7 F 4/7 J 2/7 A. This strategy maintains 86% of the F_1 heterosis (6).

Only a few studies (22, 25, 30) have shown crossbreeding to result in sufficient heterosis to provide greater economic returns than the best of existing breeds. Ayrshire × Holstein, Brown Swiss × Holstein and Holstein × (Ayrshire × Brown Swiss) cows had higher returns over costs for feed, health, animal losses and dry cow maintenance than Holstein cows up to the end of the first lactation (25), and herds using a two-breed rotation between Ayrshire and Holstein were 3.2% more profitable than straightbred herds (22). The purpose of the present study was to evaluate the effects of different mating systems on the profitability of New Zealand dairy herds.

MATERIALS AND METHODS

A deterministic model was developed to simulate, on an annual basis, the nutritional, biological and economic performance of dairy herds, using three breeds (F, J and A), and three mating systems (straightbreeding or rotational crossbreeding with either two- or three-breeds). Herds using rotational crossbreeding were assumed to be at equilibrium with respect to cow breed composition.

The herds, including replacements, were grazed on ryegrass-clover pasture during the whole year. The cows calved in early spring, produced milk for only 225 d during the period of rapid pasture growth, and were dried off before winter, the period of slow pasture growth (14).

Herd Structure

The herd had 11 age classes: 0 (rising 1 yr old), 1 (rising 2 yr old), and 2 to 10 (cows in first to ninth lactation). Cows first calved at 24 mo and maintained an average calving interval of 12 mo. Cows were artificially inseminated 8 wk using semen from straightbred sires. After this period, a bull was used for natural service of nonpregnant cows for a further 4-wk period. Heifers were artificially inseminated for a 3-wk period, followed by natural mating for 10 wk. At the end of the mating period, 90% of the animals were pregnant, with 80% of the cows and 30% of the heifers pregnant to artificial insemination.

The proportion (d_j) of the herd in each age class j (j = 0 to 10) was derived from probabilities of survival for each age class. The proportions of animals in age classes 0 and 1 were calculated as $d_0 = d_1/s_0$ and $d_1 = d_2/s_1$, respectively, where s_0 = probability of survival from birth up to 1 yr, calculated as 1 minus the proportion of rising 1 yr olds culled for death, diseases and sales of surplus heifers; and s_1 = probability of survival from 1 up to 2 yr calculated as 1 minus the proportion of rising 2 yr olds culled for death, diseases and infertility. The proportion of the herd in older age classes (j = 2 to 10) was derived using Markov chains (4):

$$d_j = \prod_{i=2}^{j} s_i \Big/ \sum_{k=2}^{10} \prod_{i=2}^{k} s_i \, .$$

where si = probability of a cow surviving from age i to age i + 1 (i = 2 to 10), shown in Table 1. Cows remaining in the herd after 11 yr were sold for slaughter.

Causes of wastage among young replacements and cows were sorted into five categories: deaths, diseases (including mastitis, bloat, metabolic problems and facial eczema), poor fertility (including nonpregnant and abortions), age and suitability for dairying (including low production, type and temperament). Culling rates for each cause of wastage were derived from Harris (12) and Holmes et al. (14).

TABLE 1. Estimated breed additive effects for lactation yields of milk, fat and protein; live weight, and survival for Holstein-Friesian (F), Jersey (J), and Ayrshire (A) dairy cattle in New Zealand (Livestock Improvement, 1997, unpublished data).

	Age class, yr								
	2	3	4	5	6	7	8	9	10
Milk, L per cow									
F	4014	3982	3911	3862	3831	3758	3740	3730	3709
J	3186	3128	3081	3005	2971	2935	2947	2981	2977
A	3716	3649	3624	3601	3571	3516	3504	3494	3477
Fat, kg per cow									
F	180.5	178.6	176.8	175.3	174.5	173.0	171.2	170.6	169.5
J	170.1	168.6	165.2	165.2	164.6	162.8	160.1	159.3	158.1
A	164.2	162.8	161.7	160.3	159.9	158.5	157.3	156.3	155.3
Protein, kg per cow									
F	142.1	140.3	139.1	137.9	136.7	133.9	132.2	131.7	131.5
J	125.3	122.5	120.6	119.5	119.0	117.4	116.5	117.4	116.9
A	133.1	131.0	130.3	129.6	128.7	126.9	126.2	125.9	125.0
Live weight, kg per cow									
F	496.0	494.7	494.6	491.3	489.4	486.7	488.0	485.0	484.9
J	407.9	407.0	406.2	404.3	406.1	406.6	413.7	415.2	415.6
A	456.4	453.6	453.6	455.3	454.8	452.7	452.6	452.9	453.1
Survival, %									
F	0.84	0.84	0.84	0.81	0.77	0.73	0.68	0.63	...
J	0.89	0.88	0.86	0.83	0.79	0.75	0.70	0.63	...
A	0.87	0.86	0.82	0.83	0.81	0.74	0.70	0.63	...

Mortality rates were 4, 3 and 1.4% in rising 1 yr old, rising 2 yr old and mixed age cows, respectively. Culling rates for diseases were 1, 1 and 3.4% for rising 1 yr old, rising 2 yr old and mixed age cows, respectively, and 8% of all age-groups were culled for failure to conceive. The difference between survival rate and the sum of culling for deaths, diseases, poor fertility and age were culled because they were unsuitable for dairying.

It was assumed that 50% of calves born were male and that 96% survived to sale. Female calves that were not needed as herd replacements were sold for beef at the same value per kg of carcass as that for male calves.

The heterotic effects for survival (Table 2) may be due to several reasons including heterosis for fertility, resistance to diseases, reduced mortality and the ability of the cow to delay culling for low production, unsuitable type and temperament. In the absence of data for heterotic effects for these traits in New Zealand dairy cattle, it was assumed that heterosis for survival was caused by heterosis for fertility (40%), resistance to diseases (30%) and voluntary culling (30%).

An age-production factor (**APF**) for each herd was calculated as the weighted average of the age adjustment factors (f_j) for milk component yields:

$$\mathrm{APF} = \left(\sum_{j=2}^{10} f_j \times d_j\right) / \sum_{j=2}^{10} d_j .$$

Multiplicative age adjustment factors for milk component yields were: 0.75, 0.87, 0.95, 1.0, 0.97 and 0.92 for lactations 1, 2, 3, 4 to 7, 8 and 9, respectively. These factors were calculated from age production averages reported by Livestock Improvement (16), adjusted for genetic trends.

TABLE 2. Estimates of heterotic effects for lactation milk yields and live weight of crossbred Holstein-Friesian (F), Jersey (J) and Ayrshire (A) cows in New Zealand (Livestock Improvement, 1997, unpublished data).

First	Trait				
cross	Milk	Fat	Protein	Live weight	Survival
	(L)	(kg)			(%)
F × J	137	7.7	5.2	7.7	4.9
F × A	77	3.5	2.8	0.3	2.9
J × A	156	8.4	5.9	9.9	4.7

Cow Performance

Expected performance (EP) of cows for milk, fat and protein was simulated over the production year (calving to calving). The EP of animals of age class j (j = 2 to 10) for any trait was calculated as:

$$\mathbf{EP}_j = (\mathbf{q}_o' \, \mathbf{a}_j + \mathbf{q}_s' \mathbf{H} \mathbf{q}_d)\mathbf{f}_j$$

where:

$\mathbf{a}_j$ = vector of order 3 of breed additive effects (F, J and A) for the age class j.

$\mathbf{q}_s$, $\mathbf{q}_d$ and $\mathbf{q}_o$ = vectors of order 3, with their elements representing the proportion of F, J and A genes for the sire, dam and offspring, respectively.

$\mathbf{H}$ = a symmetric matrix of order 3 × 3, with diagonal elements being zero and off-diagonal elements being the F_1 heterotic effects.

f_j = multiplicative age adjustment factor for age class j.

The vector $\mathbf{q}_o$ was derived as $\mathbf{q}_o = (\mathbf{q}_s + \mathbf{q}_d)/2$.

Estimates of breed additive (Table 1) and heterosis (Table 2) effects for milk, fat and protein for each age class were obtained from the genetic evaluation of New Zealand dairy cattle (Livestock Improvement, 1997, unpublished data). The genetic evaluation of New Zealand dairy cattle utilises a single trait repeatability animal model fitted across breeds (13). The model includes the fixed effects of contemporary group, heterosis, month of calving, induced lactation class[a], maternal breed, genetic group, and the random effects of additive genetic value, permanent environment and residual error.

LW

The LW at age t in days (W_t) was calculated using the von Bertanlanffy equation as given by Bakker and Koops (5):

$$W_t = W_m\{1-[1-(W_0 / W_m)^{1/3}]e^{-kt}\}^3$$

where W_m = mature LW, W_0 = birth weight, k = constant related to rate of maturing and e = base of the natural logarithm. Using ratios of birth weight and 24-mo weight to mature weight of 0.078 and 0.814 (9) respectively, the von Bertanlanffy equation was reparameterized for each breed group. The LW of crossbreds were proportional to the mean values for straightbreds plus the fraction of F_1 heterosis.

Energy and Dry Matter Requirements

Pasture was assumed to contain 18.4 MJ gross energy and 10.5 MJ metabolisable energy (ME) per kg dry matter (DM) (14). The corresponding metabolisability of the pasture at maintenance (q_m) was calculated at 0.57. The efficiencies of utilisation of ME were calculated as defined in AFRC (1):

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[a] In some herds late pregnant cows are injected with a hormone preparation to induce early parturition in order to maintain a compact seasonal pattern of calving.

Efficiency for maintenance	$k_m = 0.35\ q_m + 0.503$
Efficiency for lactation	$k_l = 0.35\ q_m + 0.420$
Efficiency for growth of lactating cows	$k_g = 0.95\ k_l$
Efficiency for growth of growing replacements	$k_f = 0.78\ q_m + 0.006$
Efficiency for growth of concepta	$k_c = 0.133$.

Cow maintenance. The ME required for maintaining (ME_m) cows was calculated in 1-mo periods within the production year as follows: Fm (MJ/d) = $30.5\ \{0.53\ (W_t/1.08)^{0.67}\}$, Ac (MJ/d) = $0.016W_t$ and $ME_m = (Fm + Ac)/k_m$, where Fm = fasting metabolism requirements, Ac = energy required for activity calculated for cows walking 3 km and grazing pasture (1) and W_t = average weight over the 1-mo period.

Cow growth. Live weights were predicted over 1-mo intervals from 24 to 132 mo (11 yr) of age. The LW gains (**LWG**) of growing lactating cows were assumed to be linear between adjacent monthly weights. Metabolisable energy required for growing lactating cows was calculated as: $ME_g = (LWG \times EV_g)/k_g$, were EV_g = energy value of 1 unit of LWG calculated as (1): EV_g (MJ/kg) = $\{1.3\ (4.1 + 0.0332\ W_t - 0.000009\ W_t^2)\}/\{1 - 0.1475\ LWG\}$.

Cow gestation. Gestation length was assumed at 280 d for all breeds (14). Requirement of ME to maintain pregnancy (ME_c) was scaled to a 40.0 kg calf birth weight as follows (1): EV_c (MJ/d) = $0.025\ W_0\ (E_t\ 0.0201\ e^{-0.0000576t})$ and $MEc = EV_c/k_c$, where EV_c = retained energy in the fetus and E_t = total energy retention at day t of gestation derived from $\log_{10} E_t$ (MJ/d) = $151.665 - 151.64\ e^{-0.0000576t}$.

Cow lactation. The net energy value of milk (EV_l) was predicted for each age class using the formula of Tyrrell and Reid (31). This equation was EV_l (MJ) = 37.6 Fy + 20.9 Py + 0.948 My where Fy, Py and My are the expected performance for fat, protein and milk, respectively, for each age class. The requirements of ME for lactation was determined as ME_l (MJ) = EV_l/k_l. Cows which died or were culled were credited with 85% and 93% (15) of the total lactation yield. No comparable estimates were available for New Zealand dairy cattle.

The total requirements of ME (ME_{total}) were adjusted for feeding level (1) as:

$$ME_{total}\ (MJ) = \{1 + 0.018\ (FL - 1)\} \times \{ME_m + ME_g + ME_c + ME_l\}$$

where FL is the level of feeding as a multiple of ME_m.

Calf requirements. All new born calves were fed colostrum during the 1st d of life and milk and meal during the following 60 d. Subsequently, pasture was the only source of feed. Gross energy density of meal was assumed at 18.6 MJ/kg DM. Values of q_m for milk and meal were 0.85 and 0.7, respectively. Energy requirements for maintenance and LWG (ME_{mp}) for replacements were adjusted for feeding level (1). Live weights were predicted over 1-mo intervals from birth to 24 mo of age, and LWG were assumed to be linear between adjacent weights. Energy retained as LWG (E_f) was scaled to the energy required for maintenance (E_m) as $R = E_f/E_m$ where E_f and E_m were calculated as E_f (MJ/d) = LWG × $1.1EV_g$ and $E_m = Fm + Ac$ where $Ac = 0.007W_t$. ME_{mp} was calculated as ME_{mp} (MJ/d) = $(Fm/k_r) \times \ln \{B/(B - R - 1)$ where $k_r = k_m \times \ln (k_m/k_f)$ and $B = k_m/(k_m - k_f)$. Energy requirements to support pregnancy for rising 2 yr old heifers were added.

Each calf was assumed to eat 20 kg DM of meal during the first 60 d of life. Requirements of milk were calculated as the difference between the total energy required and the energy supplied by the meal. The quantities of milk, fat and protein fed to calves was accounted for in determining the sale value for milk produced by the herd.

Total herd requirements for ME were calculated as:

$$ME_{herd} = \sum_{j=0}^{10} ME_{total,j} \times d_j$$

and requirements for DM were calculated dividing ME_{herd} by the content of ME per kg pasture DM. It was assumed that animals could at all times consume the pasture needed to meet their specified energy demands. Requirement for DM per cow, including DM for growing of replacements, was calculated by dividing the total requirements for DM of the whole herd by the number of cows older than 2 yr old.

Stocking Rate

Under New Zealand conditions, about 15,000 kg DM/ha is produced by ryegrass-clover pastures growing on fertile soils, and about 80% or 12,000 kg DM/ha is harvested by the animals. Stocking rate, defined as the number of cows grazing per hectare, was calculated as 12,000 kg DM divided by the total DM required per cow (including the DM required for the replacements). This calculation assumes that the number of animals grazed per hectare was adjusted to meet the DM requirements, which in turn are determined by the production levels of the animals.

Economic Analysis

Economic analysis was based on average values of marketable products and costs of a New Zealand dairy farm. Profitability was measured as net income per hectare calculated from gross income minus production costs.

Income. Income was derived from the sale of milk and disposed animals plus NZ$17/ha from other sources. The current payment system of New Zealand is based on an index combining volume (litres) and milk components (kilograms) as follows: (NZ$2.72 × fat) + (NZ$5.91 × protein) – (NZ$0.041 × milk). New Zealand exports 90% of its dairy produce, therefore, values for milk, fat and protein are sensitive to the price for which milk products are sold to the international market. A sensitivity analysis was undertaken using lower (1:4) and higher (4:1) values for the ratio of fat to protein (Table 3) with the same milk value per litre. The ratio 1:2.2 corresponds to the values paid to farmers in the season 1996-97.

TABLE 3. Values of fat (kilograms), protein (kilograms) and milk (litres) for different ratios of fat value to protein value.

Fat to protein ratio	Fat	Protein	Milk
	(NZ$)		
1:4	1.78	7.12	–0.041
1:2.2[1]	2.72	5.91	–0.041
4:1	6.12	1.53	–0.041

[1] Current.

Beef income was derived from the sale of male calves, surplus female calves and culled rising 2 yr old and older cows. Carcass yield for calves and rising 2 yr old were assumed at 50 and 53%, respectively. Live weights of disposed animals were determined using the von Bertanlanffy equation. The following equations were used to estimate carcass yield (CY) of culled cows (23): F cows, $CY = 0.41 + 0.000208\ W_t$; J cows, $CY = 0.39 + 0.000208\ W_t$; and A cows, $CY = 0.40 + 0.000208\ W_t$. The carcass yields for crossbreds were proportional to straightbred means according to their breed composition. No heterotic effects for carcass yield were included. The value of disposed animals depended on a schedule of prices shown in Table 4. A sensitivity analysis was undertaken for an increase of 50% in the carcass value of disposed animals (Table 4).

Production costs. Average farm production costs were taken from Livestock Improvement (17) and included both direct expenses and overheads. Direct expenses per cow were: labour, NZ$190; animal health, NZ$46; breeding and herd testing, NZ$28; farm dairy expenses, NZ$17; electricity, NZ$21; freight, NZ$8; and others, NZ$6. Direct expenses per hectare were: pasture renovation, NZ$20; fertiliser, NZ$299; weed and pest control, NZ$16. Overheads per hectare were: repairs and maintenance, NZ$152; vehicle expenses, NZ$118; administration, NZ$69; standing charges, NZ$176; and depreciation, NZ$221. Additional costs (meal, labour, animal health and breeding) for rising 1 yr and 2 yr olds were NZ$93 and NZ$82 per animal, respectively. Capital costs for cows and replacements were included as the cost of borrowing capital at 12%

interest. Values of rising 1 yr olds were: F, NZ$364; J, NZ$327; and A, NZ$346. Values of rising 2 yr olds were: F, NZ$704; J, NZ$651; and A, NZ$678. Values of cows (CV) were calculated from the following equations: F, $CV = 916 - 48\ X_l$; J, $CV = 889 - 61\ X_l$; and A, $CV = 901 - 53.4\ X_l$, where X_l is the number of lactations.

TABLE 4. Values of disposed livestock.

Type of animal and carcass weight	Value for beef	
	Current	High[1]
	(NZ$/kg of carcass)	
Male and female calves		
<13.5 kg	1.12	1.68
13.5 to 18.5 kg	1.17	1.76
>18.5	1.46	2.19
Rising 2 yr old		
<195 kg	1.07	1.61
195 to 220 kg	1.18	1.77
220 to 245 kg	1.35	2.03
245 to 270 kg	1.41	2.12
>270 kg	1.47	2.21
Cows		
<220 kg	1.18	1.77
220 to 245 kg	1.25	1.88
245 to 270 kg	1.31	1.97
>270 kg	1.32	1.98

[1] High value of carcass was obtained by increasing the current values by 50%.

RESULTS

Replacement Rates

The FJ, JA and FJA herds had the lowest replacement rate (18.6, 18.6 and 18.7%, respectively). The J herd had a lower replacement rate (19.6%) than the F and A herds (21.9% and 20.9%). The replacement rate of the FA crossbred herd was 20.1%. The APFs for FJ, JA and FJA herds were 0.920, slightly higher than for F (0.910), J (0.917), A (0.913) and FA (0.915) herds.

Productive Performance

Performances per cow and per hectare of different herds are shown in Table 5. For LW, and milk and protein yield per cow, the F herd ranked highest, and the J herd ranked lowest. The FJ herd ranked highest for fat yield per cow, with LW higher than the average of the F and J herds. Herds that included the J breed had small cows producing high fat yields in low volumes of milk.

The FA herd ranked highest for milk production per hectare followed by the FJA, A, FJ, JA and J herds. The J herd had the highest fat production per hectare whereas the F and A herds had the lowest fat production per hectare. The FJA and JA crossbred herds ranked highest for protein production per hectare followed by the FJ, J, FA, A and F herds.

Dry Matter Requirements and Stocking Rate

Total DM requirements for each herd, expressed per cow, are shown in Table 5, together with the amounts required for maintenance, lactation, pregnancy, LWG and replacements. The J herd had the lowest total DM requirement and the highest stocking rate, whereas the F herd had the highest total DM requirements and the lowest stocking rate. The A herd had values which were intermediate between F and J herds. The JA herd had lower DM requirements and higher stocking rates than all other herds except the J herd.

TABLE 5. Dry matter requirements, stocking rates and production of milk and milk components per cow and per hectare for the different herds[1].

	Straightbreeds			Two- and three-breed rotations			
	F	J	A	FJ	FA	JA	FJA
Live weight, kg	481	399	445	446	464	428	448
Production per cow							
Milk, L/yr	3402	2706	3172	3161	3350	3037	3217
Fat, kg/yr	154	147	142	156	151	149	154
Protein, kg/yr	121	107	114	118	120	114	118
Dry matter requirements per cow							
Maintenance, kg/yr	1867	1635	1764	1774	1820	1721	1778
Lactation, kg/yr	1838	1636	1702	1799	1803	1724	1794
Replacements, kg/yr	956	673	820	737	835	696	735
Pregnancy and LWG[2], kg/yr	321	255	291	285	302	273	286
Total, kg/yr	4982	4199	4577	4595	4760	4414	4593
Stocking rate, cows/ha	2.41	2.86	2.62	2.61	2.52	2.72	2.61
Production per hectare							
Milk, L/yr	8194	7733	8318	8257	8447	8257	8405
Fat, kg/yr	371	419	371	408	380	406	402
Protein, kg/yr	291	305	299	308	302	310	310

[1] F = Holstein-Friesian, J = Jersey, and A = Ayrshire.

[2] Live weight gain.

The DM required for lactation divided by the total DM requirements provides a measure of biological efficiency. The values for the J, FJ, JA and FJA herds were 39.0, 39.1, 39.1 and 39.1%, respectively, which were slightly higher than those for F, A and FA herds (36.9, 37.2 and 37.9%, respectively).

Economic Analysis

Production costs and incomes per cow and per hectare of different herds are shown in Table 6. The F herd had the highest milk income (NZ$993), beef income (NZ$82) and production costs (NZ$917) per cow, whereas the J herd had the lowest milk income (NZ$920), beef income (NZ$54) and production costs (NZ$829) per cow. The A and crossbred herds were intermediate between the F and J herds.

Net income per hectare is a more important measurement of economic efficiency than is net income per cow for New Zealand dairy farmers. The FJ herd had the highest net income per hectare (NZ$505) followed by the FJA (NZ$493), JA (NZ$466), J (NZ$430), FA (NZ$430), F (NZ$398), and A (NZ$338) herds.

The profitability of the herds under different market values for beef and different values for the fat to protein ratio are presented in Table 7. A 50% increase in the value for beef caused increases in net income per hectare which were higher for the F (NZ$100) than for the FA (NZ$92), A (NZ$88), FJA (NZ$83), FJ (NZ$82) and J (NZ$72) herds.

With a high value for fat and a low value for protein (ratio 4:1) the FJ herd ranked highest for net income per hectare (NZ$548) followed by the J (NZ$521), FJA (NZ$507), JA (NZ$490), FA (NZ$403), F (NZ$389) and A (NZ$293) herds. With a low value for fat and a high value for protein (ratio 1:4), net income per hectare was higher for all crossbred herds than for the straightbred herds, with the FJ and FJA herds being highest. A change in the fat to protein value ratio from 1:2.2 (current) to 1:4 slightly increased net income per hectare for A (NZ$13), FA (NZ$8) and F (NZ$3) herds, but slightly reduced net income per hectare for the J (NZ$25), FJ (NZ$12), JA (NZ$6) and FJA (NZ$3) herds.

TABLE 6. Gross and net income and production costs per cow and per hectare for the different herds[1].

	Straightbreeds			Two- and three-breed rotations			
	F	J	A	FJ	FA	JA	FJA
Incomes and costs per cow							
Milk income, NZ$/yr	993	920	929	992	980	956	987
Beef income, NZ$/yr	82	54	66	63	73	57	63
Gross income, NZ$/yr	1082	979	1001	1061	1060	1019	1056
Production costs, NZ$/yr	917	829	872	868	889	848	868
Net income, NZ$/yr	165	150	129	193	171	171	189
Incomes and costs per hectare							
Milk income, NZ$/yr	2392	2629	2436	2591	2471	2599	2578
Beef income, NZ$/yr	198	153	173	164	184	155	164
Gross income, NZ$/yr	2607	2799	2626	2772	2671	2772	2760
Production costs, NZ$/yr	2209	2369	2288	2267	2241	2305	2267
Net income, NZ$/yr	398	430	338	505	430	466	493

[1] F = Holstein-Friesian, J = Jersey, and A = Ayrshire.

TABLE 7. Average farm net income for different herds[1] with different values for beef and ratios of fat value to protein value (4:1, 1:2.2 and 1:4).

Value for beef	Straightbreeds			Two- and three-breed rotations			
	F	J	A	FJ	FA	JA	FJA
	(NZ$/ha)						
Current							
4:1	389	521	293	584	403	490	507
1:2.2[2]	398	430	338	505	430	466	493
1:4	401	405	351	493	438	460	490
High[3]							
1:2.2	498	502	426	587	522	540	576

[1] F = Holstein-Friesian, J = Jersey, and A = Ayrshire.

[2] Current ratio of fat value to protein value.

[3] The values for disposed animals were 50% higher than the current values.

DISCUSSION

Estimates of additive breed and heterotic effects for survival, LW and yields of milk and its components assumed in this model were obtained from the genetic evaluation of New Zealand dairy cattle under an animal model fitted across breeds (Livestock Improvement, 1997, unpublished data). These values agree with those reported previously in New Zealand (3, 13) and elsewhere for breeds in temperate climates (7, 8, 11, 19, 21, 24, 30).

Heterosis for survival increased the profitability of crossbred herds in two ways. First, replacement rates for crossbred herds (except for the FA herd) were lower than for straightbred herds, therefore, crossbred herds had more animals available for sale and less replacements required for rearing. Second, the proportions of mature animals in crossbred herds (except for the FA herd) were slightly higher than in straightbred herds, resulting in higher yields for milk, fat and protein from crossbred herds than straightbred herds due to an age effect.

Ahlborn-Breier and Hohenboken (3) calculated expected fat yields for cows of different proportions of F and J breeds. The F_1 F × J cows produced 5.0 kg and 15.5 kg more fat than F and J cows, respectively, similar to the present results (Table 5). Heterotic effects caused the FJ herd to produce higher fat yields per cow than the F and J herds. The joint combination of heterosis and breed effects for milk, LW and survival caused the FA herd to produce the highest milk production per hectare whereas the JA and FJA herds produced the highest protein yields per hectare.

Experimental results in New Zealand (2) indicate that F produce higher yields of milk, fat and protein per cow, whereas J produce higher yields of fat and protein per hectare when both breeds were stocked at the same LW. These findings were confirmed in the present study. The F herd produced 696 L more milk, 7 kg more fat and 14 kg more protein per cow than J herd, but the J herd produced 48 kg more fat and 14 kg more protein per hectare than the F herd when both herds consumed 12,000 kg DM per hectare (Table 5).

Biological efficiency per cow (DM for lactation as a proportion of total DM) was higher for herds using the J breed than for herds using the F or A breeds. These results agree with experimental comparisons between J and F (18), and J and Friesians (10, 27, 28).

Stocking rate was calculated so that the total amount of DM required by all cattle to achieve the expected performance of the animals of the herd was equal to 12,000 kg DM/ha. Hence, in this study, stocking rate was the consequence rather than the cause of feeding levels, whereas in practice and at least over a reasonable range of stocking rates, an increase in stocking rate causes a decrease in pasture intake and production per cow but an increase in production per hectare (2, 14). This difference may affect the interpretation of the present results.

The LW of cows is important in the grazing production system because it affects the stocking rate and profitability of the dairy farm through its effects on feed requirements for maintenance and value of disposed animals. The DM requirements for maintenance and for the growth of replacements for the J herd were lower than for the other herds (Table 5). Consequently, the J herd had a lower DM intake per cow and higher stocking rate than the other herds. The current value for disposed animals was low and, therefore, beef income per hectare was a low percentage of gross income per hectare, ranging from 5.5% (J herd) to 7.6% (F herd). The combination of low DM for maintenance and low value for beef resulted in the smaller cows having higher net income per hectare than bigger cows, in agreement with results for beef cattle (26) in which small animals were more profitable than bigger animals for a fixed resource area.

Some of the production costs were defined on a per hectare basis and some on a per cow basis. Herds with a higher number of animals per hectare, therefore, have lower production costs per cow than herds with a lower number of animals per hectare, because the costs per hectare are invariable to the number of cows per hectare. This is the case of J herds compared to F herds. The J herd ranked lowest for production costs per cow (NZ$829), F herd ranked highest (NZ$917) and A and crossbred herds were intermediate. However, herds with a higher stocking rate (J) had higher production costs per hectare (NZ$2369) than those with lower a stocking rate (F, NZ$2209).

Results from this study confirm the conclusion that crossbreeding among two or more dairy breeds must be judged on a number of traits, mainly those related to viability, reproductive and productive performances (25). The FJ had the highest profitability per hectare (Table 7). Direct comparison between the net returns estimated in this study and those of McAllister et al. (22), McDowell and McDaniel (25), and Touchberry (30) may be difficult for the following reasons: 1) in this study profit was expressed on a per hectare basis, whereas for the other studies profit was expressed on a per cow basis and not all production costs were included in the evaluation, and 2) in this study, milk income was calculated from a formula that rewards fat and protein but penalises volume, whereas in the other studies milk income was calculated from a formula which rewards volume and fat. However, results from all the studies suggest that crossbreeding can increase net farm returns.

The genetic evaluation of New Zealand dairy cattle enables cows to be compared in terms of production worth, which is the sum of production values (breeding value plus permanent environment effect plus average heterosis effect) for fat, protein, milk and LW each weighted by their corresponding economic value. Economic values for fat, protein and herd survival are positive, whereas economic values for milk (volume) and LW are negative (13, 16, 29). Results from the genetic evaluation (13, 16) indicate that average production worths for crossbred F × J cows are higher than those for F, J and A cows, in agreement with the findings in the present study.

The most profitable dairy animal under a given production circumstance may not necessarily be the best in other circumstances (25). The present sensitivity analyses showed that the effect of increased value for beef animals was more significant in the herds using F and A breeds than in herds using J breed (Table 7). A decrease in the value of fat and an increase in the value of protein caused a decrease in the net income per hectare for all the herds using the J breed, but an increase for the F, A and FA herds (Table 7). Nevertheless the FJ and the FJA herds had the highest net incomes for all three fat to protein value ratios. It seems likely that the value of protein relative to fat will continue to increase in the future as world demand and markets for protein expand (20), which will favour rotational crossbreeding between F and J, and perhaps A also.

In the development of the model, herds using rotational crossbreeding were assumed to be at equilibrium with respect to cow breed composition. In the FJ herd, for example, half of the cows were assumed to be 2/3 F 1/3 J and the other half were assumed to be 1/3 F 2/3 J. In practice, this equilibrium would be difficult to achieve because it will take at least seven generations (28 to 32 yr) starting with a straightbred F or J herd. Therefore, results obtained in this study for rotational crossbred herds would be different if equilibrium is not assumed.

The widespread implementation of a rotational crossbreeding strategy in the New Zealand dairy industry would require the availability of straightbred bulls of high genetic for the production of semen. Cows available for selection as mothers of young bulls are known as active cows, which may be registered (pedigree) or not registered (grade) animals provided that they are the result of at least three generations of artificial breeding to sires of one breed. The adoption of crossbreeding might reduce the rate of genetic gain by reducing the number of active cows. Therefore, in the long term, a balance between crossbreeding and selection needs further study.

CONCLUSIONS

The results of this simulation study indicate that crossbred cows are more productive and can be more profitable than straightbred cows. Dairy herds with F_1 F × J cows should be considered as a major option to utilise the benefits of heterosis and breed resources. However, the real challenge is to establish breeding programs that retain the merits of the F_1. Rotational crossbreeding would be the best option for New Zealand commercial dairy farmers. This requires controlled mating, which is possible given the present status of artificial insemination and recording in the dairy industry.

REFERENCES

1 AFRC. 1993. Energy and Protein Requirements of Ruminants. An Advisory Manual Prepared by the AFRC Technical Committee on Response to Nutrients. CAB Int., Wallingford, United Kingdom.

2 Ahlborn, G., and A. M. Bryant. 1992. Production, economic performance and optimum stocking rates of Holstein-Friesian and Jersey cows. Proc. N. Z. Soc. Anim. Prod. 52:7-9.

3 Ahlborn-Breier, G., and W. D. Hohenboken. 1991. Additive and nonadditive genetic effects on milk production in dairy cattle: evidence for major individual heterosis. J. Dairy Sci. 74:592-602.

4 Azzam, S. M., A. M. Azzam, M. K., Nielsen, and J. E. Kinder. 1990. Markov chains as a shortcut method to estimate age distributions in herds of beef cattle under different culling strategies. J. Anim. Sci. 68:5-14.

5 Bakker, H., and W.J. Koops. 1978. An approach to the comparison of growth curves of Dutch Friesian, British Friesian and Holstein Friesian cows. Pages 705-715 *in* Patterns of Growth and Development in Cattle. H. de Boer and J. Martin, ed. Martin Nijhoff Publ., The Hague, The Netherlands.

6 Dickerson, G. E. 1969. Experimental approaches in utilising breed resources. Anim. Breed. Abstr. 37:191-202.

7 Donald, H. P., D. Gibson, and W. S. Russell. 1977. Estimations of heterosis in crossbred dairy cattle. Anim. Prod. 25:193-208.

8 Ericson, K., B. Danell, and J. Rendel. 1988. Crossbreeding effects between two Swedish dairy breeds for production traits. Livest. Prod. Sci. 20:175-192.

9 Garcia-Muñiz J. G., C. W. Holmes, D. J. Garrcik, N. Lopez-Villalobos, B. W. Wickham, G. F. Wilson, I. M. Brookes, and R. W. Purchas. 1998. Growth curves and productivity of Holstein-Friesian cows bred for heavy or light mature live weight. Proc. N. Z. Soc. Anim. Prod. 58:68-72.

10 Gibson, J. P. 1986. Efficiency and performance of genetically high and low milk-producing British Friesian and Jersey cattle. Anim. Prod. 42:161-182.

11 Grosshans, T., O. Distl, G. Seeland, and J. Wolf. 1994. Estimation of individual cross-breeding effects on milk production traits of the German Black Pied dairy cattle using different genetic models. J. Anim. Breed. Genet. 111:472-492.

12 Harris, B. L. 1989. New Zealand dairy cow removal reasons and survival rate. N. Z. J. Agric. Res. 32:355-358.

13 Harris, B. L., J. M. Clark, and R. G. Jackson. 1996. Across breed evaluation of dairy cattle. Proc. N. Z. Soc. Anim. Prod. 56:12-15.

14 Holmes, C. W., G. F. Wilson, D. D. S. MacKenzie, D. S. Flux, I. M. Brookes, and A. W. F. Davey. 1987. Milk Production from Pasture. Butterworth Agric. Books, Wellington, New Zealand.

15 Keller, D. S., and F. R. Allaire. 1990. Economic weights for genetic changes in milk component yields at the herd level. J. Dairy Sci. 73:1631-1643.

16 Livestock Improvement. 1997. Dairy Statistics 1996-1997. Livestock Imp. Corp. Ltd., Hamilton, New Zealand.

17 Livestock Improvement. 1997. Economic Survey of Factory Supply Dairy Farmers 1996-1997. Livestock Imp. Corp. Ltd., Hamilton, New Zealand.

18 Mackle, T. R., C. R. Parr, G. K. Stakelum, A. M. Bryant, and K. L. Macmillan. 1996. Feed conversion efficiency, daily pasture intake, and milk production of primiparous Friesian and Jersey cows calved at two different liveweights. N. Z. J. Agric. Res. 39:357-370.

19 Madgwick, P. A., and M. E. Goddard. 1989. Comparison of purebred and crossbred dairy cattle for Victoria: estimation of genetic effects for yield. Aust. J. Exp. Agric. 29:1-7.

20 Marshall, K. R. 1992. The value of different components in 2002. Dairyfarm. Annu. 44:107-110.

21 McAllister, A. J. 1986. The role of crossbreeding in breeding programs for intensive milk production in temperate climates. Proc. 3rd World Congr. Genet. Appl. Livest. Prod., Lincoln, NE IX:47-61.

22 McAllister, A. J., A. J. Lee, T. R. Batra, C. Y. Lin, G. L. Roy, J. A. Vesely, J. M. Wauthy, and K. A. Winter. 1994. The influence of additive and nonadditive gene action on lifetime yields and profitability of dairy cattle. J. Dairy Sci. 77:2400-2414.

23 McCall, D. G., and P. R. Marshall. 1991. Factors affecting beef finishing efficiency on pasture. Proc. N. Z. Soc. Anim. Prod. 51:453-457.

24 McDowell, R. E. 1982. Crossbreeding as a system of mating for dairy production. Bull. No. 259, Southern Coop. Ser. Baton Rouge, LA.

25 McDowell, R. E., and B. T. McDaniel. 1968. Interbreed matings in dairy cattle. III. Economic aspects. J. Dairy Sci. 51:1649-1658.

26 Melton, B. E., W. A. Colette, K. J. Smith, and R. L. Willham. 1994. A time-dependent bioeconomical model of commercial beef breed choices. Agric. Syst. 45:331-347.

27 Oldenbroek, J. K. 1986. The performance of Jersey heifers and heifers of larger dairy breeds on two complete diets with different roughage contents. Livest. Prod. Sci. 14:1-14.

28 Oldenbroek, J. K. 1988. The performance of Jersey cows and cows of larger dairy breeds on two complete diets with different roughage contents. Livest. Prod. Sci. 18:1-17.

29 Spelman, R. J., and D. J. Garrick. 1997. Effect of live weight and differing economic values on responses to selection for milk fat, protein, volume, and live weight. J. Dairy Sci. 80:2557-2562.

30 Touchberry, R. W. 1992. Crossbreeding effects in dairy cattle: the Illinois experiment, 1949 to 1969. J. Dairy Sci. 75:640-667.

31 Tyrrell, H. F., and J. T. Reid. 1965. Prediction of the energy value of cow's milk. J. Dairy Sci. 48:1215-1223.

Chapter 4

Effects of selection and crossbreeding on long-term rates of genetic gain in New Zealand dairy cattle

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ABSTRACT

A deterministic model was developed to evaluate the concurrent effects of selection and crossbreeding on the rate of genetic gain and productivity of New Zealand dairy cattle over 25 yr. Selection was based on an index which included live weight and lactation yields of milk, fat and protein. Mating strategies involving the Holstein-Friesian, Jersey and Ayrshire breeds were evaluated. Effects of heterosis and age were included to calculate live weight and yields of milk, fat and protein per cow. Feed requirements were estimated for maintenance, lactation, pregnancy and for replacement heifers. Stocking rate was calculated assuming 12,000 kg DM utilised annually per hectare. Upgrading to either Jersey or Holstein-Friesian increased the number of potential bull mothers and resulted in genetic gains of 0.27 genetic SD/yr, for both options. Rotational crossbreeding Holstein-Friesian × Jersey decreased the number of potential bull mothers and resulted in a genetic gain of 0.24 genetic SD/yr. Upgrading to Jersey resulted in the smallest increase in milk (5%), and the biggest increase in fat (16%) and protein (27%) per hectare, with a small decrease in stocking rate (0.4%). Upgrading to Holstein-Friesian reduced stocking rate by 11% and increased production of milk, fat and protein per hectare by 10%, 8% and 27%, respectively. Rotational crossbreeding Holstein-Friesian × Jersey, resulted in productions per hectare above the intermediate productions between upgrading to Jersey and upgrading to Holstein-Friesian. Crossbreeding can be used in combination with selection to exploit the effects of heterosis while maintaining genetic diversity to cover changes in marketing conditions.
(**Key words:** selection, crossbreeding, genetic gain, productivity)

Abbreviation key: **A** = Ayrshire, **AB** = artificial breeding, **BW** = breeding worth, **F** = Holstein-Friesian, **J** = Jersey, **PW** = production worth, **UBB** = use of the best bulls, **UPGA** = upgrading to A, **UPGF** = upgrading to F, **UPGJ** = upgrading to J.

INTRODUCTION

The New Zealand dairy industry comprised 3.1 million cows distributed in 14,741 herds for the season 1996-97 (19). The breed structure of the national herd was 57% Holstein-Friesian (**F**), 16% Jersey (**J**), 18% crossbred F × J, 2% Ayrshire (**A**) and 7% other dairy breeds and their crosses (19). Artificial insemination was used in 84% of the cows with F, J and A semen in proportions of 62, 33 and 5%, respectively. Mating records showed that dairy farmers were using crossbreeding, with 18% and 2% of F cows inseminated with J and A semen, and 13% and 3% of J cows inseminated with F and A semen (19). Between 1994 and 1996, the use of J semen increased from 26 to 33%, whereas the use of F semen decreased from 70 to 63%, and the use of A semen remained static at 4%.

In the pastoral system of New Zealand, milk production per hectare is a very important determinant of farm profit and therefore management practices focus on utilisation of the pasture. Annual pasture yields can exceed 15,000 kg dry matter (DM) per hectare with about 80% of pasture (12,000 kg DM/ha) actually utilised for milk production. The average dairy farm is 86 hectares, with 208 lactating cows grazing on mainly ryegrass-clover pastures, at 2.42 cows per hectare (19).

Genetic evaluation of New Zealand dairy cattle is across breeds, with a single trait repeatability animal model (13). Breeding values for live weight and lactation yields of milk, fat, protein are obtained for all animals and production values (breeding value plus permanent environment effect plus average heterosis effect) are generated for cows. Animals to be parents of the next generation can be selected across breeds on an index which is a measure of net income per 4.5 tonnes DM consumed. The index is termed breeding worth (**BW**), and is calculated as the sum of the breeding values for live weight, survival and lactation yields of milk, fat and protein, each weighted by an economic value. Cows can also be compared in terms of production worth (**PW**) which is the sum of production values for fat, protein, milk and live weight, each weighted by their corresponding economic value. Economic values used in BW and PW differ and are assessed using an economic model of a pastoral New Zealand farm enterprise (12).

Results from the genetic evaluation show that J animals currently have higher average BW values than F and A animals (13, 19) and that F × J cows have higher average PW values than cows of the other breeds. These results might encourage farmers to use more J semen, with the aim of upgrading the herd to the Jersey breed (**UPGJ**), or to use semen of the best bulls (**UBB**) irrespective of breed to produce herd replacements. Alternatively, two- or three-breed rotational crossbreeding might be exploited to harness both additive and heterotic effects.

For each of the three straightbred populations the selection schemes use four pathways of selection (21), namely, cows to breed cows, cows to breed bulls, bulls to breed cows and bulls to breed bulls. Cows available for selection as bull mothers are referred to as active cows. Active cows may be registered (pedigree) or nonregistered (grade) animals, provided they are the result of at least 3 generations of artificial breeding (**AB**) to sires of one breed (20). Active F, J and A cows represented only 4.9%, 3.7% and 0.3% of the total cow population (B. L. Harris, 1997, personal communication). Studies in New Zealand (23) have found that the size of the active cow population has a significant effect on the rate of genetic gain, and on net farm income of the dairy farmer.

One unique feature of the New Zealand dairy industry is the use of fresh semen rather than frozen semen. The use of fresh semen has reduced the number of sperm required per dose from 20 million used with frozen semen to 2 million or less (24) and this enables many more inseminations to be achieved per proven bull than would be possible with frozen semen. A single bull can be mated to more than 200,000 cows in a 2-mo mating season (24). This enables high selection intensity on the bull to cow pathway allowing one of the fastest rates of genetic gain of any progeny testing and AB scheme in the world (6).

Genetic evaluation across breeds would allow crossbreeding strategies to be superimposed on the classical four pathway dairy breeding system (27). Swan and Kinghorn (27) suggested two alternatives: either using crossbreeding in non-elite matings only, or using crossbreeding in both elite and non-elite matings. In the first alternative, there is a reduction in selection intensity for bull mothers because of the proportionally smaller pool of straightbred candidates. In the latter strategy, increased selection differentials are realised as crossbreed cows are now candidates for selection as bull mothers. According to the definition of an active cow in the New Zealand dairy industry, only the first alternative is applicable. One objective of the present study was to evaluate the effect of some crossbreeding strategies on the availability of bull mothers and the resulting rate of genetic gain for the next 25 yr in the New Zealand dairy industry. The other objective was to predict the averages values for live weight and milk production per cow, and milk production per hectare of the national herd if the dairy industry used crossbreeding in combination with selection for 25 yr.

MATERIALS AND METHODS

A model was developed to simulate the annual events of selection, mating, herd growth and production of the New Zealand national herd for the next 25 yr. The modelling program is dynamic, deterministic and discrete-event oriented. The model starts with the creation of the base animals defined according to the number of generations of AB, breed, age class and genetic merit. A set of genetic and phenotypic parameters and economic values are supplied to construct a selection index, and to calculate the standard deviation of the aggregate genotype, the accuracies of selection and correlated responses. Additional parameters related to survival and reproduction are supplied to model growth of the herd. Mating strategies and selection pathways for each breed are defined within the context of the entire population. Requirements of DM for the entire national herd, including pasture needed for the growing of the replacements, are estimated in the model. Parameters related to the yield of pasture, utilisation of pasture and content of metabolisable energy (ME) in the pasture are required. Stocking rate is calculated assuming that a fixed quantity of pasture DM is utilised per hectare.

Once the starting values are defined the following procedures are executed every year: ageing and culling of animals, selection of parents, matings, updating number and genetic merit of cows and bulls, estimation of live weight, milk production and DM requirements per cow, estimation of stocking rate and production per hectare. A description of these events is given in the following sections.

Population Structure

The starting values represented the New Zealand dairy cattle population for the production season 1996-97. The size of the dairy cow population was 3,064,526 cows of which 60% were Holstein-Friesian, 18% Jersey, 2% Ayrshire and 20% crossbred F × J. The size was constant through the simulation with an age structure at equilibrium; 21.9% 2-yr olds, 18.3% 3-yr olds, 15.5% 4-yr olds, 13.0% 5-yr olds, 10.5% 6-yr olds, 8.1% 7-yr olds, 6.0% 8-yr olds, 4.1% 9-yr olds, and 2.6% 10-yr olds. Ninety percent of females were recorded in the national data base.

The cow population was classified within breed and age group according to the number of generations of AB male ancestors on the female side of their pedigree. Across breed groups and age classes the starting values were 32% with 0, 22% with 1, 34% to 38% with 2 and 4% to 8% with 3 generations of AB. Active cows (≥3 generations of AB and ≥7/8 of genes of one breed) numbered 149,251 Holstein-Friesian, 112,816 Jersey, and 10,716 Ayrshire cows (B. L. Harris, 1997, personal communication).

Mating Strategies and Herd Growth

Nine mating strategies were simulated: straightbreeding, upgrading to F (**UPGF**), UPGJ, upgrading to A (**UPGA**) and two- and three-breed rotational crossbreeding involving F, J and A and UBB. Cows were artificially inseminated over 8 wk using fresh semen from straightbred sires. After this period, a bull was used to naturally mate nonpregnant cows for a further 4 wk. Fifteen-mo old heifers were artificially inseminated for only 3 wk, followed by natural mating for 10 wk. On average, 1.3 services were required per pregnant cow. At the end of the 12-wk total mating period, 92% of the animals were pregnant, with 80% of the cows and 30% of the heifers pregnant to artificial insemination. This strategy maintained a calving interval of 365 d.

Causes of wastage among young replacements and cows were: deaths, diseases (including mastitis, bloat, metabolic problems and facial eczema), poor fertility (including nonpregnancy and abortions), age and suitability for dairying (including low production, type and temperament). Culling rates for each cause of wastage were derived from Harris (11) and Holmes et al. (17).

Female progeny from non AB bulls were sold for beef within the 1st wk after calving and the female progeny from AB bulls that were not recorded in the national data base were classified within the subpopulation having zero generations of AB. Numbers of animals were updated each year using a herd-growth model (29).

Straightbreeding. The objective of this strategy was to avoid crossbreeding and maintain current breed composition of F, J and A cows. Cows with a higher proportion of genes from one breed were inseminated with semen of that breed. In the case of cows with equal proportions of genes of two breeds, for example 1/2F 1/2J, half were inseminated with F semen and half with J semen.

Upgrading strategies. The aim of these strategies was to create one dominant breed in the cow population. The relative use of semen from each breed was chosen in such a way that the sizes of the other subordinate breeds were not reduced below 44,000 cows (to maintain a source of bull mothers) in 25 yr time. For UPGF, all A cows were inseminated with A semen, J cows with F and J semen in proportions of 0.35 and 0.65 respectively, and remaining cows with F semen. For UPGJ, all A cows were inseminated with A semen, F cows with F and J semen in proportions of 0.49 and 0.51, respectively, and remaining cows with J semen. Similarly, for UPGA, F cows were inseminated with F and A semen in proportions of 0.49 and 0.51 respectively, J cows with J and A semen in proportions of 0.65 and 0.35 respectively, and remaining cows with A semen.

Two- and three-breed rotational crossbreeding. The aims of all these systematic crossbreeding strategies were to have the dairy cow population dominated by crossbred cows, while maintaining the three straightbred populations with at least 44,000 cows for the supply of straightbred bulls.

For the rotational FJ strategy, F and J semen was used in proportions of 0.49 and 0.51, respectively, to inseminate F cows, and in proportions of 0.35 and 0.65 to inseminate J cows. All Ayrshire cows were inseminated with A semen. Holstein-Friesian semen was used in crossbred cows having a dominance of J genes, and J semen was used in crossbred cows having a dominance of F genes regardless of the proportion of A genes.

For the rotational FA strategy, F and A semen was used in proportions of 0.49 and 0.51, respectively, to inseminate F cows. Holstein-Friesian, J and A semen was used in proportions of 0.175, 0.65 and 0.175, respectively to inseminate J cows. Ayrshire semen was used to inseminate all A cows. Holstein-Friesian semen was used in crossbred cows having a dominance of A genes, and A semen was used in crossbred cows having a dominance of F genes regardless of the proportion of Jersey genes.

For the rotational JA strategy, F cows were inseminated with F, J and A semen in proportions of 0.49, 0.255 and 0.255, respectively. Jersey cows were inseminated with J and A semen in proportions of 0.65 and 0.35, respectively. All A cows were inseminated with A semen. Jersey semen was used in crossbred cows having a dominance of A genes, and A semen was used in crossbred cows having a dominance of J genes regardless of the proportion of F genes.

For the three-breed rotational strategy, F cows were inseminated with F, J and A semen in proportions of 0.49, 0.255 and 0.255 respectively, and J cows were inseminated with F, J and A semen in proportions of 0.175, 0.65 and 0.175, respectively. All A cows were inseminated with A semen. Crossbred cows with the lowest proportion of F genes were inseminated with F semen, crossbred cows with the lowest proportion of J genes were inseminated with J semen, and crossbred cows with the lowest proportion of A genes were inseminated with A semen.

UBB. In this strategy, the top 10% of available 5-, 6- and 7-yr old proven bulls, regardless of breed, were selected to supply semen for the insemination of 15-mo heifers and cows. The bulls were selected by truncation across breed-age subclasses based on their additive genetic merit ignoring the heterotic contribution to daughter performance. The semen usage in cows was directly proportional to the proportion of bulls from one breed in the selected bull team. The intake of young bulls was directly proportional to the semen usage.

These mating strategies caused dynamic exchanges of females between subpopulations. The active population for each of the breeds could be increased if more cows with two generations of AB and with at least 5/8 genes of one breed were mated to straightbred bulls of that breed, or reduced if mated to bulls of another breed. These changes in the size of the active cow populations have an effect on the selection intensity applied in the cow to breed bulls selection pathway, and result in changes in the rate of genetic gain. These mating strategies also change the breed composition of the national herd and so affect the productivity of the entire dairy industry.

Selection Index

The aggregate genotype (T) was defined as: $T = v_w G_w + v_m G_m + v_f G_f + v_p G_p$ where G_w, G_m, G_f and G_p are additive genetic values for mature live weight and for lactation yields of milk, fat and protein and v_w, v_m, v_f and v_p, are the respective economic values. These values were –NZ\$0.427/kg live weight, –NZ\$0.05/L milk, NZ\$0.47/kg fat and NZ\$4.054/kg protein, which corresponded to the production season 1996-97 (19). An estimate of T (known as BW) was calculated as $BW = v_w EVB_w + v_m EBV_m + v_f EBV_f + v_p EBV_p$ where EVB_w, EBV_m, EBV_f and EBV_p are the estimated breeding values for each of the traits. This aggregate genotype and BW are simplified forms of the actual

T and BW for the New Zealand dairy industry as the contribution of survival was omitted.

Selection responses for live weight and lactation yields of milk, fat and protein were calculated from the regression of the trait values on the selection index assuming that EBVs were obtained from best linear prediction (15). Estimates of genetic and phenotypic parameters used in the selection index were as in Spelman and Garrick (26). Genetic and environmental correlations were assumed to be equal for all breeds. The standard deviation of T was calculated as NZ$26.

Selection Pathways

Within-breed selection of animals to be parents of the next generation was undertaken by truncation across age classes following Ducrocq and Quaas (9). Age classes were characterised by the mean genetic merit and the reliabilities of genetic evaluations. Reliabilities of genetic evaluations (represented as the squared correlation between T and BW) were based on the number of lactation records for individual cows and information from the 50 to 85 first crop daughters for bulls.

The population was assumed under selection prior to the base year. For each breed, genetic merit of bulls and cows in each of the age classes (Table 1) were obtained from the national genetic evaluation (Livestock Improvement, 1997, unpublished).

Selection on the cow to cow pathway was considered to be negligible. Only straightbred bulls selected from the top 10% of live 5-, 6- and 7-yr old proven bulls were used to produce female replacements in the herd. Mortality rate of bulls was 5% in 1-yr olds and 2% in 2- to 7-yr olds, and culling rate for conformation or semen quality was 10%. Because the population structure was not static, the intake of male calves for each breed in one year was calculated as: (number of cows to be artificially inseminated in 5 yr time × services per conception)/(average semen doses per bull × 0.232). The predicted numbers of cows to be inseminated in 5 yr time were calculated according to the mating

TABLE 1. Average genetic merit[1] of cows and bulls at the start of the simulation (Livestock Improvement, 1997, unpublished).

	Age class										
	0	1	2	3	4	5	6	7	8	9	10
	(NZ$)										
Cows[2]											
F	41	36	31	27	22	17	13	8	3	−2	−6
J	53	48	44	39	34	29	25	20	15	11	6
F × J crossbred	49	44	40	35	30	26	21	16	11	7	2
A	27	22	17	13	8	3	−1	−6	−11	−15	−20
Bulls											
F	98	93	89	84	79	75	70	65			
J	110	106	101	96	92	87	82	77			
A	84	80	75	70	65	61	56	51			

[1] The genetic merit is measured in NZ$ of aggregate genotype.

[2] F = Holstein-Friesian, J = Jersey, and A = Ayrshire.

strategies developed in this model. It was assumed that on average, 60,000 semen doses per year were effectively used per bull and that each bull was available up to 3 yr. The factor 0.232 is derived from the product of the mortality and culling rates, productive life of the bull and proportion selected.

Within each breed, 6.6 contract matings were required to produce 1 progeny-tested bull. Each year, the selected active cows were mated to the 3 best bulls which were selected from dead and live 5-, 6- and 7-yr old proven bulls. Dead bulls were eligible as bull fathers because frozen semen was held.

Young bulls were progeny tested in a population of 100,000 cows generating between 50 and 85 daughters per each bull. In accord with actual practice, bulls of one breed with the highest predicted semen demand for that breed were evaluated on the performance of 85 daughters, and bulls of breed with the lowest predicted semen demand were evaluated on the performance of 50 daughters. Bulls of the other breed were evaluated on the performance of 65 daughters. Progeny tests were completed when the bulls were 5-yr old. For the base year, a bull population was constructed assuming that in the entire population, 247 bulls were progeny tested: 155 Holstein-Friesian, 79 Jersey and 13 Ayrshire bulls.

Each year the model calculated the genetic merit of new progeny as the average of the genetic superiority of the selected parents. Each age class became 1 yr older. The asymptotic genetic gain in straightbred populations could be derived by calculating the year-by-year change in genetic values until the steady state was reached. Convergence can be accelerated using deterministic prediction following Rendel and Roberston (21). However, in this model convergence would take several years because there was a continuous exchange of cows between active and non-active cow populations and between breed groups. Therefore, for each of the straightbred populations and for the entire population, a measure of the rate of genetic gain was calculated over the last 5 yr as the regression of estimated breeding values for 2-yr old cows on time.

The relative contribution (RC_{CB}) of the cow to bull pathway to genetic gain was calculated as: $RC_{CB} = [(\Delta G_1 - \Delta G_2) \times 100]/\Delta G_1$ where ΔG_1 and ΔG_2 are annual genetic gains calculated as: $\Delta G_1 = [(I_{CB} + I_{BC} + I_{BB}) \times \sigma_T]/(L_{CC} + L_{CB} + L_{BC} + L_{BB})$ and $\Delta G_2 = [(I_{BC} + I_{BB}) \times \sigma_T]/(L_{CC} + L_{CB} + L_{BC} + L_{BB})$ where the subscripts refer to the cows to breed cows (CC), cows to breed bulls (CB), bulls to breed cows (BC) and bulls to breed bulls (BB); L is the generation interval in years; I is the genetic superiority calculated as the product of selection intensity and accuracy of selection (correlation between T and BW); and σ_T is the standard deviation of the aggregate genotype. To calculate ΔG_2, selection intensity for the cow to breed bulls pathways was assumed negligible and therefore I_{BC} was set to zero.

Expected Performance

For each of the subclasses, expected phenotypic performances per cow for live weight and lactation yields of milk, fat and protein were calculated as the sum of the breed effects (Table 2) plus correlated responses and, in the case of crossbred cows, plus effects of heterosis (Livestock Improvement, 1997, unpublished). Age adjustment factors for milk and milk component yields per cow were 0.75, 0.88, 0.95, 1.0, and 0.90 for lactations 1, 2, 3, 4-7, and 8-9, respectively. These factors were calculated from age production averages reported by Livestock Improvement (19) adjusted for genetic trends.

TABLE 2. Estimates of additive breed and heterotic effects for milk traits and live weight for New Zealand dairy cattle[1] (Livestock Improvement, 1997, unpublished).

	Lactation yield			Live
	Milk	Fat	Protein	weight
	(L)	(kg)		
Additive breed effects				
F	3896	176	138	492
J	3064	166	121	407
A	3614	161	130	454
First cross heterotic effects				
F × J	137	7.7	5.2	7.7
F × A	77	3.5	2.8	0.3
J × A	156	8.4	5.9	9.9

[1] F = Holstein-Friesian, J = Jersey, and A = Ayrshire.

Dry matter intake of dairy cows and replacements was calculated by summing the ME requirements for maintenance, live weight gain, pregnancy and lactation (1, 17), assuming an energy density of 10.5 MJ ME per kg pasture DM. It was assumed that 15,000 kg DM/ha was produced by ryegrass-clover pastures growing on fertile soils, and that 80% or 12,000 kg DM/ha was harvested by the animals. Stocking rate, defined as the number of cows grazing per hectare, was calculated as: 12,000 kg DM divided by the total DM required per cow (including DM required for the replacements). This calculation assumes that the number of animals grazed per hectare was adjusted to meet the DM requirements, which in turn are determined by the production levels of the animals. Industry averages for live weight per cow and milk production per cow and per hectare were calculated each year by weighting averages of age-breed subclass by number of animals.

RESULTS

Breed Composition of the National Herd

The F breed was dominant at the start of the simulation (60% of the total population) (Table 3). After 25 yr, straightbreeding resulted in a cow population composed of three separate straightbred groups where the F comprised 73% of national herd. The upgrading strategies resulted in one breed group dominating the national herd, with 91% F, 86% J and 81% A after 25 yr of upgrading to each breed respectively (Table 3). Crossbred cows were a small proportion of the final populations, but they were large proportions in the early years of the UPGJ and UPGA strategies.

Two- and three-breed rotational crossbreeding strategies increased the number of crossbred cows at the expense of straightbred F and J cows (Table 3). These mating strategies lead to F, J and A populations of 3%, 3% and 2%, respectively, of the national herd. The UBB strategy resulted in a cow population dominated by F × J and J cows.

Active Cows and Rate of Genetic Gain

Long-term effects of the mating strategies on the number of active cows and rates of genetic gain are shown in Table 4 for the different breeds and crosses, and in Table 5 for the entire population. Straightbreeding increased the three active cow populations (Table 4) and was the strategy which caused the largest increase in total active cows in

TABLE 3. Changes in breed composition of the national herd[1] under different mating strategies for 25 yr.

Mating strategy	Breed group[2] F	J	A	FJ	FA	JA	FJA
	(%)						
Base year	60	18	2	20			
Year 25							
Straightbreeding	73	25	2				
Upgrading to F	91	3	2	4			
Upgrading to J	3	86	2	9			
Upgrading to A	3	3	81		9	4	
Rotational FJ	3	3	2	92			
Rotational FA	3	3	2	1	85	1	5
Rotational JA	3	3	2	1	1	72	18
Rotational FJA	3	3	2	2	1	1	88
UBB[3]	12	35	2	51			

[1]The number of cows was 3,064,526 for all strategies and across years.

[2]F = Holstein-Friesian, J = Jersey, and A = Ayrshire.

[3]Use of best bulls regardless of the breed.

the population (Table 5). The genetic gain in the last 5 yr of straightbreeding were 0.27, 0.26 and 0.21 genetic SD/yr per cow for the F, J and A breeding schemes, respectively (Table 4). The genetic gain of the entire dairy population under straightbreeding was 0.26 genetic SD/yr per cow (Table 5).

Generation intervals showed little variation between mating strategies and were 5.1 yr for cows to breed cows, 4.5 to 4.8 yr for cows to breed bulls, 6.7 yr for bulls to breed cows and 6.6 yr for bulls to breed bulls.

TABLE 4. Effect of long-term mating strategies on number of active cows and within-breed rate of genetic gain.

	Number of active cows			Annual genetic gain[2]		
Mating strategy[1]	F	J	A	F	J	A
					(σ_T)	
Base year	149,251	112,816	10,716			
Year 25						
Straightbreeding	1,628,247	557,620	44,610	0.27	0.26	0.21
Upgrading to F	2,042,758	60,464	44,610	0.28	0.22	0.21
Upgrading to J	63,809	1,920,106	44,610	0.23	0.27	0.21
Upgrading to A	63,809	60,464	1,819,405	0.22	0.23	0.27
Rotational FJ	63,809	60,464	44,610	0.24	0.24	0.21
Rotational FA	63,809	60,464	44,610	0.24	0.23	0.24
Rotational JA	63,809	60,464	44,610	0.22	0.24	0.24
Rotational FJA	63,809	60,464	44,610	0.24	0.23	0.24
UBB[3]	275,441	770,580	44,610	0.26	0.25	0.21

[1] F = Holstein-Friesian, J = Jersey, and A = Ayrshire.

[2] σ_T = Standard deviation of the aggregate genotype calculated as NZ$26.

[3] Use of best bulls regardless of the breed.

Upgrading strategies increased the active cow population of the breed concerned up to 1.8 to 2.0 million cows, and maintained the active cow populations of the other breeds at 63,089 Holstein-Friesians, 60,464 Jerseys and 44,610 Ayrshires (Table 4). Rotational crossbreeding systems reduced the three active cow populations to these same numbers (Table 4), and the total number of active cows was reduced from 272,783 cows for the base year to 168,883 for the year 25 of the simulation (Table 5). The UBB strategy increased the number of J active cows to a greater extent than for F and A breeds.

The size of the active cow population had an effect on the rate of genetic gain as shown in Tables 4 and 5. Faster annual rates of genetic gain corresponded to those

TABLE 5. Effect of mating strategies on the total number of active cows and the relative contribution (RC_{CB}) of the cow to breed bulls selection pathway to the genetic gain of the entire population.

Mating strategy[1]	Number of active cows	Proportion selected	Annual genetic gain[2]	RC_{CB}
		(%)	— (σ_T) —	— (%) —
Base year	272,783			
Year 25				
Straightbreeding	2,230,477	0.10	0.26	35
Upgrading to F	2,147,831	0.10	0.27	35
Upgrading to J	2,028,525	0.10	0.27	35
Upgrading to A	1,943,677	0.11	0.25	35
Rotational FJ	168,883	1.15	0.24	29
Rotational FA	168,883	1.15	0.23	29
Rotational JA	168,883	1.15	0.23	29
Rotational FJA	168,883	1.15	0.23	29
UBB[3]	1,090,631	0.19	0.25	34

[1] F = Holstein-Friesian, J = Jersey, and A = Ayrshire.

[2] σ_T = Standard deviation of the aggregate genotype calculated as NZ$26.

[3] Use of best bulls regardless of the breed.

populations with higher number of active cows. The highest annual genetic gain was obtained in the F population when the dairy cow population was upgraded to F (Table 4). Upgrading to J and F resulted in the highest genetic gain for the entire population at 0.27 genetic SD/yr per cow (Table 5). Genetic gains for rotational FJ and for UBB were 11% and 6% slower than gains for UPGJ and UPGF.

The proportion of active cows selected and the relative contribution of the cow to breed bulls pathway to genetic gain are in Table 5. For straightbreeding and upgrading strategies the proportions selected were 0.1% and the relative contribution of this pathway to genetic gain was 35%, whereas for rotational crossbreeding strategies, the proportions selected were 1.15%, and the contributions to genetic gain were 29%. Mating strategies that increased the size of the active cow population resulted in faster rates of genetic gain because higher selection intensities were achieved.

Different rates of genetic gains were obtained with the same size of the active cow population under different mating strategies. Upgrading to F and rotational FJ resulted in the same number of J active cows at 60,464 animals after 25 yr, but in different annual genetic gains for the J breeding scheme at 0.22 and 0.24 genetic SD/yr per cow, respectively (Table 4). The difference was caused by changes in the selection intensity of bulls to breed bulls. More J bulls were progeny tested for the rotational FJ than for UPGF because the demand for J semen was higher for the former strategy than for the latter.

Performance per Cow and per Hectare

Effects of long-term selection and mating strategies on industry average production per cow and per hectare are shown in Table 6. Selection and effects of heterosis caused increases in yields of milk, fat and protein per cow and per hectare. This was despite decreases in stocking rates caused by increased feed requirements per cow, given a fixed amount of feed eaten per hectare.

Results of straightbreeding show that selection on BW alone will increase the phenotypic performance per cow of the national herd by 613 L milk (24.5 L/yr), 30 kg fat (1.2 kg/yr), 39 kg protein (1.6 kg/yr) and 8 kg live weight (0.3 kg/yr), with a corresponding increase in feed requirements by 446 kg DM (17.8 kg/yr) (Table 6). Compared to the mean for the base year, annual increases per cow were 0.8% for milk and fat and 1.3% for protein, while increases per hectare were 0.4% for milk and fat and 0.9% for protein.

TABLE 6. Effects of mating strategies on the productivity of the national dairy herd.

	Average per cow							Average per hectare		
Mating strategy[1]	Breeding worth	Live weight	Milk	Fat	Protein	Dry matter	Stocking rate	Milk	Fat	Protein
	(NZ$)	(kg)	(L)	(kg)	(kg)	(kg)	cows/ha	(L)	(kg)	(kg)
Base year	23	460	3222	152	117	4796	2.502	8061	381	293
Year 25										
Straightbreeding	198	468	3835	182	157	5242	2.289	8780	417	359
Upgrading to F	196	485	3988	184	160	5392	2.226	8875	410	356
Upgrading to J	202	415	3405	178	149	4814	2.493	8488	444	371
Upgrading to A	166	452	3684	168	148	5012	2.394	8821	403	354
Rotational FJ	195	453	3739	184	156	5152	2.329	8709	429	364
Rotational FA	174	468	3833	176	153	5193	2.311	8857	406	354
Rotational JA	180	439	3614	177	151	4986	2.407	8698	425	363
Rotational FAJ	183	454	3745	180	154	5123	2.342	8772	421	361
UBB[2]	197	442	3641	182	154	5062	2.371	8631	432	365

[1] F = Holstein-Friesian, J = Jersey, and A = Ayrshire.

[2] Use of best bulls regardless of the breed.

Upgrading to F resulted in the heaviest cow producing the highest yield of milk, fat and protein with the highest feed requirements. Upgrading to J resulted in the lightest cow with the lowest feed requirements and, consequently, the highest stocking rate and the highest production per hectare of fat and protein. Upgrading to F would create a national herd producing 583 L more milk, 6 kg more fat and 11 kg more protein per cow than UPGJ, with the cows being 69 kg heavier and requiring 578 kg more pasture DM per cow. When the comparison is made on the basis of production per hectare, the UPGF strategy resulted in 0.267 less cows being carried (and proportional replacements), 387 L more milk, 34 kg less fat and 15 kg less protein than UPGJ. Rates of genetic gain for the Holstein-Friesian and Jersey breeding schemes were reduced by rotational FJ (Table 4). The effects of these reductions resulted in industry averages per cow that were slightly higher than the intermediate between UPGJ and UPGF (Table 6), despite effects of heterosis being exploited at 67% of the heterosis expressed in the first crosses (8). The differences between rotational FJ and the average of UPGF and UPGJ were 2.8 kg for live weight, 42.5 L for milk, 3.0 kg for fat and 1.9 kg for protein.

DISCUSSION

Selection and crossbreeding in dairy cattle have nearly always been studied separately, even though breeding programs in several countries involve both (14). The present study simulated the effects of simultaneous selection and crossbreeding on the rate of genetic gain and the productivity of New Zealand dairy cattle.

Crossbreeding in dairy cattle has not been widespread in temperate climates, largely because of the notable merit of the Holstein breed for liquid milk production (28). However, crossbreeding can give rise to economic gains for dairy farmers if the basis of milk pricing puts less emphasis on milk volume and more emphasis on fat and protein and other traits, such as adaptability to milking, live weight, longevity and reproductive performance, all of which play important roles in breeding objectives (8, 27, 28).

Shannon (23) concluded that the size of the active cow population (potential bull mothers) has a significant effect on the rate of genetic gain of New Zealand dairy cattle. This was supported in the current study. Upgrading strategies increased the number of active cows resulting in increased rates of genetic gains (Tables 4 and 5). In contrast, crossbreeding in non-elite matings only, as suggested by Swan and Kinghorn (27), reduced the size of the active cow populations and rates of genetic gains.

The cow to bull pathway affects the rate of genetic gain significantly, because high selection intensities can be achieved in the selection of bull mothers (7, 10, 22, 25). The present study found that relative contribution of the cow to breed bulls pathway to the genetic gain was 29% when the proportion selected was 1.15%, and 35% when the proportion selected was 0.1% (Table 5). When the proportions selected are in the range from 1 to 5%, multiple ovulation and embryo transfer has been suggested as a method to increase the selection intensity of this pathway, whereby the rate of genetic progress in the entire population might be increased by 2.5 to 6.0% (16) or up to 10% (5).

A possible alternative to reduce the compromise between crossbreeding and size of active cow population would be the use of multiple ovulation and embryo transfer in the bull mother selection pathway. In the New Zealand breeding scheme, about 7 cows are selected to produce one progeny-tested bull. If this ratio could be halved through the use of multiple ovulation and embryo transfer, the proportion selected would be halved and the selection intensity in the cows to breed bulls pathway would be increased to levels similar to those achieved with a larger population size of active cows. However, a cost-benefit analysis is required to evaluate this alternative.

The genetic gains obtained in this study ranged from 0.21 genetic SD/yr for a small breeding scheme (Ayrshire) to 0.28 genetic SD/yr for a large breeding scheme (Holstein-Friesian and Jersey), which agree well with other studies. Theoretically, genetic gains of 0.26 genetic SD/yr can be achieved for an optimal progeny testing breeding scheme (7) or 0.16 genetic SD/yr for a less rigorous scheme (lower selection intensities) (31). The realised rates of genetic gain have been estimated at 0.10 genetic SD/yr for the US

Holstein population (30) and 0.36 genetic SD/yr for the Italian Holstein population (4). The high estimate for the Italian dairy population, however, could have been mainly due to importation of semen from other countries.

Effects of selection alone (straightbreeding) on the phenotypic performance per cow of the national herd confirm the genetic trends for the New Zealand Holstein-Friesian breeding scheme calculated by Spelman and Garrick (26). Increases in production per hectare, however, were lower than increases in production per cow because stocking rate had to be reduced to maintain pasture utilisation at 12,000 kg DM/ha across the years.

Upgrading to J in combination with selection on the current selection objective seems to be the best option to increase dairy farm productivity. After 25 yr, this strategy resulted in the lowest milk production and the highest fat and protein production per hectare with the highest stocking rate. Because the New Zealand payment system penalises volume and rewards fat and protein, these outputs must result in the highest milk income. However, this strategy may also result in high production costs, because some costs are directly related to the number of cows farmed and are largely independent of yield (e.g. herd testing, artificial insemination and animal health). Further, income from the selling of surplus and cull stock may be reduced, as the live weight of the animals was reduced by this strategy.

Genetic improvement should be considered as contributing to the efficient production for the whole national production and marketing system (14). If there is uncertainty about future market requirements, there may be advantages (from the national view point) in maintaining (and even in creating) genetic diversity to cover possible future conditions (18). A range of breeds may be maintained to exploit selection and heterosis. Rotational crossbreeding schemes and UBB are alternatives to making use of within-breed genetic gains and the effects of heterosis. Furthermore, these schemes maintain the genetic diversity in the population, thereby retaining the ability of the dairy industry to adjust for future modifications in processing and marketing conditions. Milk characteristics such as colour and hardness are traits that sometimes have significant effect on the yield and market value of dairy products. Some international markets prefer dairy products that are white, but removal of yellow colour increases processing costs and may reduce the market value because the process may also remove natural flavours. Similarly, spreadable butter has a higher market value than hard butter but at higher processing costs.

The implementation of rotational crossbreeding systems requires a stratified organisation in the dairy population, namely, straightbred selection schemes supplying straightbred sires of high genetic merit to be used for crossbreeding in the commercial population. This might be a difficult task, as it requires the organisation of the whole industry.

A number of factors should be considered when interpreting the results obtained in the present study. In the development of the model, the reduction of genetic variance (3) and the effects of inbreeding were not accounted for. For a straightbreeding scheme, reduction in the genetic variance of the selected animals might reduce the genetic gain (7) and inbreeding might reduce the productivity of the animals. In the present study, however, these effects were not expected to be significant because the number of cows was large and the sires were used for crossbreeding.

The number of young bulls to be progeny tested was calculated from the anticipated demand for semen for all mating strategies except for the UBB strategy. In practice, it is difficult to predict farmer attitudes and choices. A high demand for semen will reduce the selection intensities in the bulls to breed cows selection pathway because more proven bulls must be selected. The UBB strategy resulted in lower genetic gain than upgrading strategies, but higher gain than rotational crossbreeding strategies, even when selection was not maximised, because selection intensities varied each year. This strategy reflects the current trend in the New Zealand dairy industry, where demand for J semen has increased because bulls of this breed have been identified as having higher genetic merit (high BW). If the demand for J semen increases, the size of the crossbred and J populations will increase, which would reverse the change in the breed composition that has occurred since 1960 when the New Zealand dairy cow population was dominated by the Jersey breed (17).

Phenotypic and genetic correlations and heritabilities for milk traits and live weight were assumed to be equal for the three breeds because studies (2) show that these estimates are consistent between F and J under New Zealand conditions. If these parameters really are different between the breeds considered in this study, selection responses must be calculated for the appropriate genetic parameters.

CONCLUSIONS

The present study shows that current progeny testing schemes for the three main breeds in New Zealand have the potential to achieve high rates of genetic gain by increasing the size of the active cow populations and maintaining high selection intensity on the bull to cow pathway through the use of fresh semen. Genetic evaluations across breeds and selection on BW allows identification of high genetic merit bulls, which can be used for crossbreeding, with the aim of increasing farm income by exploiting the effects of heterosis for traits of economic importance. The widespread implementation of a crossbreeding strategy requires the supply of straightbred bulls of high genetic merit, which in turn requires the availability of straightbred bull mothers, thereby creating a compromise between crossbreeding and the need for a large population of active cows.

Upgrading to J over 25 yr in combination with selection, resulted in the highest rate of genetic gain for the total dairy cow population, the highest fat and protein production per hectare, the highest stocking rate and the lowest milk production per hectare. For the current payment system, these outputs will result in the highest milk income but further economic evaluations are required because this strategy would also result in the highest on-farm production costs. The UBB and rotational crossbreeding strategies reduced the rate of genetic gain, but allowed the exploitation of heterotic effects and maintained the genetic diversity which would be important to cover future husbandry practices and marketing conditions.

REFERENCES

1 AFRC. 1993. Energy and Protein Requirements of Ruminants. An Advisory Manual Prepared by the AFRC Technical Committee on Response to Nutrients. CAB Int., Wallingford, United Kingdom.

2 Ahlborn, G., and L. Dempfle. 1992. Genetic parameters for milk production and body size in New Zealand Holstein-Friesian and Jersey. Livest. Prod. Sci. 31:205-219.

3 Bulmer, M. G. 1971. The effect of selection on genetic variability. Am. Nat. 105:201-211.

4 Burnside, E. B., G. B. Jansen, G. Civati, and E. Dadati. 1992. Observed and theoretical genetic trends in a large dairy population under intensive selection. J. Dairy Sci. 75:2242-2253.

5 Cunningham, E. P. 1976. The use of egg transfer techniques in genetic improvement. Page 345 in Eur. Econ. Com. Seminar on Egg Transfer in Cattle. L. E. A. Rowson, ed. Com. Eur. Commun. Luxumberg, Belgium.

6 Cunningham, E. P. 1983. Structure of dairy cattle breeding in Western Europe and comparisons with North America. J. Dairy Sci. 66:1579-1587.

7 Dekkers, J. C. M. 1992. Structure of breeding programs to capitalize on reproductive technology for genetic improvement. J. Dairy Sci. 75:2880-2891.

8 Dickerson, G. E. 1969. Experimental approaches in utilising breed resources. Anim. Breed. Abstr. 37:191-202.

9 Ducrocq, V., and R. L. Quaas. 1988. Prediction of genetic response to truncation selection across generations. J. Dairy Sci. 71:2543-2553.

10 Everett, R. W. 1984. Impact of genetic manipulation. J. Dairy Sci. 67: 2812-2818.

11 Harris, B. L. 1989. New Zealand dairy cow removal reasons and survival rate. N. Z. J. Agric. Res. 18:117-139.

12 Harris, B. L. 1998. Breeding dairy cattle for economic efficiency: a New Zealand pasture-based system. Proc. 6th World Congr. Genet. Appl. Livest. Prod., Armidale, Australia 25: 383-386.

13 Harris, B. L., J. M. Clark, and R. G. Jackson. 1996. Across breed evaluation of dairy cattle. Proc. N. Z. Soc. Anim. Prod. 56:12-15.

14 Harris, D. L., and T. S. Stewart. 1990. The role of computer simulation and laboratory animals in the design of breeding programs. Proc. 4th World Congr. Genet. Appl. Livest. Prod. Edinburgh, Scotland 12:257-268.

15 Henderson, C. R. 1963. Selection index and expected genetic advances. Pages 141-163 *in* Statistical genetics and plant breeding. W. D. Hanson and H. F. Robinson, ed. National Academy of Sciences, National Research Council Publication No. 982, Washington, DC.

16 Hill, W. G., and R. B. Land. 1976. Superovulation and ovum transplantation in genetic improvement programmes. Page 355 in Eur. Econ. Com. Seminar on Egg Transfer in Cattle. L. E. A. Rowson, ed. Com. Eur. Commun. Luxumberg, Belgium.

17 Holmes, C. W., G. F. Wilson, D. D. S. MacKenzie, D. S. Flux, I. M. Brookes, and A. W. F. Davey. 1987. Milk Production from Pasture. Butterworth Agric. Books, Wellington, New Zealand.

18 Land, R. B. 1981. An alternative philosophy for animal breeding. Livest. Prod. Sci. 8:95-99.

19 Livestock Improvement. 1997. Dairy Statistics 1996-1997. Livestock Imp. Corp. Ltd., Hamilton, New Zealand.

20 Macdonald Committee Report. 1992. Herd Testing and Related Services. N. Z. Dairy Board. Wellington, New Zealand.

21 Rendel, J. M., and A. Robertson. 1950. Estimation of genetic gain in milk yield by selection in a closed herd of dairy cattle. J. Genet. 50:1-8.

22 Robertson, A., and J. M. Rendel. 1950. The use of progeny testing with artificial insemination in dairy cattle. J. Genet. 50:21-31.

23 Shannon, P. 1989. Increasing rates of genetic gain. Proc. Ruakura Farmers' Conf. 41:6-11.

24 Shannon, P., B. Curson, and A. P. Rhodes. 1984. Relationship between total spermatozoa per insemination and fertility of bovine semen stored in caprogen at ambient temperature. N. Z. J. Agric. Res. 1984; 27:35-41.

25 Skjervold, H. 1963. The optimum size of progeny group and optimum use of young bulls in A. I. breeding. Acta Agric. Scand. 13:131-140.

26 Spelman, R. J., and D. J. Garrick. 1997. Effect of live weight and differing economic values on responses to selection for milk fat, protein, volume, and live weight. J. Dairy Sci. 80:2557-2562.

27 Swan, A. A., and B. P. Kinghorn. 1992. Evaluation and exploitation of crossbreeding in dairy cattle. J. Dairy Sci. 75:624-639.

28 Touchberry, R. W. 1992. Crossbreeding effects in dairy cattle: the Illinois experiment, 1949 to 1969. J. Dairy Sci. 75:640-667.

29 Upton, M. 1989. Livestock productivity assessment and herd growth models. Agric. Syst. 29:149-164.

30 Van Tassell, C. P., and L. D. Van Vleck. 1991. Estimates of genetic selection differentials and generation intervals for four paths of selection. J. Dairy Sci. 74:1078-1086.

31 Van Vleck, L. D. 1981. Potential genetic impact of artificial insemination, sex selection, embryo transfer, cloning, and selfing in dairy cattle. Pages 221-242 in New Technologies in Animal Breeding. B. C. Brackett, G. E. Seidel, and S. M. Seidel, ed. Academic Press, London, England.

Chapter 5

Effects of selection and crossbreeding strategies on industry profit in the New Zealand dairy industry

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ABSTRACT

The effects of selection and crossbreeding on the net income of the New Zealand dairy industry were evaluated with a deterministic model over 25 yr. Several mating strategies involving Holstein-Friesian, Jersey and Ayrshire cattle were evaluated. These strategies were straightbreeding, upgrading to Holstein-Friesian, upgrading to Jersey, upgrading to Ayrshire, use of the best bulls irrespective of breed and two- and three-breed rotational crossbreeding. Industry productions of milk, fat, protein and lactose were calculated assuming that 12,000 kg dry matter/ha was utilised from 1,224,911 hectares of pasture. Profitability was the difference between income (international sale of whole milk powder, casein, butter and beef from salvage animals) and costs (farm expenses, milk collection, manufacture and marketing). Casein and whole milk powder were valued at NZ$8.345 and NZ$3.306 per kg, respectively, over the 25 yr. Butter was valued at NZ$2.995 per kg for base year production levels and NZ$0.45 per kg for marginal increases in production. Upgrading to Holstein-Friesian resulted in the highest industry net income (NZ$1119 million) followed by straightbreeding (NZ$1086 million) and two-breed rotational Holstein-Friesian × Jersey (NZ$1076 million). However, if the marginal value of extra butter production was assumed equal to the average base value, then upgrading to Jersey resulted in the highest industry net income (NZ$1185 million) followed by two-breed rotational Holstein-Friesian × Jersey (NZ$1177 million) and use of the best bulls (NZ$1173 million). Future costs and prices of dairy products have a major impact on decisions on mating strategies.

(**Key words:** dairy industry, selection, crossbreeding, profitability)

Abbreviation key: **A** = Ayrshire, **F** = Holstein-Friesian, **J** = Jersey, **UBB** = use of the best bulls, **UPGA** = upgrading to A, **UPGF** = upgrading to F, **UPGJ** = upgrading to J, **WMP** = whole milk powder.

INTRODUCTION

New Zealand accounts for only about 2.5% of the total milk produced by dairy cattle in the world, but for 25% of milk traded internationally in the form of dairy products (25). Milk production for the season 1996-97 was 10,339 million L milk, 506 million kg fat and 375 million kg protein from 3.1 million cows distributed in 14,741 herds (19). The breed composition of the national herd was 57% Holstein-Friesian (**F**), 16% Jersey (**J**), 18% crossbred F × J, 2% Ayrshire (**A**) and 7% other dairy breeds and their crosses (19).

The dairy industry is orientated towards export production, with 90% of the milk manufactured into a range of dairy products and exported to many countries. The main dairy products are whole milk powders (**WMP**), butter, cheese, skim milk powder and casein (25). Payment to farmers for milk is based on the quantity of milk, fat and protein, and its value is determined by the prices received for the resultant dairy products on the world market minus costs of processing and marketing. For the season 1996-97, returns to farmers were NZ$5.91/kg protein, NZ$2.72/kg fat and –NZ$0.041/L milk.

Selection and crossbreeding are two strategies which can be employed to alter the yield of milk and its components (10, 11). Annual theoretical rates of genetic gain for the New Zealand Holstein-Friesian scheme are 30 L milk, 1.9 kg fat, 2.0 kg protein and –0.2 kg live weight per cow (29). Significant breed differences (2, 3, 13, 23) and heterosis (3, 13) for yields of milk, fat, protein and for live weight have been reported for New Zealand dairy cattle.

Selection and crossbreeding affect many aspects of dairy industry profitability. Farm costs can be reduced if the same amount of milk solids are produced per hectare by a smaller number of cows. Milk collection and manufacture costs can be reduced if the same amount of milk solids are processed from a smaller volume of milk.

Few studies have compared the production of dairy products and industry returns from different breeds. On the basis of production per hectare, Jerseys had an advantage for butter, a combination of butter and casein, and for cheese production, but production of milk powder favoured the Friesians (5). A simulation study showed that net farm incomes per hectare (gross income minus production costs) were similar for the two breeds when milks were processed into WMP and butter (31) but net income for Jersey was higher than for Friesian when milks were processed into cheese (32). The objective of the present study was to evaluate the effect of selection and mating strategies on industry production of milk components, yields of dairy products and industry net income for the New Zealand dairy industry over the next 25 yr.

MATERIALS AND METHODS

The Productivity Model

Lopez-Villalobos et al. (21) developed a deterministic model to simulate the long-term effects of selection and crossbreeding on the annual rate of genetic gain and productivity of the New Zealand dairy industry over 25 yr. Only the essential features of this model will be described here.

The numbers of cows and bulls, and their genetic merit for the base year, were representative of the production season 1996-97 with an age structure at equilibrium. The cow population was classified according to the number of generations of artificial breeding male ancestors on the female side of their pedigree. Numbers of animals were updated each year using a herd-growth model (30).

The aggregate genotype (T) was defined as: $T = \Sigma v_j G_j$ where v_j was the economic value in dollars of trait j and G_j was the additive genetic value of the individual for trait j. Economic values and traits were: –NZ\$0.427/kg live weight, –NZ\$0.05/L milk, NZ\$0.47/kg fat and NZ\$4.054/kg protein. An estimate of T was defined as breeding worth (BW) which was calculated as $BW = \Sigma v_j EBV_j$ where EBV_j was the estimated breeding value for trait j. Traits included in BW were the same as those included in T. Selection responses for live weight and lactation yields of milk, fat and protein were calculated from the regression of the trait values on the selection index assuming that EBVs were obtained from best linear prediction (14). Estimates of genetic and phenotypic parameters used in the selection index were as in Spelman and Garrick (29). The standard deviation of T was calculated as NZ$26. Reliabilities of genetic evaluations (the squared correlation between T and BW) were based on the number of lactation records for individual cows and information from the 60 to 85 first-crop daughters for bulls.

Selection of animals to be parents of the next generation was undertaken by truncation across age classes following Ducrocq and Quaas (9). Selection of cows to breed cows was considered to be negligible. Bulls mothers were selected from those with at least 3 generations of artificial breeding and with ≥7/8 of genes of one breed. For each young bull to be progeny tested, 6.6 cows were contracted. Within-breed, the selected active cows were mated to the 3 best bulls, which were selected from dead and live 5-, 6- and 7-yr old proven bulls. Results of progeny tests were obtained when bulls were 5 yr old. Bulls to breed cows were selected from live 5-, 6- and 7-yr olds. Numbers of bulls selected depended on anticipated future demand for semen.

The model predicted the breed composition of the national herd for each of nine mating strategies involving F, J and A breeds. The mating strategies simulated were: straightbreeding, upgrading to F (**UPGF**), upgrading to J (**UPGJ**), upgrading to A (**UPGA**), rotational FJ, rotational FA, rotational JA, rotational FJA and use of the best bulls (**UBB**) regardless of breed. In all mating strategies, not less than 44,000 straightbred cows of each breed were retained to maintain a source of bull mothers.

Correlated responses, effects of heterosis and age adjustment factors were included in calculating industry averages for live weight and yields of milk, fat and protein per cow. Environmental factors, such as temperature and annual rainfall, and complex interactions between animal and pasture that contribute to herd-year effects were not included in the model. Accordingly, the predicted yields of milk and its components for the various breed-age groups did not exhibit annual fluctuations from these causes, and might be different to the actual yields. The number of animals and their genetic merit in the 1996-97 season in an average climatic year were used to derive the performance of an average cow for the base year.

Feed requirements per cow were estimated for maintenance, lactation and pregnancy, and for growth of the replacements (1, 16). Stocking rate, defined as number of cows per hectare, was calculated by assuming 12,000 kg dry matter utilised annually per hectare, and productivity per hectare was calculated as performance per cow multiplied by stocking rate.

Table 1 shows the average live weight per cow, the stocking rate and the productivity per hectare for the base year and year 25 for each mating strategy derived in Lopez-Villalobos et al. (21). These values were the input values used to calculate the net incomes of the dairy industry.

Industry Production

Industry outputs of milk, fat, protein, lactose and ash were calculated assuming a fixed area of 1,224,911 ha was available for dairying, the area needed to satisfy the feed requirements of the national herd in the base year. Lactose and ash were calculated by assuming that percentages of lactose and ash were constant across breed groups at 4.7% and 0.7%, respectively. Industry productions for year 25 were calculated by multiplying production per hectare by the fixed area for dairying. Similarly, the number of cows comprising the national herd was scaled from stocking rate.

Yields of WMP, casein and butter were calculated assuming that WMP was standardised to contain 2.8% water, 26.5% fat and 25.1% protein (18). Quantities of fat and protein extracted were calculated as the difference between the contents in milk

TABLE 1. Stocking rate and production per hectare of milk, fat and protein for the New Zealand dairy industry with different mating strategies comprising of Holstein-Friesian (F), Jersey (J) and Ayrshire (A) breeds.

		Means after 25 yr								
	Base year	Straight-breeding	Upgrading			Two- and three-breed rotations				
			F	J	A	FJ	FA	JA	FJA	UBB[1]
Cow live weight, kg	460	468	485	415	452	453	468	439	454	442
Stocking rate, cows/ha	2.502	2.289	2.226	2.493	2.394	2.329	2.311	2.407	2.342	2.371
Production per hectare										
Milk, L/yr	8061	8780	8875	8488	8821	8709	8857	8698	8772	8631
Fat, kg/yr	381	417	410	444	403	429	406	425	421	432
Protein, kg/yr	293	359	356	371	354	364	354	363	361	365

[1] Use of best bulls regardless of the breed.

minus the contents in WMP. Yield of butter was calculated as fat extracted × 1.19 (31), and the yield of casein was calculated as protein extracted × 0.87 (6).

Industry Profit

Industry net income was calculated as the difference between the gross income and production costs. Gross income was derived from the sale of dairy products at the international market value, sale of salvage animals and other diverse incomes. Production costs were: costs on the farm, costs for milk collection and the manufacture of dairy products, and costs of sales and marketing.

Gross income. Industry returns were derived from the sale of WMP, butter and casein. Casein and WMP were valued at NZ\$8.345 and NZ\$3.306 per kg, respectively, over the 25 yr, whereas butter was valued under two scenarios. In scenario I, butter was valued at NZ\$2.995 per kg for all butter over the 25 yr and in scenario II, butter was valued at NZ\$2.995 per kg for the quantity produced in the base year and only NZ\$0.45 per kg (vegetable oil equivalent) for all marginal production. Therefore, the value of butter per kg for year t (vb_t) was calculated as:

$$vb_t = \{[z_0 \times vb_0] + [(z_t - z_0) \times 0.45]\}/z_t,$$

where, z_0 is initial volume of butter produced, z_t is volume of butter in year t and vb_0 is base value of butter.

Beef income was derived from the sale of male calves, surplus female calves and culled rising 2-yr olds and older cows, as explained in Lopez-Villalobos et al. (22). Carcass yield for calves and rising 2-yr olds were assumed at 50% and 53%, respectively. Carcass yield of culled cows was calculated as: $CY = 0.41 + 0.000208\ W$ where W is the live weight at disposal (28). Values of disposed animals depended on a schedule of prices as shown in Lopez-Villalobos et al. (22). Other income was considered to be NZ\$17.00/ha.

Farm production costs. Average farm production costs were taken from Livestock Improvement (20), and included both direct expenses and overheads as given in Lopez-Villalobos et al. (22). Direct expenses per cow were NZ$316 and included: labour, animal health, breeding and herd testing, farm dairy expenses, electricity and freight. Direct expenses and overheads per hectare were NZ$1071 and included: pasture renovation, fertiliser, weed and pest control, repairs and maintenance, vehicle expenses, administration, standing charges and depreciation. Additional costs (meal, labour, animal health and breeding) for rising 1-yr and 2-yr olds were NZ$93 and NZ$82 per animal, respectively. Capital costs for cows and replacements were included as the cost of borrowing capital at 12 % interest. Values of rising 1-yr olds were: F, NZ$364; J, NZ$327; and A, NZ$346. Values of rising 2-yr olds were: F, NZ$704; J, NZ$651; and A, NZ$678. Values of cows were: F, NZ$868; J, NZ$828; and A, NZ$848. Values of crossbred animals were proportional to straightbred means according to their breed composition.

Processing, sales and marketing costs. These costs were derived from an engineering model of a milk company integrated for the manufacture of standardised WMP, butter and casein. Manufacturing costs were based on the models suggested by Bangstra et al. (4), Hillers et al. (15) and Wiles (31), and values were updated to represent averages for the New Zealand dairy industry (K. Kirkpatrick, 1998, personal communication). To account for differences in milks with different compositions, some costs were related to volume of milk processed and others were related to the amount of end products. Costs per kilogram of product processed decreased as the yield of the product from a given volume of milk increased.

The operating costs for the milk vats and collection tankers (labour, diesel, repairs and maintenance and road user charges) were added to the capital costs. These costs were estimated at NZ$17/1000 L milk, regardless of milk composition. For the manufacture of WMP, some costs were considered to be related to the volume of milk processed up to the completion of evaporation (31), and other costs were related to the amount of milk solids after evaporation. Costs of labour, repairs and maintenance, energy, cleaning, administration and capital costs were split, with 35% related to volume of milk processed and the remaining 65% to the amount of end product. Costs of packing and storage were directly related to the yield of WMP. It was estimated that for the manufacture of WMP, the costs were NZ\$26/1000 L milk plus NZ\$459/tonne WMP processed. Manufacturing costs per tonne of butter and casein were estimated at NZ\$350 and NZ\$1350, respectively. Costs of sales and marketing included tariffs, transport, distribution and marketing incurred in New Zealand and overseas. Across dairy products, these costs were calculated at NZ\$580/tonne of product.

The parameters of economic efficiency calculated were: farm costs per hectare, farm costs per kilogram of milk solids (fat plus protein), and the sum of vats, collection and manufacturing costs per kilogram of milk solids.

Pricing System

The part of the model which simulated the yield of dairy products and in-plant processing costs was also used to calculate the values for fat, protein and milk that the dairy company would pay to the dairy farmers supplying the milk under the formula:

$$\text{Pay-out} = a\,(\text{kg fat}) + b\,(\text{kg protein}) - c\,(\text{L milk})$$

where the factor a relates to the value per kg of fat, the factor b relates to the value per kg of protein and the factor c relates to the value of milk volume (6, 26). In each year, given the values of various dairy products, the model calculated the marginal returns of one unit of milk (mv_m), fat (mv_f) or protein (mv_p). The factor c was equal to mv_m, and the factors a and b were obtained by solving the following equation system:

$$\begin{aligned} a\,\text{TF} + b\,\text{TP} &= \text{IDP} - \text{MSMC} - c\,\text{TM} \\ a - b\,(mv_f/mv_p) &= 0 \end{aligned}$$

where TF, TP and TM were the total quantities of fat, protein and milk, respectively, IDP was the income from dairy products and MSMC was the costs of vats and milk collection plus costs of manufacturing, selling and marketing of dairy products. The marginal value for milk took into account costs related to vats, collection and manufacture, which were associated with the volume of milk handled. The marginal values for fat and protein took into account the realised income from the dairy products after deduction of the costs associated with the weight of product produced and that part of the costs (in the case of WMP) connected with the volume handled. The proportion mv_f/mv_p forces the solution for a and b to be in proportion to the value received for fat and protein in the international market after processing costs.

RESULTS

Industry Production of Milk Components

Industry outputs of milk, fat, protein and lactose are shown in Table 2. Compared to the production for the base season, 25 yr of selection within-breed (straightbreeding) increased the yields of milk (880 million L; 9%), fat (43 million kg; 9%), protein (80 million kg; 22%) and lactose (41 million kg; 9%), and decreased the number of cows (260, 000; 8%). Upgrading to J caused the smallest increase in milk volume (523 million L; 5%) and lactose (25 million kg; 5%), the largest increase in fat (77 million kg; 16%) and protein (95 million kg; 27%) and the smallest decrease in number of cows (12,000; 0.4%). Upgrading to F caused the largest increase in milk volume (997 million L; 10%) and lactose (47 million kg; 10%), an increase in fat by 35 million kg (8%) and protein by 77 million kg (21%) and the largest decrease in number of cows (339,000; 11.0%). Effects of rotational crossbreeding strategies were only slightly different from the intermediate between the effects caused by UPGF, UPGJ and UPGA. The UBB strategy was ranked second (after UPGJ) for total production of fat and protein.

Industry Production of Dairy Products

Total industry production of milk products after 25 yr of selection and breeding are shown in Table 2. Relative to the base year, straightbreeding resulted in an increase in WMP (104 million kg; 9%), butter (19 million kg; 10%) and casein (47 million kg, 82%). Upgrading to F resulted in the largest increase in WMP (118 million kg; 10%), an increase in butter by 5 million kg (3%) and an increase in casein by 41 million kg (72%). Upgrading to J resulted in the lowest increase in WMP (62 million kg; 5%), and the largest increase in butter (72 million kg; 39%) and casein (70 million kg; 123%). Upgrading to A decreased butter by 3 million kg. The two-breed FJ rotation increased casein by values which were intermediate between those achieved by UPGF and UPGJ, but the increases in WMP and butter were higher than the intermediate increases.

Value of Butter

In scenario II, the average value of butter depended on the total amount of butter sold. Upgrading the cow population to J for 25 yr resulted in 72 million kg butter being sold at the marginal value of NZ$0.45 per kg whereas UPGF increased butter production by only 5 million kg. Accordingly, the average values of butter in year 25 were NZ$2.287 and NZ$2.939 per kg for UPGJ and UPGF, respectively (Table 2).

Industry Profit

Industry incomes from dairy products are shown in Table 3. Selection for 25 yr resulted in increases in income from dairy products ranging from NZ$688 million (14%) for UPGA up to NZ$1000 million (20%) for UPGJ when value of butter was assumed constant through the years (scenario I). When marginal production of butter was paid at NZ$0.45 per kg, income from dairy products ranged from NZ$688 million (14%) for UPGA up to NZ$817 million (17%) for UPGJ.

TABLE 2. Number of cows, industry production of milk and dairy products, and value of butter for the New Zealand dairy industry with different breeding strategies comprising of Holstein-Friesian (F), Jersey (J) and Ayrshire (A) breeds from 1,224,911 ha.

		Means after 25 yr								
	Base year	Straight-breeding	Upgrading			Two- and three-breed rotations				
			F	J	A	FJ	FA	JA	FJA	UBB[1]
Cows, 10^3	3065	2804	2726	3053	2932	2853	2831	2947	2869	2904
Milk components										
Milk, 10^6 L/yr	9874	10,754	10,871	10,397	10,804	10,668	10,849	10,654	10,745	10,572
Fat, 10^6 kg/yr	467	510	502	544	493	525	497	521	515	529
Protein, 10^6 kg/yr	359	439	436	455	433	446	434	445	443	447
Lactose, 10^6 kg/yr	464	505	511	489	508	501	510	501	505	497
Dairy Products										
WMP[2], 10^6 kg/yr	1170	1274	1288	1232	1280	1264	1285	1262	1273	1252
Butter, 10^6 kg/yr	186	205	191	258	183	226	186	221	211	234
Casein, 10^6 kg/yr	57	104	98	127	97	112	97	112	107	116
Value of butter (scenario II)[3], NZ$/kg	2.995	2.767	2.939	2.287	2.995	2.548	2.995	2.592	2.695	2.480

[1] Use of best bulls regardless of the breed.

[2] Whole milk powder.

[3] In scenario II, butter produced above the production level for the base year was valued at 15% of the base value.

Income from beef in the base year, NZ$231 million, accounted for 5% of the total gross income (Table 3). After 25 yr, this was reduced to NZ$225 million by UPGF and to NZ$186 million by UPGJ, because the number of animals in the national herd was reduced to meet the increases in feed requirements per cow caused by the improvement in milk production and changes in live weight. Breed effects on beef income were important; UPGF created a national herd with fewer but heavier cows than UPGJ, causing the income from beef to be higher for UPGF than for UGPJ.

Farm expenses were reduced after 25 yr due to the reduction in number of cows. The largest reduction in farm expenses was caused by UPGF (NZ$151 million; 6%) whereas the smallest reduction was caused by UPGJ (NZ$29 million; 1%) (Table 3). This resulted in farm costs per hectare being lower for UPGF than for UPGJ. Rotational FJ, UPGJ and UBB had the lowest farm costs per kilogram of milk solids (Table 4).

Upgrading to F resulted in the largest increase in costs of vats and collection (10%), whereas UPGJ increased these costs by only 5% (Table 3). Other mating strategies resulted in increases intermediate between UPGF and UPGJ. Manufacture, sales and marketing costs of dairy products were NZ$1752 million for the base year (Table 3). Selection and UPGJ for 25 yr resulted in the highest increase in these costs (NZ$278 million; 16%) followed by rotational FJ and UBB (NZ$259 million, 15%). However, UPGJ also resulted in the lowest processing costs per kilogram of milk solids (Table 4).

The industry net income for the base year was NZ$489 million. Under scenario I, 25 yr of selection and UPGJ resulted in the highest net income followed by rotational FJ and UBB. By contrast, under scenario II, which assumed that the production of extra butter above the base year level will be worth only NZ$0.45/kg, the highest industry net income was achieved by UPGF, followed by straightbreeding and rotational FJ.

TABLE 3. Gross and net incomes and production costs for the New Zealand dairy industry with different breeding strategies comprising of Holstein-Friesian (F), Jersey (J) and Ayrshire (A) breeds from 1,224,911 ha.

		Means after 25 yr								
	Base	Straight-	Upgrading			Two- and three-breed rotations				
	year	breeding	F	J	A	FJ	FA	JA	FJA	UBB[1]
Income from dairy products, NZ$$10^6$										
Scenario I[2]	4903	5694	5645	5903	5591	5789	5615	5767	5734	5805
Scenario II	4903	5647	5634	5720	5591	5688	5615	5677	5671	5685
Income from beef, NZ$$10^6$	231	215	225	186	206	201	218	199	203	198
Gross income, NZ$$10^6$										
Scenario I	5155	5930	5891	6110	5818	6010	5854	5987	5958	6024
Scenario II	5155	5883	5880	5927	5818	5909	5854	5898	5894	5904
Farm expenses, NZ$$10^6$	2749	2628	2598	2720	2681	2643	2640	2680	2650	2663
Vats and collection, NZ$$10^6$	165	180	182	174	181	179	182	179	180	177
Manufacture, sales and marketing, NZ$$10^6$	1752	1989	1982	2030	1964	2011	1972	2004	2001	2011
Total expenses, NZ$$10^6$	4666	4798	4762	4924	4826	4833	4794	4863	4830	4851
Net income, NZ$$10^6$										
Scenario I	489	1133	1129	1185	993	1177	1059	1124	1127	1173
Scenario II	489	1086	1119	1002	993	1076	1059	1035	1064	1052

[1] Use of best bulls regardless of the breed.

[2] In scenario I, values for whole milk powder, casein and butter were assumed to be constant across 25 yr. In scenario II, butter produced above the production level for the base year was valued at 15% of the base value.

Pricing System

The calculated values for the factors *a*, *b* and *c* for the payment of milk are shown in Table 4. Values for the base year were NZ$2.737/kg fat, NZ$5.917/kg protein and –NZ$0.042/L milk. Factor *c* was not sensitive to the changes in milk composition caused by selection and crossbreeding strategies. This factor was constant at –NZ$0.042/L milk across years and mating strategies. Under scenario I, factors *a* and *b* were insensitive to the changes in the yield of milk components, mainly because the values of dairy products were assumed to be constant. However, under scenario II, UPGJ, rotational FJ and UBB caused the factor *a* to be reduced and the factor *b* to be increased more significantly than the other strategies.

DISCUSSION

The present study evaluated the effect of selection and mating strategies on industry production of milk components and dairy products, and industry net income for the New Zealand dairy industry over 25 yr. Results confirm that variation within and between breeds for milk production can be exploited to alter yields of milk and its components through selection and crossbreeding (11). Each selection and mating strategy resulted in different levels of industry production of milk components and dairy products (Table 2). In agreement with the predictions of Wiles (31, 32) and Campbell (5), UPGF resulted in the highest production of milk and lactose, which led to the highest production of WMP. Upgrading to J resulted in the highest production of fat and protein, which led to the highest production of butter and casein (Table 2).

Industry income from dairy products was sensitive to the amount of butter and its value for each of the breeding strategies. Under scenario II, UPGJ resulted in 72 million kg butter being sold at the marginal value of NZ$0.45 per kg, whereas UPGF increased butter production by only 5 million kg. Accordingly, the average values of butter in the year 25 were NZ$2.287 and NZ$2.939 per kg for UPGJ and UPGF, respectively (Table

TABLE 4. Payment for milk components and economic efficiency in the production of milk and manufacture of dairy products by the New Zealand dairy industry with different breeding strategies comprising of Holstein-Friesian (F), Jersey (J) and Ayrshire (A) breeds.

		Values after 25 yr								
	Base	Straight-	Upgrading			Two- and three-breed rotations				
	year	breeding	F	J	A	FJ	FA	JA	FJA	UBB[1]
Payments for milk components										
Scenario I[2]										
Factor for fat, NZ$/kg	2.737	2.726	2.730	2.710	2.731	2.720	2.731	2.721	2.724	2.717
Factor for protein, NZ$/kg	5.917	5.891	5.901	5.858	5.903	5.879	5.903	5.881	5.887	5.874
Factor for volume, NZ$/L	−0.042	−0.042	−0.042	−0.042	−0.042	−0.042	−0.042	−0.042	−0.042	−0.042
Scenario II										
Factor for fat, NZ$/kg	2.737	2.726	2.678	1.989	2.731	2.280	2.731	2.325	2.433	2.205
Factor for protein, NZ$/kg	5.917	5.891	5.937	6.319	5.903	6.172	5.903	6.143	6.083	6.210
Factor for volume, NZ$/L	−0.042	−0.042	−0.042	−0.042	−0.042	−0.042	−0.042	−0.042	−0.042	−0.042
Efficiency										
Farm costs, NZ$/ha	2245	2145	2121	2221	2189	2157	2155	2188	2164	2174
Farm costs, NZ$/kg of MS[3]	3.327	2.767	2.771	2.724	2.894	2.721	2.835	2.774	2.767	2.728
Manufacture costs, NZ$/kg of MS	1.328	1.318	1.333	1.268	1.338	1.299	1.336	1.302	1.312	1.291

[1] Use of best bulls regardless of the breed.

[2] In scenario I, values for whole milk powder, casein and butter were assumed to be constant across 25 yr. In scenario II, butter produced above the production level for the base year was valued at 15% of the base value.

[3] Milk solids, defined as kilograms of fat plus kilograms of protein.

2). This caused income from dairy products to be significantly reduced by UPGJ and only slightly reduced by UPGF (Table 3).

The live weight of cows affects the stocking rate and profitability of the dairy farm through its effects on feed requirements for maintenance, value of disposed animals and farm costs. Income from beef in year 25 was higher for UPGF than for UPGJ (Table 3), confirming that Holstein-Friesian produce higher income from beef than Jerseys (2, 31). Upgrading to F reduced the national herd by 9%, whereas UPGJ reduced the national herd by only 1% (Table 2), therefore UPGJ caused the smallest reduction in farm expenses per hectare (Table 4). Higher beef income and lower farm costs have likely contributed to the growing popularity of the Holstein-Friesian breed in New Zealand (16). However, farm costs per kilogram of milk solids were lower for rotational FJ and UPGJ than for UPGF. Compared to UPGF, the mating strategies UPGJ, UBB and rotational FJ resulted in a larger quantity of milk solids from a smaller volume of milk (Table 2). Consequently, manufacturing costs per kilogram of milk solids were lower for these latter three strategies than for UPGF (Table 4).

Results shown in Table 3 show that adoption of mating strategies will depend on the future economic realisations of milk components and costs incurred. Under the assumption that the value of butter remains constant through the years (scenario I), UPGJ resulted in the largest net income followed by rotational FJ and UBB. On the other hand, if extra production of butter is assumed to be sold at NZ$0.45/kg (scenario II), UPGF resulted in the largest net income, followed by straightbreeding and rotational FJ.

One objective of the milk payment system in New Zealand is to provide market indicators to farmers of the relative values of milk components (26). This is achieved by valuing milk on the returns from international sale of dairy products partitioned according to fat and protein yields, after accounting for total volume. Under scenario II, the factors a, b and c differed more widely between mating strategies than under scenario I (Table 4). The more extreme differences were between UPGF and UPGJ, reflecting differences in the value of butter products and processing costs. Selection and UPGF for 25 yr resulted in values for *a*, *b* and *c* similar to the base year, whereas selection and UPGJ reduced the value for the factor *a* and increased the value for the factor *b* because under scenario II, the value of marginal butter was only NZ$0.45/kg.

It must be noted that the model assumed a fixed amount of dry matter utilised per hectare from a fixed area for dairying. Therefore, the numbers of cows and replacements were reduced to allow for the increased feed requirements per animal due to increases in production of milk components and changes in live weight. Another option would have been to assume that increases in feed requirements could be met either by extending the area for dairying, improving the pasture growth or using supplementary feed. The model can accommodate these alternatives but the present study focused on the improvement in the biological and economic efficiency for a given amount of metabolisable energy.

Possible effects of selection and heterosis on the reproductive performance of cows were not considered in the present study. Published genetic correlations between fertility and production traits for New Zealand dairy cattle (12) show that there is an antagonism between milk production and fertility. Studies (24, 7) have shown that high genetic merit cows have a greater number of services per conception, lower pregnancy rates to first and second service and, subsequently, higher infertility rates. Mayne (27) indicated that the negative effect of production on reproduction was caused indirectly by the inability of genetically improved cows to consume enough additional feed in early lactation to support their greater potential milk production and avoid the loss in live weight in early lactation. Reports on effects of breed and heterosis on the reproductive performance of dairy cows are scarce. The study of Grosshans et al. (12) showed that under New Zealand conditions there are differences in reproductive performance, with Jersey cows being superior to Friesian cows. In Britain, Donald and Russell (8) found that crossbred cows were about 10% more likely to conceive than straightbreds. Results obtained from the present study might be different if these effects were considered because reproductive performance influences profitability through its effects on milk production, reproductive culling rates and animal sales.

Breed and heterosis effects for survival were not considered in the present study because there were no estimates of phenotypic and genetic correlations between this trait and the others considered in the selection objective. Net income of crossbreeding strategies are likely to be underestimated because heterosis for survival and fertility increase the profitability of crossbred herds through its impact on age structure and animal sales (22).

Rotational FJ seems to be an alternative mating strategy to exploit variation within and between breeds for milk production through a stratified breeding scheme combining selection and crossbreeding as methods of genetic improvement. At the level of industry, this mating strategy might allow that future changes in the production system (e.g., farm practices, calving pattern and new pastures) and market conditions to be covered more efficiently than by a strategy with only one breed (17). However, the implementation of this systematic crossbreeding system requires a stratified organisation in the dairy population, with a commercial crossbreeding population being supplied with semen from straightbred sires of high genetic merit produced in open nucleus herds. In reality, most of the dairy herds in New Zealand are composed of a mixture of straightbred and crossbred cows, and trends in semen usage show that farmers are using semen of the best available bulls regardless of breed (19).

CONCLUSIONS

National genetic evaluation of New Zealand dairy cattle shows that crossbred F × J and J cows have higher merit for farm income than F and A cows. Results from the present study show that widespread implementation of crossbreeding or changes to other breeds have important effects on profitability of the dairy industry. For a fixed amount of feed (or area) utilised for milk production, selection and crossbreeding strategies affect the size of the national herd and the yield of milk components and dairy products, which in turn affect the income from dairy products and beef, and costs for the production of milk, and the manufacture and marketing of dairy products.

Adoption of crossbreeding strategies for the New Zealand dairy industry will depend on the future values of dairy products and the costs incurred. The present study found that the relative profitability of UPGF or UPFJ depends on the future value of butter. Crossbreeding strategies and UBB maintain the genetic diversity in the population and will allow the dairy industry greater flexibility to adjust for future modifications in farm practices and processing and marketing conditions.

REFERENCES

1 AFRC. 1993. Energy and Protein Requirements of Ruminants. An Advisory Manual Prepared by the AFRC Technical Committee on Response to Nutrients. CAB INTERNATIONAL, Wallingford, United Kingdom.

2 Ahlborn, G., and A. M. Bryant. 1992. Production, economic performance and optimum stocking rates of Holstein-Friesian and Jersey cows. Proc. N. Z. Soc. Anim. Prod. 52:7-9.

3 Ahlborn-Breier, G., and W. D. Hohenboken. 1991. Additive and nonadditive genetic effects on milk production in dairy cattle: evidence for major individual heterosis. J. Dairy Sci. 74:592-602.

4 Bangstra, B. A., P. J. Berger, A. E. Freeman, R. E. Deiter, and W. S. La Grange. 1988. Economic value of milk components for fluid milk, cheese, butter, and nonfat dry milk and responses to selection. J. Dairy Sci. 71:1789-1798.

5 Campbell, I. L. 1966. Are we using the right breed? Dairyfarm. Annu., Massey Univ. 18:9-18.

6 Creamer, L. K., and W. A. McGillivray. 1972. Payment for milk. II. Relationships between net value of milk supplies and pay-out calculated by different methods. N. Z. J. Dairy Sci. Technol. 7:80-91.

7 Dillon, P., and F. Buckley. 1998. Effects of genetic merit and feeding on spring calving dairy cows. Proc. Ruakura Farmers' Conf. 50:50-56.

8 Donald, H. P., and W. S. Russell. 1968. Some aspects of fertility in purebred and crossbred dairy cattle. Anim. Prod. 10:465-471.

9 Ducrocq, V., and R. L. Quaas. 1988. Prediction of genetic response to truncation selection across generations. J. Dairy Sci. 71:2543-2553.

10 Gibson, J. P. 1987. The options and prospects for genetically altering milk composition in dairy cattle. Anim. Breed. Abstr. 55:231-243.

11 Gibson, J. P. 1989. Altering milk composition through genetic selection. J. Dairy Sci. 72:2815-2825.

12 Grosshans, T., Z. Z. Xu, L. J. Burton, D. L. Johnson, and K. L. Macmillan. 1997. Performance and genetic parameters for fertility of seasonal dairy cows in New Zealand. Livest. Prod. Sci. 51:41-51.

13 Harris, B. L., J. M. Clark, and R. G. Jackson. 1996. Across breed evaluation of dairy cattle. Proc. N. Z. Soc. Anim. Prod. 56:12-15.

14 Henderson, C. R. 1963. Selection index and expected genetic advances. Pages 141-163 *in* Statistical genetics and plant breeding. W. D. Hanson and H. F. Robinson, ed. National Academy of Sciences, National Research Council Publication No. 982, Washington, DC.

15 Hillers, J. K., V. H. Nielsen, A. E. Freeman, J. Dommerholt, and R. E. Deiter. 1980. Value of fat and protein in producer milk. J. Dairy Sci. 63:322-327.

16 Holmes, C. W., G. F. Wilson, D. D. S. MacKenzie, D. S. Flux, I. M. Brookes, and A. W. F. Davey. 1987. Milk Production from Pasture. Butterworth Agricultural books, Wellington, New Zealand.

17 Land, R. B. 1981. An alternative philosophy for animal breeding. Livest. Prod. Sci. 8:95-99.

18 Lankveld, J. M. G. 1994. Protein standardized milk products; composition & properties. Pages 70-81 *in* Milk Protein - Definition & Standardization. Int. Dairy Fed., Brussels, Belgium.

19 Livestock Improvement. 1997. Dairy Statistics 1996-1997. Livestock Imp. Corp. Ltd., Hamilton, New Zealand.

20 Livestock Improvement. 1997. Economic Survey of Factory Supply Dairy Farmers 1996-1997. Livestock Imp. Corp. Ltd., Hamilton, New Zealand.

21 Lopez-Villalobos, N., D. J. Garrick, H. T. Blair, and C. W. Holmes. 1998. Effect of selection and crossbreeding on long-term rates of genetic gain in New Zealand dairy cattle. J. Dairy Sci. (Submitted).

22 Lopez-Villalobos, N., D. J. Garrick, C. W. Holmes, H. T. Blair, and R. J. Spelman. 1998. Profitabilities of some mating systems for dairy herds in New Zealand. J. Dairy Sci. (Accepted).

23 Mackle, T. R., C. R. Parr, G. K. Stakelum, A. M. Bryant, and K. L. Macmillan. 1996. Feed conversion efficiency, daily pasture intake, and milk production of primiparous Friesian and Jersey cows calved at two different liveweights. N. Z. J. Agric. Res. 39:357-370.

24 Macmillan, K. L., I. J. Lean, and C. T. Westwood. 1996. The effects of lactation on the fertility of dairy cows. Aust. Vet. J. 73:141-147.

25 MAF. 1997. Situation and outlook for New Zealand agriculture 1997. Ministry Agric., Wellington, New Zealand.

26 Marshall, K. R. 1989. The origin and history of the A + B - C payment system. Pages 9-11 *in* Milk Payment and Quality, Animal Industries Workshop. G. K. Barrell, ed. Lincoln Coll., Canterbury, New Zealand.

27 Mayne, S. 1998. Selecting the correct dairy cow for grazing systems. Proc. Ruakura Farmers' Conf. 50:45-49.

28 McCall, D. G., and P. R. Marshall. 1991. Factors affecting beef finishing efficiency on pasture. Proc. N. Z. Soc. Anim. Prod. 51:453-457.

29 Spelman, R. J., and D. J. Garrick. 1997. Effect of live weight and differing economic values on responses to selection for milk fat, protein, volume, and live weight. J. Dairy Sci. 80:2557-2562.

30 Upton, M. 1989. Livestock productivity assessment and herd growth models. Agric. Syst. 29:149-164.

31 Wiles, P. G. 1987. Cost model comparing differences in returns for milk produced by Friesian and Jersey type herds. N. Z. J. Dairy Sci. Technol. 22:221-240.

32 Wiles, P. G. 1988. Cost model comparing differences in returns for milk produced by Friesian and Jersey type herds. II. Milk manufactured into cheese. N. Z. J. Dairy Sci. Technol. 23:223-237.

Chapter 6

General Discussion: Further topics on crossbreeding for the New Zealand dairy industry

The present study focused on the joint effects of continued within breed selection and systematic crossbreeding on the productivity and profitability of the New Zealand dairy industry. Mating strategies involving the main breeds farmed in New Zealand; Holstein-Friesian (F), Jersey (J) and Ayrshire (A), were simulated. Effects of mating systems on profitability (net income per hectare) of commercial herds were evaluated in Chapter 3.

The effects of crossbreeding systems in combination with selection implemented in the whole industry on long-term rates of genetic gain and profit (net income) of the industry were evaluated in chapter 4 and chapter 5, respectively. The mating strategies simulated were upgrading to F (UPGF), upgrading to J (UPGJ), upgrading to A (UPGA), two- and three-breed rotation and use of best bulls (UBB) irrespective of breed.

This chapter discusses the effects of mating strategies implemented at the industry level on the profitability of individual farmers. In addition, further aspects of crossbreeding for the New Zealand dairy industry will be addressed: multibreed selection index, nucleus herds, inclusion of crossbred cows as bull mothers, use of crossbred bulls and future payment systems.

WHOLE INDUSTRY AND INDIVIDUAL FARM PROFIT

Productivities and profitabilities per cow and per hectare in the base year and year 25 for F, J and crossbred F × J herds when the industry uses three different mating strategies are shown in Table 1. Income from milk for the herds were calculated by using the values for fat, protein and milk volume derived for each of the mating strategies (chapter 5, Table 5, scenario II). They were:

Base year,

$$[(\text{NZ\$}2.74 \times \text{kg fat}) + (\text{NZ\$}5.92 \times \text{kg protein}) - (\text{NZ\$}0.042 \times \text{L milk})]$$

Year 25,

UPGF, [(NZ\$2.68 × kg fat) + (NZ\$5.94 × kg protein) – (NZ\$0.042 × L milk)]

UPGJ, [(NZ\$1.99 × kg fat) + (NZ\$5.94 × kg protein) – (NZ\$0.042 × L milk)]

Rotational FJ, [(NZ\$2.28 × kg fat) + (NZ\$6.17 × kg protein) – (NZ\$0.042 × L milk)]

Income from beef and on-farm costs were as explained in chapter 3. Widespread use of rotational crossbreeding system resulted in lower farm incomes for F, J and crossbred F × J herds than herds of the same breed when the cow population was upgraded to F or J. These results show that mating strategies used at the level of the industry affect the number of active cows and the rate of genetic gain, which in turn affect the profitability of individual farmers. The difference in net income per hectare of a J herd when the entire population was upgraded to J and a J herd when the entire population was upgraded to F is NZ\$25 (NZ\$1068 – NZ\$1043). These results also show that herds using rotational FJ had higher net income than F and J herds across all industry mating strategies.

From these results it can be concluded that the dairy industry must maintain good communication and organisation between dairy farmers, so that appropriate breeding objectives for the entire industry can be defined. The model developed in the present study provides accurate forecasts of total industry yields of milk and dairy products, and of production costs. Accurate predictions of the future value of dairy products and trends in demand for current and new dairy products are needed to make informed decisions about crossbreeding and selection strategies.

MULTIBREED SELECTION INDEX

In most countries, breeding values for traits of economic importance are estimated using best linear unbiased prediction (BLUP) procedures (13) under an animal model for single trait or multiple traits. These procedures were originally developed to allow the genetic evaluation of animals of a specific breed. Many industries utilise crossbred

TABLE 1. Productivities and profitabilities per cow and per hectare in the base year and year 25 for three different herds[1], when the industry uses three different mating strategies.

				Industry mating strategy (year 25)								
	Base year			Upgrading to F			Upgrading to J			Rotational FJ		
	Herd			Herd			Herd			Herd		
	F	J	Rot FJ	F	J	Rot FJ	F	J	Rot FJ	F	J	Rot FJ
Live weight, kg	481	399	446	489	407	454	489	409	455	489	407	454
Production per cow												
Milk, L	3402	2706	3161	4022	3322	3810	3986	3373	3819	3977	3332	3793
Fat, kg/yr	154	147	156	185	177	188	183	179	188	182	177	187
Protein, kg/yr	121	107	118	161	147	160	159	149	160	158	147	158
DM requirements per cow, kg/yr	4982	4199	4595	5427	4661	5062	5403	4698	5068	5396	4665	5048
Stocking rate, cows/ha	2.41	2.86	2.61	2.21	2.58	2.37	2.22	2.55	2.37	2.22	2.57	2.38
Production per hectare												
Milk, L/yr	8194	7733	8257	8894	8552	9034	8854	8615	9041	8844	8571	9016
Fat, kg/yr	371	419	408	408	455	446	406	457	446	405	456	445
Protein, kg/yr	291	305	308	355	379	378	352	381	378	351	378	376
Gross income, NZ$/ha	2607	2799	2772	3046	3248	3247	3026	3300	3245	3019	3284	3233
Production costs, NZ$/ha	2209	2369	2267	2116	2240	2156	2121	2231	2154	2122	2239	2159
Net income, NZ$/ha	398	430	505	930	1043	1092	905	1068	1090	897	1045	1075

[1] F = Holstein-Friesian, J = Jersey, and Rot FJ = Rotational FJ.

animals but few industries measure performance of these crossbreds and maintain a database for both straightbred and crossbred animals. For these last industries, a multibreed genetic evaluation is required to account for breed and heterotic effects in the estimation of breeding values. This is the case for the New Zealand dairy industry where BLUP procedures have been developed to estimate breeding values across breeds for cow mature live weight, survival, and lactation yields of milk, fat and protein (10). Breed and heterotic effects are estimated simultaneously.

In a straightbred population, parents of the next generation can be selected on breeding values or on an economic index which combines economic values and estimated breeding values (12, 25). In a multibreed population, selection of parents is more complicated because nonadditive effects have to be considered.

A multibreed selection index (MSI) has been proposed by Kinghorn (16, 17) to simultaneously use within and between breed selection in a structured way. An index is constructed for each candidate animal from the within breed estimated breeding value and a crossbreeding component value calculated from breed and heterotic effects expressed in the potential progeny of the candidate animal. Consequently, the value of the crossbreeding component depends on the breed composition of the candidate animal and its mates. A conceptually similar approach was applied to the North American beef cattle industry (22).

Several authors (6, 7, 28) proposed strategies to rank sires in a multibreed population using BLUP procedures. Similar to Kinghorn (16, 17), the genetic value of a sire was defined as the sum of two parts: one affected by additive genetic effects and another affected by nonadditive genetic effects. The additive genetic component corresponds to breeding value within breed and the nonadditive component refers to the interaction between the animal and its mates.

One limitation of MSI is that only the performance of the progeny is maximised and future improvement still depends on the improvement in the straightbred populations by means of within breed selection (28). In other words, straightbred selection schemes must be maintained to improve the additive genetic merit of animals and further improvement can be achieved by a mating strategy in which both breed and heterotic effects are exploited. Shepherd and Kinghorn (27) and Hayes et al., (11) proposed improvements on the mating algorithm to maximise the predicted performance of the grand progeny (two generations). However, these improvements demand considerable computing capacity.

In the present study (chapter 4), the selection processes considered only the additive genetic merit of bulls and cows. The expected performance of progeny was calculated as the average superiority of selected parents (breed effect plus within breed estimated breeding value) plus expected heterosis in the case of crossbred animals. However, parents were not selected for improvement in crossbred progeny performance. A further study is recommended to evaluate a mating strategy in which cows of one breed are mated to bulls of the same or another breed, with the objective of improving the performance of progeny considering both the additive and the non-additive effects as suggested by Kinghorn (18) and Hayes et al. (11).

NUCLEUS HERDS

Results from chapter 4 show that upgrading strategies increased the number of active cows and consequently the rate of genetic gain, confirming results published by Shannon (26). However, wide use of crossbreeding caused a reduction in the numbers of active cows with the consequent erosion of selection intensity in the cows to breed bulls selection pathway, and in the rate of genetic gain as predicted by Swan and Kinghorn (29).

The compromise between the advantages of crossbreeding and the adverse effects on the size of the active cow population would be reduced by the use of multiple ovulation and embryo transfer (MOET) in the bull-mother selection pathway, or by the creation of nucleus herds using MOET coupled with full-sib selection, embryo-splitting, sexing, cloning, and in-vitro fertilisation (5). Ahlborn-Breier and Hohenboken (1) suggested the creation of straightbred F and J nucleus herds, carrying out genetic improvement through within breed selection and then supplying semen from high genetic merit bulls to commercial herds employing a two-breed rotational crossbreeding system. Creation of nucleus herds can also be important for the dairy industry if novel milk characteristics (e.g., milk proteins, milk colour and milk hardness) gain importance. A cost-benefit analysis should be carried out to evaluate the economic feasibility of this strategy.

CROSSBRED COWS AS BULL MOTHERS AND CROSSBRED BULLS

Currently, only straightbred (active) cows and bulls are selected on breeding worth (BW) to be used for the production of straightbred male replacements that can be progeny tested based on records of straightbred and crossbred daughters. However, crossbred cows and bulls could also be considered as bull parents because they can be ranked on BW. If crossbred cows are accepted as bull mothers, faster rates of genetic gains may result due to increased selection intensities in the cows to breed bulls selection pathway. The progeny resulting from crossbred cows will also be crossbred animals. Therefore, accepting crossbred cows as bull mothers also requires the acceptance of crossbred bulls to breed bulls and cows. Existing straightbred cows may be lost in such a scheme, leading to an amalgamation of the current separate straightbred selection schemes (8).

FUTURE PAYMENT SYSTEMS

Dairy farmers in New Zealand are paid on the yields of fat and protein with a penalty for volume. The system is known as: $a + b - c$, where a and b are the values per kilogram of fat and protein, respectively, and c is the penalty per litre of milk.

This payment system was proposed in 1968 but it was not adopted until 1987 (21). In 1972, Creamer and McGillivray (4) showed that considerable disparities existed between the actual net realisations for milk of different compositions and the payout based on the fat only system. They also showed that the disparities could be reduced, but not eliminated, by the $a + b - c$ system. Paul (24) also showed that payment for milk based on yields of fat, protein and lactose would be better than the payment based only on yields of fat.

Changes in the milk payment system were immediately followed with changes in the selection criteria for cows and bulls. In 1987, the payment breeding index (PBI) was introduced in the New Zealand dairy industry, and was calculated as the sum of products between relative economic values and breeding indexes for fat, protein and milk volume (31). The relative economic values for fat, protein and milk used in 1987 and 1988 were: 1 (kg fat) : 1 (kg protein) : –0.01 (L milk).

Future milk payment systems have been discussed by Garrick and Lopez-Villalobos (8). Farmers have stressed the need to change the basis for ranking animals to reflect milk components other than milkfat, protein and volume. A number of farmers believe lactose should be included in the breeding programme, although these farmers seem to be divided as to whether the lactose should have a positive value or a negative value. Some researchers believe that casein will soon be the sole protein component for which farmers will be paid (30).

Polymorphisms at the loci of β-lactoglobulin, α-s_1 casein and κ-casein can influence the processing and yield of cheese. The B allele of β-lactoglobulin has a negative effect on the concentration of whey proteins (2) and increases the efficiency of conversion of protein into cheese. The BB genotype for κ-casein leads to shorter renetting time (23). Graham et al. (9) showed that if all cows in Australia were homozygous for the B variants of β-lactoglobulin, α-s_1 casein, β-casein and κ-casein, cheese yield would be increased by 5%.

It may be possible in the future to pay for different variants of milk proteins from individual herds with the particular variant segregated from other milks. The overall benefits have to be sufficiently large to cover the extra costs involved.

Future payment systems might consider others milk traits such as colour and flavour (8). Milk colour varies markedly between breeds and it affects the desirability of milk products in some countries. Processing costs for the removal of colour from milk are high, moreover, removal of colour may also remove the natural milk fat flavour (15).

The fatty acid composition of milk is of growing interest in human nutrition, particularly in relation to disease, and is of concern in milk processing because of its relation to the palatability and flavour of milk and the hardness of butter. There is variation within (14, 20) and between (3, 19) breeds for fat composition. MacGibbon (19) showed that, under New Zealand conditions, J cows produce milk with higher concentration of medium chain length saturated fatty acids (c8:0, c10:0, c12:0) than F cows, and also had higher c14:0, c18:0, c18:3 and lower c18:2c fatty acid proportions. MacGibbon (19) also found that the concentration of these fatty acids was significantly correlated with SFC_{10} (the solid fat content at 10°C), which is a measurement of butter hardness. These results might explain why butter from J cows is harder than butter from F cows. Therefore, future payment systems might also consider differences in the composition of fat.

One conclusion in chapter 5 was that the New Zealand dairy industry has the flexibility to adjust to future changes in the market situation by the means of selection and crossbreeding. This requires that the dairy industry must maintain the genetic resources (breeds) or create new genetic material through selection (lines), crossbreeding (crossbreds and new breeds) or genetic engineering (transgenic animals). A possible future scenario is the development of niche market milks, customised for particular products and markets (8). It is possible that the creation of cows with particular combinations of characteristics will increase the profit from the milk to a much greater extent than is achievable by current selection practices aimed at increasing total yields of protein and fat relative to feed costs. However, selection for customised milk characteristics will require a change in the payment system and processing systems which might involve milk segregation. Crossbreeding may assist in achieving these industry goals more efficiently.

GENERAL CONCLUSIONS

The main conclusions from this thesis were the following:

- Between breed differences and heterotic effects for cow mature live weight and lactation yields of milk, fat and protein are significant in New Zealand dairy cattle. Commercial dairy farmers can exploit these effects and simultaneously take advantage of within breed improvement through a rotational FJ crossbreeding system to increase farm profit.

- Wide implementation of rotational FJ crossbreeding, superimposed on the current within breed selection schemes, reduces the number of potential bull mothers and penalises the rate of genetic gain of the industry. MOET might be an alternative to maintain the selection intensity in the cow to bull pathway but this requires further study.

- Selection of parents on the basis of BW and maintaining the current breed composition of the national herd will result in a marked increase in milk volume, milkfat, and protein yield per cow, with negligible increase in live weight.

- Changes in the breed composition of the national herd will affect the average values for live weight and yields of milk, fat and protein per cow and per hectare. The widest divergences are between UPGF and UPGJ.

- Mating strategies in combination with within breed selection will result in different industry yields of milk and its components and they will be produced from different numbers of cows from a fixed amount of pasture utilised for dairying. These differences in turn will affect the yield of dairy products, on-farm and off-farm costs, resulting in different industry profits for the different strategies.

- Crossbreeding can be used in combination with selection to exploit the effects of heterosis while maintaining genetic diversity to cover changes in marketing conditions. Future costs and prices of dairy products have a major impact on decisions on mating strategies.

REFERENCES

1 Ahlborn-Breier, G., and W. D. Hohenboken. 1991. Additive and nonadditive genetic effects on milk production in dairy cattle: evidence for major individual heterosis. J. Dairy Sci. 74:592-602.

2 Akbas, Y., S. Brotherstone, and W. G. Hill. 1993. Animal model estimation of non-additive genetic parameters in dairy cattle, and their effect on heritability estimation and breeding value prediction. Journal of Animal Breeding and Genetics 110:105-113.

3 Beaulieu, A. D., and D. L. Palmquist. 1995. Differential effects of high fat diets on fatty acid composition in milk of Jersey and Holstein cows. J. Dairy Sci. 78:1336-1344.

4 Creamer, L. K., and W. A. McGillivray. 1972. Payment for milk. II. Relationships between net value of milk supplies and pay-out calculated by different methods. N. Z. J. Dairy Sci. Technol. 7:80-91.

5 Dekkers, J. C. M. 1992. Structure of breeding programs to capitalize on reproductive technology for genetic improvement. J. Dairy Sci. 75:2880-2891.

6 Elzo, M. A., and T. R. Famula. 1985. Multibreed sire evaluation procedures within a country. J. Anim. Sci. 60:942-952.

7 Elzo, M. A., and D. L. Wakeman. 1998. Covariance components and prediction for additive and nonadditive preweaning growth genetic effects in an Angus-Brahman multibreed herd. J. Anim. Sci. 76:1290-1302.

8 Garrick, D. J., and N. Lopez-Villalobos. 1998. Tomorrow's cows - some kiwi cows of the future. Proc. Ruakura Farmers' Conf. 50:39-44.

9 Graham, E. R. B., D. M. McLean, and P. Zviedrans. 1984. Effects of milk protein genetic genotypes on the cheesemaking properties of milk and on the yield of cheese. Proc. Aust. Assoc. Anim. Breed. Genet. 4:136-137.

10 Harris, B. L., J. M. Clark, and R. G. Jackson. 1996. Across breed evaluation of dairy cattle. Proc. N. Z. Soc. Anim. Prod. 56:12-15.

11 Hayes, B. J., R. K. Shepherd, S. Newman, and B. P. Kinghorn. 1998. A tactical approach to improving long term response in across breed mating plans. Proc. 6th World Congr. Genet. Appl. Livest. Prod., Armidale, Australia 25:439-442.

12 Henderson, C. R. 1963. Selection index and expected genetic advances. Pages 141-163 *in* Statistical genetics and plant breeding. W. D. Hanson and H. F. Robinson, ed. National Academy of Sciences, National Research Council Publication No. 982, Washington, DC.

13 Henderson, C. R. 1973. Sire evaluation and genetic trends. Pages 10-41 *in* Proc. Anim. Breeding Genet. Symp. in Honor of Dr. J. L. Lush, Am. Soc. Anim. Sci., Am. Dairy Sci. Assoc., Champaign, IL.

14 Karijord, Ø., N. Standal, and O. Syrstad. 1982. Sources of variation in composition of milk fat. Z. Tierz. Zuechtungsbiol. 99:81-93.

15 Keen, A. R. 1986. Future developments for profitable dairy farming: the colour and flavour of dairy products. Dairyfarm. Annu., Massey Univ. 38:36-39.

16 Kinghorn, B. P. 1982. Genetic effects in crossbreeding. II. Multibreed selection indices. Z. Tierz. Zuechtungsbiol. 99:315-320.

17 Kinghorn, B. P. 1984. A single approach to genetic improvement which exploits both selection and crossbreeding effects. Pages 473-482 *in* Proc. 2nd World Congr. Sheep and Beef Cattle Breed., Pretoria.

18 Kinghorn, B. P. 1986. Mating plans for selection across breeds. Proc. 3rd World Congr. Genet. Appl. Livest. Prod., Lincoln, NE XII:233-244.

19 MacGibbon, A. K. H. 1996. Herd-to-herd variations in the properties of milk fat. Proc. N. Z. Soc. Anim. Prod. 56:224-227.

20 Mackle, T. R., S. F. Petch, A. M. Bryant, and M. J. Auldist. 1997. Variation in the characteristics of milkfat from pasture-fed dairy cows during late spring and the effects of grain supplementation. N. Z. J. Agric. Res. 40:349-359.

21 Marshall, K. R. 1989. The origin and history of the A + B - C payment system. Pages 9-11 *in* Milk Payment and Quality, Animal Industries Workshop. G. K. Barrell, ed. Lincoln Coll., Canterbury, New Zealand.

22 Notter, D. R. 1989. EPD's for use across breeds. Pages 63-78 *in* Proc. Beef Impr. Fed., 21st Meeting, Nashville, TN.

23 Oldenbroek, J. K., and E. W. Brascamp. 1994. Breeding goals for milk composition. Proc. 5th World Congr. Genet. Appl. Livest. Prod., Guelph, Canada 18:224-226.

24 Paul, K. J. 1985. A new direction for the payment for milk. Proc. Ruakura Farmers' Conf. 37:77-85.

25 Schneeberger, M., S. A. Barwick, G. H. Crow, and K. Hammond. 1992. Economic indices using breeding values predicted by BLUP. J. Anim. Breed. Genet. 109:180-187.

26 Shannon, P. 1989. Increasing rates of genetic gain. Proc. Ruakura Farmers’ Conf. 41:6-11.

27 Shepherd, R. K. and Kinghorn, B. P. 1998. A tactical approach to the design of crossbreeding programs. Proc. 6th World Congr. Genet. Appl. Livest. Prod., Armidale, Australia 25:431-438.

28 Swan, A. A. 1992. Multibreed evaluation procedures. Ph.D. Thesis, Univ. New England, Australia.

29 Swan, A. A., and B. P. Kinghorn. 1992. Evaluation and exploitation of crossbreeding in dairy cattle. J. Dairy Sci. 75:624-639.

30 Vickers, M. 1997. Protein - what's that?. Pages 20-21 *in* Black and White News. Issue No. 40. N. Z. Holstein-Friesian Assoc.

31 Wickham, B. W. 1989. Breeding for future profit. Pages 37-41 *in* Milk Payment and Quality, Animal Industries Workshop. G. K. Barrell, ed. Lincoln Coll., Canterbury, New Zealand.

Curriculum vitae

Nicolás López Villalobos was born on the 6th of December 1961 in Villamatamoros, Chihuahua, México. He completed his primary education in 1975 in the school "Benito Juárez", Cd. Cuauhtémoc, Chihuahua, México. He finished his secondary school in 1978 in the technical school "Lázaro Cárdenas", Cd. Cuauhtémoc, Chihuahua, México. In 1978 he was awarded with a full scholarship for seven years by the Universidad Autónoma Chapingo, Chapingo, México, to complete the high school and the Bachelor degree in Agriculture. In 1985 he graduated from the "Departamento de Investigación y Enseñanza en Zootecnia", of the Universidad Autónoma Chapingo, obtaining the title of "Ingeniero Agrónomo Especialista en Zootecnia" with First Class Honours. He obtained the highest score among the students of that year, and was awarded with a travel and expenses scholarship to Cuba for two weeks. From 1985 to 1988 he was employed by the Universidad Autónoma Chapingo as a farm manager of a dairy herd located in Torreón, Coahuila, México. In that time, he also worked as an adviser for dairy farmers in the fields of nutrition and genetic improvement. From 1988 to 1991 he held the position of Lecturer in the Campus "Laguna", Torreón, Coahuila, México. He lectured two main courses: “Animal Breeding” and “Systems of Milk Production with Dairy Cattle”. In 1992 he was awarded a full scholarship to study at Massey University, by the Ministry of External Relations and Trade of New Zealand. In 1994, he obtained a Masters Degree with First Class Honours from the Department of Animal Science, Massey University, New Zealand with the thesis "Scale Effects on the Genetic Evaluation of New Zealand Dairy Cattle", under the supervision of Prof. Dorian J. Garrick and Prof. Hugh T. Blair. In March 1995, he was awarded a full scholarship by the "Consejo Nacional de Ciencia y Tecnología" to realise his Ph. D studies. He started his Ph. D program in the Department of Animal Science, Massey University, New Zealand. He is going to do post-doctoral research in the Institute of Veterinary, Biomedical and Animal Sciences, Massey University, New Zealand.