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Interactions between optimal replacement policies and feeding strategies in dairy herds

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Abstract

A dynamic performance model was integrated with a model that optimised culling and insemination policies in dairy herds using dynamic programming. The performance model estimated daily feed intake, milk yield and body weight change of dairy cows on the basis of availability and quality of feed and potential milk yield. A set of cow-states was defined by lactation number (1 to 12), calving interval (11 to 16 months), potential milk yield (15 levels) and stage of lactation (months 1 to 16). Actual performance was obtained taking into account potential performance, feed properties, and feed intake constraints. Biological and economical parameters used in the model represented actual production circumstances in Costa Rican herds. Eight feeding strategies combining two forages and four concentrate allocation systems were simulated. Different feeding strategies resulted in maximal changes of 6.8 mo. in optimal average herd-life, US$26.1 in monthly income per cow and 1.9% in replacement rates, while average calving interval was not affected. The main difference was found between feeding strategies based on flat ratios of concentrate compared with feeding strategies based on daily milk yield. Feeding flat ratios of concentrate altered the course of profitability due to restriction of the variation in feeding costs between cows and its effect on animal performance. Average herd-life and monthly income under the optimal feeding strategy were highly sensitive to changes in milk price, but less sensitive to changes in price of concentrates or price of forage. Calving interval was not sensitive to any of the factors. Comparison of optimal policies with actual parameters obtained from field data indicated that cows are being culled close to the optimal herd-life with calving intervals longer than optimal. The model is an efficient tool to study interactions between nutrition, reproduction and breeding at the animal and herd level.

Keywords: Dynamic programming; Dairy cattle; Optimisation; Breeding policies; Intake prediction

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1. Introduction

The theory of optimal culling policies in dairy farming is largely developed (Van Arendonk, 1984,

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1985b, 1986; Houben et al., 1994; Kristensen, 1994). Some practical applications have already been introduced in commercial dairies (DeLorenzo et al., 1992; McCullough and DeLorenzo, 1996). This theory relies on the use of dynamic programming and the principle of optimality (Bellman, 1957). According to this principle, a cow of a particular age should be kept in the herd as long as her marginal profit is greater than the expected average profit of a young replacement cow (Lehenbauer and Oltjen, 1998). The principle has been extended to determine the optimum time to inseminate a cow. In that case, the expected present value of the cash flow when the cow was inseminated is compared with that if she had been kept open at the same time (Van Arendonk and Dijkhuizen, 1985; McCullough and DeLorenzo, 1996). A cow should be inseminated if the anticipated loss from a longer calving interval is less than that of leaving the cow open and replacing her later in lactation.

Culling and insemination policies have a direct effect on the profitability of the dairy enterprise (Van Arendonk, 1987; Lehenbauer and Oltjen, 1998). Sub-optimal decisions will reduce the profitability of the dairy enterprise, and the degree of reduction may vary according to production circumstances. These production circumstances to some extent determine the optimum policies (Van Arendonk, 1985b, 1987; McCullough and DeLorenzo, 1996).

So far optimisation of replacement policies has been based on animal performance models in which production determines feed intake. In nutritional models, however, it is often assumed that the production potential, intake capacity and the feeding regime determine the actual intake and production. The relationships among production potential, intake capacity and actual performance is ignored in most models describing the performance of animals (e.g., Van Arendonk, 1985a). Knowledge of these relationships is essential to quantify the impact of different feeding regimes with variation in feed quality on optimal management strategies for cows.

Dairy farming in Costa Rica is characterised by a large variation in production circumstances, especially with regard to feeding strategies (Van der Grinten et al., 1993; Baars, 1998; Herrero et al., 1999). As a consequence, production costs and productivity also vary among farms. Feeding strategies depend on factors such as location of the farm, season, prices and availability of by-products. Tools for determining optimal culling and insemination policies are not yet available for these farms and decisions are currently made in an empirical way. For such a tool to be developed and applied at farm level, it must be flexible enough to account for all possible variations in production circumstances, in particular the feeding regime. Recently, an animal performance model that incorporates relationships between potential production, feeding regime and actual production has been developed (Herrero et al., 1996, 1997). The model uses information on feed and animals to predict intake of grass and supplements, as well as milk yield and body weight change in dairy cows.

The objective of the present study was to integrate the animal performance model of Herrero (1997) with the replacement model of Van Arendonk and Dijkhuizen (1985) into a Culling and Insemination Decision Support System (C&I-DSS). The model was to be used to determine the impact of feeding strategies on optimisation of replacement and insemination policies in Costa Rican dairies.

2. Material and methods

2.1. Information sources

The study used information on production circumstances on dairy farms of Costa Rica, although the method can be applied to different situations. Biological parameters required as input to C&I-DSS were calculated from data provided by Universidad Nacional de Costa Rica (UNA) and have been reported in previous studies (Vargas and Solano, 1995a,b,c; Herrero, 1997; Solano and Vargas, 1997; Vargas et al., 1998a,b, 2000; Herrero et al., 1999). Data for these studies were collected from 1985 to 1997 on dairy farms in Costa Rica, which had participated in a project that focused on the collection and analysis of data related to health, milk yield, and reproduction performance in order to provide advice to farmers and to identify adequate management practices (Pérez et al., 1989). Additional data related to current production circumstances, feed properties, and prices were collected from the local dairy industry or from governmental institutions.

2.2. General approach

The C&I-DSS is composed of two complementary models (Fig. 1). Details on these two models are described in the literature (Van Arendonk, 1985a; Herrero, 1997). We will give a general description here and details on parameters and components that were modified in order to integrate models and fit local circumstances.

The first model, the animal performance model, was a modification of a nutritional model developed by Herrero (1997). This model uses information for a user-defined feeding strategy for the farm and animal characteristics (e.g., status of cows) to provide estimates of feed intake and animal performance.

The second model, the replacement model, was a modification of a model developed by Van Arendonk and Dijkhuizen (1985) to optimise culling and insemination policies. Their model uses information provided by the animal performance model to find an optimum set of culling and insemination policies making use of dynamic programming methodology. The replacement model also uses economic parameters, conception probabilities, involuntary culling rates and production transition probabilities. Optimum culling and insemination policies obtained from the replacement model for every herd feeding strategy were summarised and compared.

2.3. Feeding strategies

Eight different feeding strategies were evaluated (Table 1). These strategies were applied on a herd basis and were based on information collected in earlier studies (Van der Grinten et al., 1993; Baars, 1998; Herrero et al., 1999). These strategies represent different degrees of nutritional management found in Costa Rican dairies. The strategies differed in the type of forage on which cows were grazing, the quantity of concentrates cows were given and the

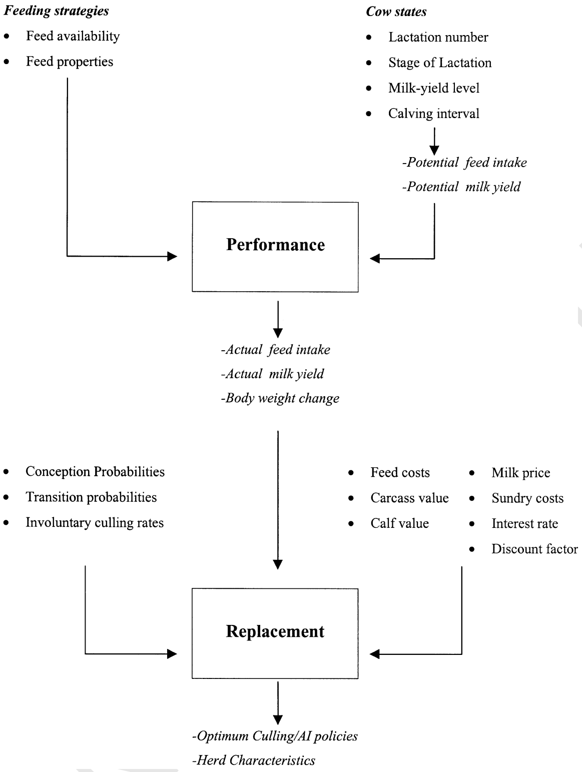


Fig. 1. General structure of the Culling and Insemination Decision Support System (C&I-DSS).

Table 1
Feeding strategies used as input for the Animal Performance model

Strategy	Grass[a]	Stage of lactation		
		0–100 d	101–200 d	201 d–end of lactation
BAS	Kikuyu	MC2:1[b]	MC3:1	MC4:1
COM	Kikuyu	MC3:1	MC3:1	FR3
FIX	Kikuyu	FR6[c]	FR4	FR2
REL	Kikuyu	MC4:1	MC4:1	MC4:1
BAS2	Star	MC2:1	MC3:1	MC4:1
COM2	Star	MC3:1	MC3:1	FR3
FIX2	Star	FR6	FR4	FR2
REL2	Star	MC4:1	MC4:1	MC4:1

[a] Grasses: Kikuyu grass (*Pennisetum clandestinum*); 600 g NDF/kg DM; 16% CP, potential degradability of NDF 58%, degradation rate of NDF 3.8%/h. Star grass (*Cynodon nlemfuensis*); 800 g NDF/kg DM; 7% CP, potential degradability of NDF 50%, degradation rate of NDF 3.0%/h. Degradation rate of soluble carbohydrate 15%/h for both grasses. Solubility and total digestibility of CP were estimated at 30 and 80%, respectively, for both grasses.

[b] MC, milk-concentrate ratio, for each '*n*' kg/day of milk, 1 kg of concentrate (NDF 120 g/kg DM, soluble carbohydrate 570 g/kg DM, of which 70% is present as starch, CP 180 g/kg DM, solubility of CP 33%, total digestibility of CP 85%, fat 30 g/kg DM) was offered.

[c] FR2,3,4,6, flat ratio. A fixed amount of 2, 3, 4, or 5 kg of concentrate, respectively, offered in the daily ration.

way the concentrate was allocated during three different stages of lactation. Two different grasses were considered in combination with four different concentrate allocation systems. A basic strategy (BAS) was defined reflecting the most common practice found in dairy farms in Costa Rica. According to this practice, cows are fed according to milk yield (milk/concentrate ratio, see notes Table 1) in three consecutive stages of lactation (0–100 d; 101–200 d; 201 d–end of lactation), as described by Herrero et al. (1999). A second strategy (COM) was evaluated in which concentrate was fed using milk/concentrate ratios during the first two stages of lactation (0–100 d; 101–200 d) with a fixed amount (flat ratio) fed during the third stage (after 200 d). Two further strategies were analysed; one was based on a regular milk/concentrate ratio (REL) identified as an optimal strategy in an earlier study (Herrero et al., 1999), and the other was based on a flat ratio (FIX). During the dry period, all cows were assumed to eat grass only.

2.4. Cow status

Status of cows was described by four state variables (Table 2), namely lactation number (1 to 12), stage of lactation (1 to 16 mo.), potential milk yield level (0.70 to 1.30, see notes Table 2) and calving interval (11 to 16 mo.).

Table 2
Description of input and output variables used in the Animal Performance model

Variable	Units	Possible values
Input variables		
Lactation number	–	1 to 12
Stage of lactation[a]	mo.	1 to 16
Milk-yield level[b]	Fraction	0.7 to 1.3
Calving interval classes	mo.	11 to 16 (+open cows)
Output variables		
Body weight change	kg/d	Dynamic
Actual forage intake	kg DM/cow/day	Dynamic
Actual concentrate intake	kg DM/cow/day	Dynamic
Actual milk yield	kg/cow/day	Dynamic

[a] Maximal number of lactation stages depended upon the calving interval class.

[b] Fifteen classes obtained as a fraction of mature equivalent milk production (level 1.0).

2.5. Structure of the C&I-DSS

2.5.1. Animal Performance model

The model is designed to predict feed intake, digestion and animal performance of dairy cows consuming grass, grains and other supplements (Herrero, 1997). The rationale behind the model is that a ruminant of a given body size, in a known physiological state, and with a target milk-yield level, will have an actual forage intake determined by physical or metabolic constraints imposed by feed properties and animal status (Herrero, 1997; Herrero et al., 1998). The model was largely based on the work of Illius and Gordon (1991, 1992), Russell et al. (1992), Sniffen et al. (1992), and AFRC (1993), and can be divided into two functional sections.

First, a dynamic section predicts actual feed intake and digestibility as a function of the nutritional quality of feeds on offer and a range of possible cow states (Herrero, 1997). The model simulates the flow and digestion of feeds through the gastrointestinal tract and consequent supply of nutrients to the animal. This section uses a series of first-order differential equations estimating intake, pool sizes of feed fractions in the rumen, small and large intestines, pools of digested material and excretion of indigestible residues. This intake section of the model has previously been tested with data from 23 tropical and temperate forages and the mean prediction error was 7% (Herrero, 1997).

Secondly, a static section of the model predicts nutrient requirements and animal performance, i.e. actual milk yield and body weight changes, on a daily basis from the estimates of feed intake and nutrients supplied from the dynamic section. Body reserve tissues are mobilised or deposited, depending on whether the energy balance is negative or positive. Two pathways controlling intake are used in the model. The first control is the physical constraint on intake caused primarily by low digestibility, while the second control is a metabolic constraint, i.e. if the supply of nutrients equals the requirements, the cow stops eating. This section of animal performance has been previously tested on data obtained from Costa Rican farms (Herrero, 1997).

Estimates of daily feed intake, milk yield and body weight change are subsequently summed on a monthly basis, as required by the replacement model.

The most important input and output parameters of this model are specified in Table 2. For more specific details, see Herrero (1997).

2.5.2. Model specification

Biological parameters used as input to the model were to represent the situation of the Holstein cattle population in Costa Rica. Mature equivalent milk production was set to 6392 kg/cow/lactation with 12.1% milk solids, 3.6% fat, 3.0% protein and 4.5% lactose (AMHL, 1992), produced by an average cow (milk-yield level 1.00) in sixth lactation, with a 1-year calving interval in the absence of genetic improvement and voluntary replacement. The lactation curve was described by a diphasic model:

$$a_1 \times b_1(1 - \tanh^2(b_1 \times (t - c_1)) + a_2 \times b_2 \times (1 - \tan^2(b_2 \times (t - c_2))$$

which was chosen on the basis of a previous study (Vargas et al., 2000). Parameters a_1, b_1, c_1, a_2, b_2 and c_2 were set equal to 436.0, 0.01537, 41.7365, 4590.5, 0.003854 and 154.9, respectively, for first lactation, and 349.8, 0.01894, 37.9415, 5446.8, 0.00409 and 98.7 for second and later lactations (Vargas et al., 2000). Age correction factors for milk yield and milk components (Appendix A) were taken from earlier studies (AMHL, 1992; Vargas and Solano, 1995b).

To calculate the mean and limits of the remaining milk-yield levels, i.e. below or above 1.00, a normal distribution of production across milk-yield levels was assumed, with a coefficient of variation of 12% (Van Arendonk, 1985b). This figure corresponds to the variation expected within the herd. The range of variation comprised 15 levels, which ranged from 0.70 to 1.30 times the average mature equivalent production.

Body weights of cows at the beginning of each lactation (Appendix A) were established according to a Brody function fitted to growth data of local cattle, with

$$y\ (\text{kg}) = 578.3(1 - 0.944\ \exp^{(-0.0098t)})$$

with t the age in weeks (Solano and Vargas, 1997). Changes in body weight were restricted to a maximum of 10% of the body weight at the beginning of the lactation. In addition, body weight change was restricted to a maximum of 0.8 kg/d. These restrictions were defined on the basis of actual variation in body weight observed for Holstein cattle in Costa Rica (Solano and Vargas, 1997).

2.5.3. Replacement model

Information on feed intake, milk yield, body weight change and carcass value obtained from the animal performance model, and economic parameters, allowed estimation of monthly costs and revenues for each cow state. Optimal culling and insemination policies were obtained using this information by dynamic programming (Bellman, 1957). The model used was based on Van Arendonk and Dijkhuizen (1985). With this model, the objective function to be maximised is the total expected discounted returns of present and replacement cows over a given planning horizon. In the present study, the planning horizon was set to 180 one-month long stages (15 yr), and the monthly discount factor was set to $0.95^{1/12}$.

Optimisation was performed by iteration on values (Kristensen, 1994) starting at the end of the planning horizon, when the value of any cow is equal to her carcass value (Van Arendonk, 1985b). Using this information the maximum present value of net returns anticipated from cows and the corresponding optimum decisions were determined at the start of the preceding stage. The process was continued backwards, stage by stage, until the present time was reached.

One-month long stages were chosen in such a way that a decision on culling or insemination could be made at monthly intervals (Van Arendonk and Dijkhuizen, 1985). Voluntary replacement or insemination of a cow was not considered up to 2 mo. after calving. From 2 to 7 mo. after calving the optimum decision for an open cow was chosen from three alternatives: inseminate the cow with a calculated probability of success, leave her open, or replace her immediately. For the remaining months of the lactation of open and pregnant cows the alternatives were to keep or to replace the cow.

Parameters used in the replacement model are given in Table 3. In addition to performance and

Table 3
Description of input parameters used in dynamic programming

Variable	Units	Possible values
Age at first calving[a]	mo.	28.0
Milk price[b]	US$/kg solids	2.23
Forage price[c]		
Kikuyu grass	US$/kg DM	0.0342
Star grass	US$/kg DM	0.0479
Concentrate price	US$/kg	0.16
Price of replacement heifer	US$	1000
Carcass value[d]	US$/kg	1.05
Calves	US$/unit	30.0
Sundry costs[e]	US$/cow/mo.	26
Discount rate	%/mo.	$0.95^{1/12}$

[a] Age at first calving (Vargas et al., 1998a,b; Vargas and Solano, 1995a).

[b] Milk price: according to the local pricing system, producers are paid by kg of milk solids.

[c] Estimated according to production costs, labour plus fertilisation (Herrero et al., 1999).

[d] Sixty percent of male carcass price (US$1.6), dressing percentage 52%.

[e] From Herrero et al. (1999).

prices, the model needs conception probabilities, transition probabilities and marginal rates of involuntary culling. Marginal conception probabilities for different months within lactation (Appendix B) were calculated from data on 37 236 parities of Holstein cows in Costa Rica (unpublished data). Production level of a cow was assumed to remain constant during lactation and any transition occurred only at the start of a new lactation. Transition probabilities for production level, i.e. the probability of a heifer/cow with milk-yield level m to have milk-yield level m' in the next lactation, were calculated as specified by Van Arendonk (1985b), assuming a repeatability for lactation production of 0.55 and 0.50 at intervals of 1 and 2 years. The marginal rates of involuntary disposal (Appendix B) were calculated from data on 910 culled cows in Costa Rica (unpublished data). Marginal rates of involuntary disposal for months 1 to 10 within the lactation, calculated on the same data, were set to 0.07, 0.03, 0.03, 0.03, 0.04, 0.06, 0.07, 0.06, 0.10, and 0.08. Due to lack of empirical data, the rates for later months (11 to 16) were set to 0, i.e. all culling was assumed voluntary. Reasons for involuntary disposal were those not related to decision making in the replacement model, such as cow mortality, disease, mastitis, temperament, or udder and teat problems. Culling for reproductive problems was included in the decision-making process. Cows that were open at the eighth month of lactation were considered infertile and were included in the involuntary culling rate, however these cows remained in the herd until the optimal time for replacement was reached.

The average optimal herd-life was calculated for an average heifer entering the herd, based on the probabilities of realization of each state that resulted from the transition probabilities (production, reproduction and involuntary culling) and the optimal decisions (Van Arendonk and Dijkhuizen, 1985). Distribution of costs and revenues for an average cow in a herd under optimal culling and insemination policies was calculated in the same way. For further information on the replacement model, see Van Arendonk and Dijkhuizen (1985).

A comparison was made between herd-life, calving interval and replacement rates for different feeding strategies, obtained from the replacement model, and actual rates calculated from field data on 910 Holstein cows.

2.6. Sensitivity analysis

Analysis of sensitivity to changes in prices of milk, concentrate and forage were performed with results for feeding strategy REL as the basis for comparison. Changes (+20% and −20%) were done one at a time, keeping all other parameters at their original value. The effects of these changes on average herd-life, monthly income and calving interval were assessed.

An additional sensitivity analysis was done to assess the effect of cow fertility on monthly income and average herd-life of a herd under optimal culling policies. Changes in fertility were associated with changes in conception probabilities (see Appendix B). First, all cows were assumed to have a calving interval of 11 mo. by setting conception probabilities at month 2 after calving equal to 1.0, while those for months 3 to 7 were set to 0. The same procedure was applied for months 3 to 7, changing the conception probabilities of the respective month to 1.0 (see Appendix B), while the remaining were set to 0. In this way, fixed calving intervals between 12 and 16 mo. were simulated.

3. Results and discussion

3.1. Potential vs. actual performance

The use of different feeding strategies had a direct effect on milk yield and body weight change, as shown in Fig. 2 for a cow in 6th lactation with a 12-mo. calving interval. Three production levels (0.7, 1.0 and 1.3) in combination with four diets (BAS, COM, FIX and REL) are illustrated. Potential milk yield was achieved only when nutrients from feeds were available in the quantity and quality necessary to fulfil the requirements of a cow. If the requirements were not fulfilled, the cow showed a decrease in milk yield and growth, which was the case for strategies REL (Fig. 2a,b) and FIX (Fig. 2c,d,e,f). In the case the requirements were fulfilled, as with strategies BAS and COM, the cow was able to reach its potential milk yield (Fig. 2a,c,e) and, when there was a surplus, also gained weight by fat deposition within the limits imposed by metabolic constraints (Fig. 2b,d,f).

None of the feeding strategies was able to provide all nutrients required to produce the potential milk yield for all possible cow-states, as illustrated for milk-yield levels 0.7, 1.0 and 1.3 (Table 4). The frequency of states in negative balance ranged from 2.3% for cows with low milk-yield level (0.7) under strategy COM, to 100% for strategy FIX2 for cows with high milk-yield level (1.3). The absolute reduction in milk yield averaged across cow-states ranged from 0.9 kg/d for strategy COM with average milk-yield level (1.0) to 9.7 kg/d for strategy FIX2 with high milk-yield level (1.3). Occurrence of negative energy balance was more likely for cows with higher milk-yield levels (Table 4). Better performance, i.e. a lower proportion of cow-states with a negative energy balance, was achieved for strategies using Kikuyu grass compared to strategies using Star grass. This trend was consistent across milk-yield levels. The reason for this difference is due to the composition of the two forages. Kikuyu in general terms has a higher quality than Star grass (Table 1). Star grass has 7% lower protein content than Kikuyu grass and therefore results in less effective rumen degradable protein, which leads to a lower microbial production in comparison to Kikuyu grass. Star grass also has a higher NDF concentration, which together with a lower rate of cell wall degradation exerts a more pronounced physical constraint on intake and digestion than Kikuyu grass. As a consequence, the lower quality of Star grass increased the frequency of cow-states with a negative energy balance.

3.2. Change in parameters describing optimal policies

The effects of feeding strategies on parameters describing optimal replacement and insemination policies are shown in Table 5.

The parameter showing the most variation was average monthly income per cow, which ranged from US$33.5 for strategy FIX2 to US$59.6 for strategy REL. Strategy REL resulted in the highest monthly income (Table 5), even though nutrient requirements were not efficiently fulfilled (Table 4), because the reduction in milk yield was also compensated by a reduction in feed. In an earlier study, Herrero et al. (1999) found that this strategy was also the most efficient when considering simultaneously the substitution effects between concentrate and pasture intake, and patterns of growth and utilisation of Kikuyu grass in a highland region of Costa Rica. Overall, this strategy leads to the most efficient use of land, labour and other resources for meeting milk quotas. Strategy COM resulted in the second highest monthly income because of the low incidence of cow-states with a negative energy balance and lower feed costs compared to strategy BAS. The most common practices in specialised dairy herds in Costa Rica, BAS and BAS2, are more efficient in fulfilling the nutritional requirements (Table 4). However, as a result of the low milk/concentrate ratio (2:1) during the first stage in lactation, there was an excess of nutrients, which made these strategies more expensive in comparison to COM or REL. An earlier study (Baars, 1998) also showed oversupplementation with concentrates in these herds. Strategies based on fixed ratios, i.e. FIX and FIX2, were less profitable because they did not fulfil requirements of nutrients for a large proportion of cow-states (Table 4). The large reduction in milk

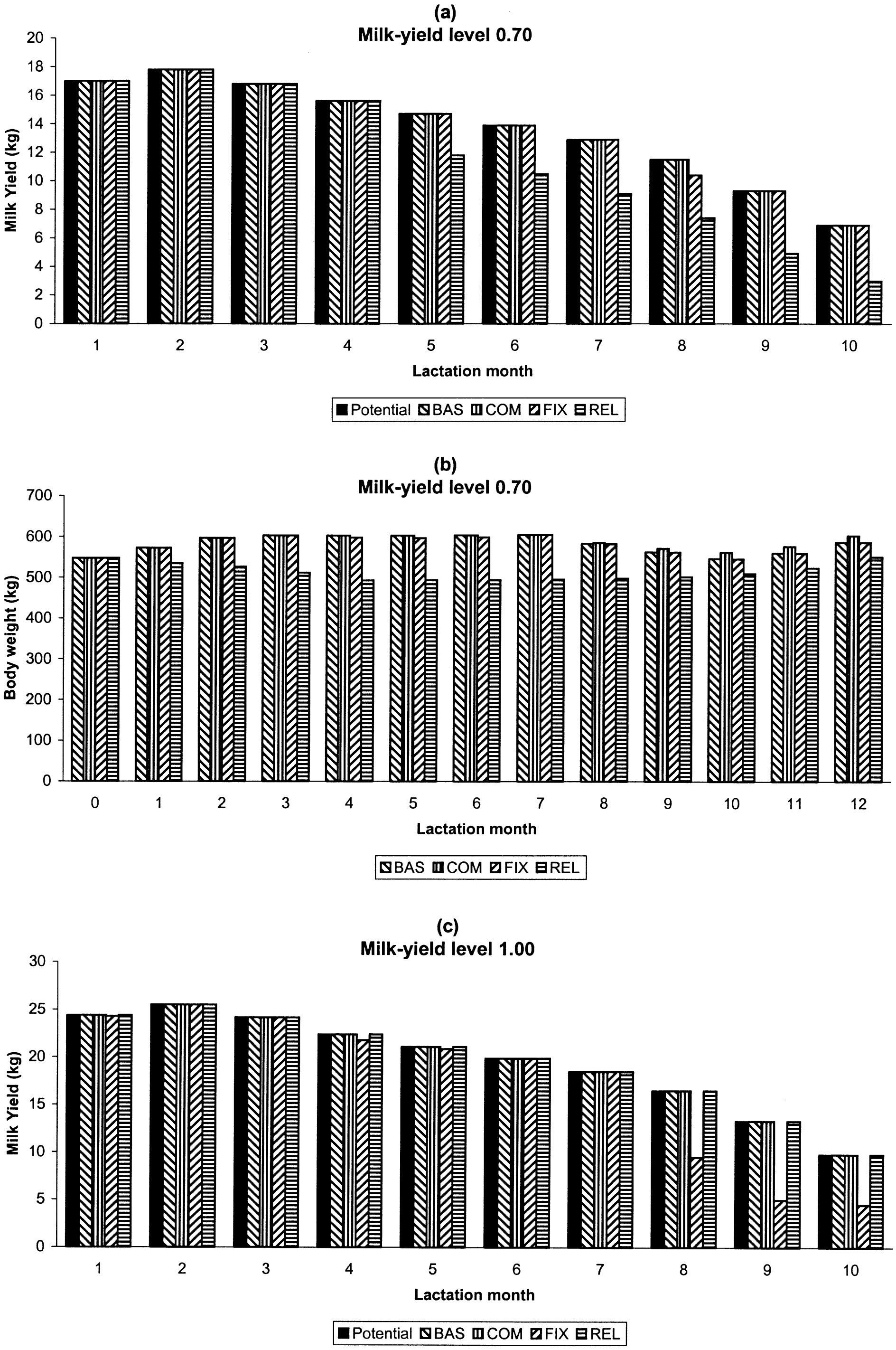
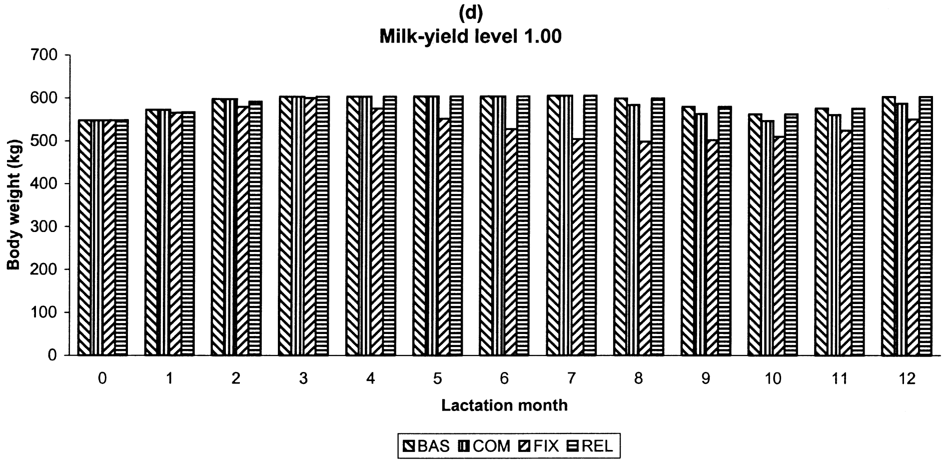
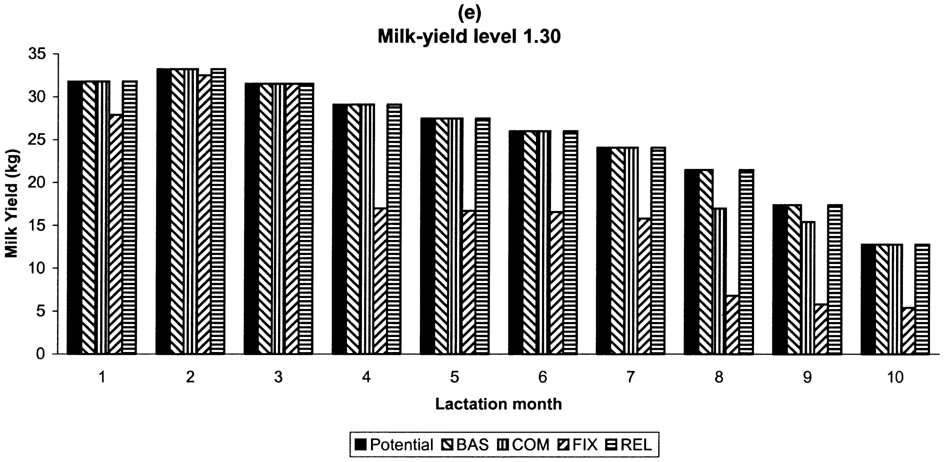


Fig. 2. Milk yield (a,c,e) and body weight change (b,d,f) of cows in sixth lactation, 12 mo. calving interval and milk-yield levels 0.70 (a, b), 1.00 (c, d) and 1.30 (e, f) consuming Kikuyu grass plus a commercial concentrate offered in four different allocation systems (BAS, COM, FIX and REL).





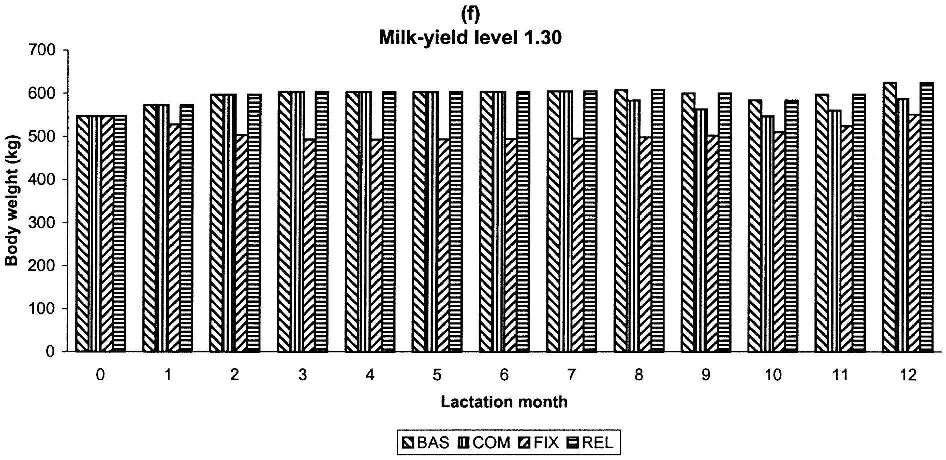


Fig. 2. (*continued*)

Table 4
Percentage of cow-states in a negative energy balance and average reduction (kg/d) in milk yield per milk-yield level and feeding strategy

Strategy	Milk-yield level					
	Cow-states with negative balance (%)			Reduction in milk yield (kg/d)		
	0.70	1.00	1.30	0.70	1.00	1.30
BAS	17.2	8.8	3.5	1.9	1.8	1.3
COM	2.3	12.3	29.17	1.5	0.9	2.7
FIX	28.6	57.5	90.3	1.4	5.3	8.2
REL	72.2	20.4	6.0	4.1	2.7	2.8
BAS2	25.6	17.1	19.7	1.9	1.8	1.1
COM2	4.0	19.1	33.4	2.7	1.4	3.3
FIX2	37.5	92.8	100.0	2.3	5.0	9.7
REL2	85.1	75.7	78.8	4.4	2.4	2.4

yield and body weight was not compensated by the reduction in feed costs. Strategy REL2 also resulted in the second lowest monthly income due to poor performance on Star grass, which resulted in a higher incidence of cow-states with negative energy balance.

The second parameter consistently affected by feeding strategy was herd-life. Optimal average herd-life ranged between 63.0 mo. for strategy COM2 and 69.8 mo. for strategy FIX2 (Table 5). The main difference in estimates of herd-life was between strategies based on fixed ratios, FIX and FIX2, and the remaining strategies. When fixed amounts of concentrate were given in the daily ration, regardless of the production potential of the cow, profitability followed a different pattern from the case when cows were fed according to production. Fixation of feeding costs resulted in slightly lower optimal replacement rates (Table 5), which as a consequence increases herd-life.

Other parameters were less affected by feeding strategies. The optimal calving interval ranged between 368.7 for FIX and 370.3 d for BAS (Table 5). This narrow range was expected because this parameter relates to culling and conception probabilities used as input to the model (Van Arendonk and Dijkhuizen, 1985), and which were kept at the same level for all feeding strategies. A more realistic approach would have been to reduce conception probabilities for cow-states depending on the size of the negative energy balance.

For herd-life, values of 44 mo. (Van Arendonk and Dijkhuizen, 1985) and 32 mo. (McCullough and DeLorenzo, 1996) have been found for Holstein cattle in temperate countries. Cardoso et al. (1999b) reported an estimate of 54.9 mo. for Holstein-Friesian cattle in the south-eastern region of Brazil, which is closer to our results. For Holstein cattle in Costa Rica, however, several factors differed significantly, such as lower mature equivalent production, lower body weight curves and lower conception probabilities. Analysis of local data indicated that the actual average herd-life in Costa Rican Holstein cattle was about 61 mo. corresponding to a replacement rate of 19.6%. The average calving interval was 385 d and cows were culled after 4.7 lactations on average. Comparing actual data with the results presented in Table 5 shows that, regardless of the feeding strategy, cows were culled close to the

Table 5
Parameters describing optimal culling and insemination policies for a herd of a fixed size according to feeding strategy

Parameter	Feeding strategy							
	BAS	COM	FIX	REL	BAS2	COM2	FIX2	REL2
Herd-life (mo.)	64.1	63.4	67.4	63.8	63.3	63.0	69.8	64.0
Calving interval (mo.)	370.3	369.4	368.7	369.9	369.6	369.3	369.5	369.9
Replacement rate (%)	18.7	18.9	17.8	18.8	19.0	19.1	17.2	18.8
Voluntary (%)	8.5	8.8	7.2	8.3	8.7	8.9	6.2	8.2
Involuntary (%)	10.2	10.1	10.6	10.5	10.1	10.2	11.0	10.4
Time to culling (d after calving)	247.5	217.0	220.0	218.9	235.9	211.1	226.1	219.1
Monthly income (US$/cow)	55.7	59.1	48.2	59.6	53.0	55.7	33.5	47.3

optimal time and a longer than optimum calving interval. However, this result might also be due to the fact that long calving intervals, i.e. above 16 mo., were not allowed in the model.

The distribution of costs and revenues for an average cow in a herd of a fixed size after applying optimal insemination and culling policies is given in Table 6. To obtain these results the probability of realisation of each cow-state is implemented in calculation of average performance, which provides a better understanding of the interaction between feeding strategies and culling policies and the final effect on revenues for an average cow when optimal culling policies are applied.

Potential milk yield was never achieved for all cow-states because of an extremely high yield in some cases together with the effect exerted by metabolic constraints. However, strategy BAS was close to achieving this potential milk yield because the realised milk yield was only 0.1 kg/mo. lower (Table 6). Milk production traits for cows fed FIX, FIX2 and REL2 were substantially less than others. The difference between potential and realised milk yield was over 100 kg/mo. for cows given FIX2 rations. The lower quality of Star grass reduced milk yield when the concentrate fed in the ration was insufficient, as occurs with strategies FIX2 and REL2.

Milk production traits did not differ substantially among strategies BAS, BAS2, COM, COM2 and REL. However, the average body weight and feed intake for cows fed BAS, BAS2, COM and COM2 were consistently higher than for those fed REL. The better quality of these feeding strategies was used mostly to increase body weight instead of milk yield. Cows fed a REL ration produced only 10 kg less milk on average and were approximately 40 kg lighter, but feed intake and costs were also substantially lower, which translated into a higher average income. Clearly, the relative differences between milk price plus feed prices, carcass value and replacement costs determine to what extent a given feeding strategy will result in a higher average income. In this sense, the model successfully integrates nutritional (feeding strategies) and management aspects (replacement policies) to obtain a final estimate of profitability for a herd in equilibrium.

3.3. Insemination decisions

When strategies based on milk/concentrate ratios are used, minimal milk-yield level for a profitable

Table 6
Average performance, feed intake and distribution of costs and revenues for a cow in a herd of a fixed size with optimum culling and insemination policies according to feeding strategy

Parameter	Feeding strategy							
	BAS	COM	FIX	REL	BAS2	COM2	FIX2	REL2
Potential milk yield (kg/mo.)	502.8	503.6	502.8	503.3	503.6	503.9	502.0	503.0
Realized milk yield (kg/mo.)	502.7	499.7	430.8	492.6	502.7	497.3	381.5	457.4
Fat (kg/mo.)	18.1	18.0	15.4	17.7	18.1	17.9	13.6	16.4
Protein (kg/mo.)	15.0	14.9	12.7	14.7	15.0	14.8	11.3	13.6
Concentrate intake (kg DM/mo.)	195.8	165.3	105.2	125.9	196.3	165.5	104.9	125.8
Forage intake (kg DM/mo.)	194.7	208.8	218.9	223.1	190.1	203.9	212.5	215.3
Average body weight (kg/cow)	583.3	574.1	515.6	549.6	578.4	573.1	509.8	538.1
Milk revenues (US$/mo.)	135.4	134.5	115.5	132.6	135.4	133.8	102.2	123.1
Average carcass value (US$/cow)	318.5	313.4	281.5	300.1	315.8	312.9	278.4	293.8
Calf value (US$)	29.1	29.1	29.1	29.1	29.1	29.1	29.1	29.1
Costs of concentrate (US$/mo.)	31.3	26.5	16.8	20.1	31.4	26.5	16.8	20.1
Cost of forage (US$/mo.)	6.7	7.1	7.5	7.6	9.1	9.8	10.2	10.3
Sundry costs (US$/mo.)	27.3	27.3	27.2	27.3	27.3	27.3	27.2	27.2
Replacement costs[a] (US$/mo.)	10.6	10.8	10.7	11.0	10.8	10.9	10.3	11.0
Average income[b] (US$/mo.)	62.1	65.4	55.9	69.2	59.3	62.0	40.3	57.0

[a] Replacement cost = (cost of replacement heifer − average carcass value)/herd-life.

[b] Income over feed, replacement and sundry costs. Involuntary culling not taken into account.

Table 7

Minimal milk-yield level[a] required for an insemination at months 3 and 7 to be profitable for cows in lactations 1 to 11 (Lac) under different feeding strategies

Lac	Month 3								Month 7							
	BAS	COM	FIX	REL	BAS2	COM2	FIX2	REL2	BAS	COM	FIX	REL	BAS2	COM2	FIX2	REL2
1	0.70	0.70	0.70	0.76	0.70	0.76	0.70	0.76	0.76	0.76	0.70	0.80	0.80	0.80	0.70	0.80
2	0.76	0.76	0.70	0.76	0.76	0.76	0.70	0.76	0.76	0.80	0.70	0.80	0.80	0.80	0.70	0.80
3	0.76	0.76	0.70	0.76	0.76	0.76	0.70	0.76	0.80	0.80	0.70	0.80	0.80	0.80	0.70	0.80
4	0.76	0.80	0.70	0.76	0.76	0.76	0.70	0.76	0.84	0.84	0.70	0.84	0.84	0.84	0.70	0.84
5	0.84	0.84	0.70	0.80	0.84	0.84	0.70	0.80	0.88	0.88	0.88	0.84	0.92	0.88	0.70	0.88
6	0.88	0.88	0.70	0.84	0.88	0.84	0.70	0.84	0.92	0.92	0.92	0.88	0.96	0.92	0.70	0.88
7	0.92	0.88	0.70	0.88	0.88	0.88	0.70	0.84	0.96	0.96	0.96	0.92	0.96	0.96	0.70	0.92
8	0.96	0.92	0.76	0.88	0.92	0.92	0.70	0.88	1.00	1.00	1.04	0.96	1.00	1.00	0.70	0.96
9	1.00	0.96	0.76	0.92	0.96	0.96	0.70	0.92	1.04	1.04	1.12	1.00	1.04	1.04	0.96	1.00
10	1.04	1.00	0.80	0.96	1.04	1.00	0.70	0.96	1.04	1.08	1.24	1.04	1.08	1.12	1.12	1.04
11	1.30	1.08	0.84	1.00	1.12	1.04	0.70	1.00	1.16	1.16	1.30	1.12	1.12	1.16	1.12	1.08

[a] Milk-yield level is given as a fraction relative to the mature equivalent milk yield.

insemination increased as the cow became old, as illustrated in Table 7 for cows in third and seventh month after calving. For a cow in first lactation the minimal milk-yield level required for a profitable insemination at the third monthafter calving ranged from 0.70 for BAS, COM and BAS2, to 0.76 for REL, COM2 and REL2. For a cow in fifth lactation the minimal milk-yield level ranged from 0.80 for REL and REL2 to 0.84 for REL. At the seventh month, the differences across feeding strategies held, but the minimal milk-yield level required for a profitable insemination was higher. At later lactations, a profitable insemination was obtained only for cows with above average milk-yield levels. Earlier studies reported similar trends (Van Arendonk and Dijkhuizen, 1985; Cardoso et al., 1999a,b).

When feeding strategies based exclusively on flat ratios are used, FIX or FIX2, the trend is different (Table 7). In this case, cows with relatively low production potentials were still profitable at later lactations. As mentioned earlier, fixation of costs due to flat ratios of concentrate had a direct effect on the course of profitability for a cow. Fixed feeding means that not all cows fully express their potential and absolute differences in milk production would become smaller.

When the production potential of the cow was low, the relatively high amount of concentrate on offer increased feeding costs. On the other hand, if the production potential was high, the cow would tend to compensate for lack of nutrients by increasing grass consumption. When this was not possible, milk yield was reduced with direct consequences on profitability.

For cows voluntary culled, the optimal time to cull after calving ranged from 211.1 for COM2 to 247.5 d for BAS. For Holstein cattle, estimates of 234 d (McCullough and DeLorenzo, 1996) and 235.4 (Cardoso et al., 1999b) have been reported. For crossbred Holstein × Zebu cattle an estimate of 181 d was found (Cardoso et al., 1999a). The actual time to culling after calving for Costa Rican Holsteins was 257 d, which is higher than the range found for the present study, meaning that the cows are milked longer than the optimum before being culled. The reason might be a lack of replacement heifers.

3.4. Sensitivity analysis

A sensitivity analysis on feed prices was performed using the strategy with the maximum monthly income, REL, as a basis for comparison (Table 8).

Decreasing the forage price by 20% caused only a US$1.4 increase in monthly income per cow, while other parameters stayed unchanged. Increasing forage price by 20% caused a reduction of US$1.4 in monthly income and a decrease in replacement rate by 1%. The small changes in the parameters were due to the relatively low costs of forage.

Milk price was the parameter with the greatest effect on replacement policies. A decrease in milk price of 20% caused an increase of 3.4 mo. in

Table 8
Sensitivity analysis on effects of prices of feed and milk on parameters describing optimal replacement policies in a herd of a fixed size

Parameter	Alternative scenarios						
	Strategy REL	Forage price		Milk price		Concentrate price	
		−20%	+20%	−20%	+20%	−20%	+20%
Herd-life (mo.)	63.8	63.8	63.7	67.2	59.7	63.8	64.1
Calving interval (mo.)	369.9	369.9	369.9	370.2	369.5	369.9	369.9
Replacement rate (%)	18.8	18.8	17.8	17.9	20.1	18.8	18.7
Voluntary replacement rate (%)	8.3	8.3	7.1	7.1	9.8	8.3	8.2
Monthly income (US$)	59.6	61.0	58.2	33.9	85.4	63.6	55.6

optimal herd-life and decreased the replacement rate by 0.9%, while monthly income was also reduced by US$26.7. An increase of 20% in milk price caused a reduction of 4.1 mo. in optimal herd-life, while replacement rate and monthly income increased by 1.3% and US$25.8, respectively. No significant changes were observed in average calving interval. Similar results have also been found in previous studies (Van Arendonk, 1985b; Cardoso et al., 1999a).

A decrease in the price of concentrates did not change estimates of optimal herd-life, calving interval or replacement rate, but monthly income was increased by US$4. An increase in the price of concentrates caused a small increase of 0.3 mo. in optimal herd-life and reduced monthly income by US$4. Optimal calving interval and replacement rate were almost unchanged. Van Arendonk (1985b) also reported similar results for changes in feed prices. The low sensitivity to changes in concentrate price in the present study can be due to the fact that the diet used as a basis for comparison was REL, which maximised forage intake. In summary, optimal herd-life, monthly income and replacement rates showed high sensitivity to changes in milk price, and low sensitivity to changes in price of concentrates or price of forage. Calving interval was not sensitive to any of the factors.

Results of sensitivity analysis of cow fertility to monthly income and herd-life estimates are shown in Table 9. Maximum income was achieved with the shortest calving interval and the lowest herd-life. The reduction in monthly income when calving interval increased from 11 to 12 mo. was only 1.3% and increased to 16.8% when calving interval was set to 16 mo. The reduction became larger for longer calving intervals. Comparison of these results to the estimate of US$59.6 obtained when using actual conception probabilities, shows that the additional increase in monthly income that can be achieved by further reduction of the calving interval is somewhere less than US$4. The extent to which this extra profit might be cost-effective depends greatly on the costs needed to increase fertility levels.

Table 9
Sensitivity analysis on effects of fertility on estimates of monthly income and herd-life for an average cow in a herd of a fixed size under optimal replacement policies using feeding strategy REL

Parameter	Actual fertility[a]	Fixed calving interval[b] (mo.)					
		11	12	13	14	15	16
Monthly income (US$/cow)	59.6	63.37	62.56	60.93	58.65	55.97	52.70
Herd-life (mo.)	63.8	65.53	69.71	72.57	77.43	81.23	80.85

[a] Actual conception probabilities were used (see Appendix B).

[b] Fixed calving intervals were assumed by setting the conception probabilities of the respective column in Appendix B to 1.0, while keeping the remaining at 0.

4. Conclusion

The present results indicate that feeding strategies have an important effect on optimum average herd-life and monthly income. Feeding strategies affect herd-life by changing the optimal time of insemination, optimal time to culling within the lactation and minimal milk-yield level needed for a profitable insemination. The course of profitability for a cow along the lactation clearly varies according to the feeding strategy, especially when comparing restricted against production-based feeding strategies. Restricted feeding alters the normal course of profitability because of fixation of feeding costs and its effect on production. Individual feeding is not a feasible practice in Costa Rican dairies. Therefore, the course of profitability for an individual cow within the herd can be far from optimum. Insemination and culling decisions should be made with this fact taken into account.

Comparison of the results for optimal policies obtained in the present study to the actual situation in Costa Rican Holstein cattle indicates that actual average herd-life is close to the optimum, but that calving interval is too long. According to the present results, lifetime profitability of cows from Costa Rican herds could be raised by increasing levels of fertility.

The integration of the performance and the replacement models provides an efficient tool to study the effect on cow profitability of interactions between nutrition, reproduction and breeding at the animal and herd level. It can be used to find adequate management practices for a broad range of production circumstances, including sub-optimal feeding practices. Further parameterisation of the effects of sub-optimal production circumstances on biological parameters included in the model is still needed.

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Appendix A. Multiplicative age adjustment factors for milk components (factors for milk yield were taken from Vargas and Solano, 1995b, fat and protein content from AMHL, 1992) and body weight (body weight per lactation from Vargas and Solano, 1997a. Changes in body weight within lactation according to the growth curve (Vargas and Solano, 1997a) and feeding strategy) at calving

Lactation	Milk yield	Fat content	Protein content	Body weight (kg)
1	0.795	1.015	0.951	412
2	0.944	1.045	0.986	485
3	1.010	1.045	0.994	526
4	1.020	1.060	1.000	548
5	1.041	1.000	1.000	548
6	1.000	0.998	0.999	548
7	0.993	0.993	0.996	548
8	0.986	0.987	0.992	548
9	0.976	0.979	0.988	548
10	0.962	0.971	0.983	548
11	0.946	0.961	0.977	548
12	0.926	0.951	0.971	548

Appendix B. Marginal conception probabilities per lactation and insemination month, marginal involuntary culling rates (ICR, %) per lactation (Lac) and reduction in milk production (%) per lactation caused by involuntary culling

Lac	Conception probabilities (months 2 to 7)						ICR	Reduction
	2rd mo.	3th mo.	4th mo.	5th mo.	6th mo.	7th mo.	(%)	in milk (%)
1	0.37	0.45	0.41	0.40	0.35	0.35	0.08	30
2	0.40	0.48	0.45	0.45	0.39	0.43	0.10	32
3	0.41	0.48	0.48	0.46	0.41	0.40	0.15	34
4	0.39	0.51	0.47	0.46	0.40	0.45	0.13	36
5	0.37	0.47	0.45	0.46	0.42	0.36	0.22	38
6	0.39	0.46	0.43	0.43	0.41	0.42	0.29	40
7	0.38	0.45	0.44	0.45	0.40	0.41	0.31	40
8	0.35	0.47	0.38	0.46	0.51	0.50	0.33	40
9	0.29	0.46	0.49	0.51	0.48	0.47	0.35	40
10	0.27	0.44	0.47	0.49	0.47	0.45	0.37	40
11	0.26	0.43	0.45	0.47	0.45	0.43	0.39	40
12	0.25	0.41	0.43	0.45	0.43	0.41	0.41	40

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