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Impacts of changing relative prices on farm level dairy production in the UK

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Abstract

This paper presents a linear programming model designed to evaluate the impact of changes in milk to milk-quota-leasing price ratios, nitrogen fertiliser and concentrate prices on the profitability of a technically efficient UK dairy farm. The model incorporates energy and protein requirements of cows of different yield levels and allows substitution between forage and concentrate feeds. The results show that there is a large financial incentive to reduce input levels and move to lower yielding cows as milk to milk-quota-leasing price ratios fall relative to prices for concentrates and nitrogen fertiliser. However, under proposed reforms to the Common Agricultural Policy, and at current UK milk prices, technically efficient producers will find it profitable to continue feeding relatively large amounts of concentrates to relatively high yielding cows. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

As a result of the favourable growing conditions for grass relative to arable crops, dairy farming in England and Wales is concentrated in the North and West (Farrar and Franks, 1998). However, dairy farms are also present, in smaller numbers, in the drier arable Eastern counties of England, farms in these areas being characterised by greater use of concentrates (feeds based largely on cereals or cereal mixes) and greater milk yield cow^{-1} (Farrar and Franks, 1998). Choice of feedstuff for milk production is also influenced by the Common Agricultural Policy (CAP), which, compared to world prices, increases the price that dairy producers

receive for their milk (through production quotas, intervention storage and levies on imports) and increases the cost of concentrates (through cereal intervention and import levies). Reforms to the CAP in the early 1990s led to a 30% cut in the cereal intervention price. The 'Agenda 2000' reforms will cut both price support for cereals and milk; however, reform of the dairy sector has been delayed until 2005–06 (Commission, 1998; Agra-Europe, 1999). Thus, recent policy changes look set to shift the milk/concentrate price ratio in favour of greater use of concentrates over the short to medium term. However, in contrast to prices in the 'euro-zone' countries, the UK milk support price has been adversely affected by exchange rate movements. In addition, the cost of gaining high milk yields through greater concentrate use is also

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affected by the cost of leasing quota for production over a farm's designated quota amount: Farrar and Franks (1998, p. 80) in a survey of English and Welsh dairy farms, found that over the 1996–97 marketing year, 11% of total quota was leased-in or purchased outright, with an average leasing price of £0.126 l^{-1} . At an average milk price of £0.249 l^{-1} for the sample as a whole, the effective price of milk was, therefore, only £0.123 l^{-1} , after accounting for the opportunity cost of holding quota.

Given this background, it is appropriate to investigate the potential impact of changing input and output prices on a typical UK dairy system. Emphasis in this paper is given to changes in the milk to milk-quota-leasing price ratio, the cost of concentrates and the cost of nitrogen fertiliser. Assuming profitability to be the major concern of producers, the analysis uses a farm-level linear programming (LP) model to establish optimum adjustment strategies under the assumption that producers are 'technically efficient', i.e. producers are operating on the technically feasible dairy production frontier for a given combination of inputs (e.g. Wilson et al., 1998). Following Ramsden et al. (1996), the costs of non-adaptation are also calculated to quantify the incentive that exists to adapt to changes in relative prices. The paper is arranged as follows. Section 2 discusses some previous LP models of livestock systems and draws out the relationships that are important to capture in modelling farmer adaptation strategies; Section 3 gives an overview of the model structure. In Section 4, a comparison of model results with actual farm data for England and Wales is given for validation purposes and model results for different input–output price combinations and adaptation strategies are presented. Section 5 concludes the paper and considers the implications of the results for the effective management of dairy farms within the UK.

2. LP modelling of livestock systems

Rigby and Young (1996) combine conventional farm-level economic models with environmental sub-models to investigate the impact of environ-

mental regulations on a sample of farms in the Northwest of England. The models include a fertiliser response function, with greater levels of nitrogen allowing increased stocking rates. Yield cow^{-1} , is (implicitly) assumed to be independent of stocking rate and no attempt is made to model yield response to concentrate use. Killen (1988) uses a similar approach to model optimum stocking rates under a quota restriction. Within the constraints of the model, milk production is assumed to be a function of the amount of nitrogen applied to grass and the profitability of alternative enterprises, with yield cow^{-1} and herd size being held constant. Berentsen and Giesen (1995) use a more sophisticated approach, which incorporates a 'bio-economic' model to determine energy requirements and dry matter intake capacity for a fixed level of milk production. Grass dry matter production is modelled using nitrogen response functions which are dependent on soil type and available ground water supply; remaining nutrient requirements are satisfied from home-grown maize and fodder beet and/or purchased concentrates and silage maize.

These approaches all assume a given milk yield, with the more sophisticated models allowing feed requirements to be met by a combination of forage (grass, silage and other fodder crops) and concentrates. Total milk output is generally assumed to be a function of the amount of nitrogen applied, with greater amounts of nitrogen allowing the stocking rate ha^{-1} of grassland to be increased. However, adjustment to changing input/output price ratios could include more complex changes than are allowed for in these models, in particular, the option of varying concentrate feed and milk output levels cow^{-1} is not explored in any detail. Furthermore, with machinery and labour costs in 1996–97 representing approximately 8 and 22% of total costs cow^{-1} , respectively (Farrar and Franks, 1998), an analysis of adjustment strategies over the medium term should also allow for changes in the level of these 'fixed' inputs. Therefore, in the following section, we describe a farm level model that attempts to incorporate a fuller range of adjustment strategies available to farmers to respond to changing input/output price ratios.

3. The farm level model

The model is represented schematically in Fig. 1. A full algebraic description (with additional notes) is given in the Appendix.

3.1. Land, labour and machinery components

The model describes an 80-ha farm divided into four 20-ha rotational blocks within which forage crops (grass, two cuts of silage and hay) and arable crops (winter and spring barley) can be grown. Forage crops are utilised by dairy animals (calves, heifers and cows) or by beef animals (retained male calves sold at 18 months). There are two types of skilled labour available, the farmer and full-time workers who supply ‘ordinary’ and ‘overtime’ labour hours; both these categories are adjusted for social (normal working week, illness) and seasonal (hours available for outdoor operations) factors. Additionally, casual and contract labour can be supplied, up to pre-specified limits;

contract labour is supplied with machinery. These five items make up the total weekly labour supply, in hours, available to the farm. Skilled labour is needed to operate machines; these, together with any contracted machines and machines not requiring an operator, make up the total machines on the farm.

Jointly, labour and machinery supply field time: the weekly hours available at different times of the year for field operations. There must be sufficient machines (with field equipment in the case of tractors) and labour to meet field operation requirements (i.e. the field workrate coefficients). For example, the model cannot draw on additional casual labour if there is insufficient machinery capacity to utilise this additional labour. The time-frame available for different operations corresponds to average conditions for southern England; crop (including forage crops) operational requirements cannot be met from field time weeks outside these boundaries. Timeframes and workrates are taken from Nix (1996).

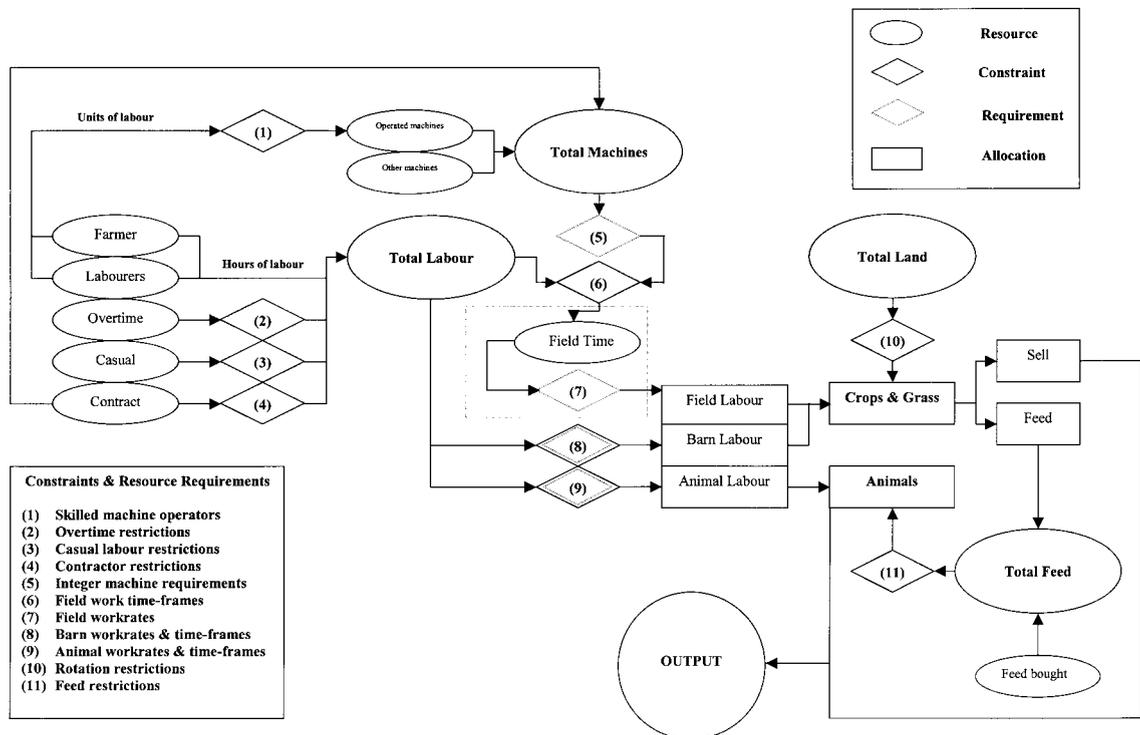


Fig. 1. Model overview.

Transfer variables ensure that surplus field time labour can be used for indoor tasks (barn labour and animal labour) and that there is a distinction between indoor and outdoor tasks, with the time-frames for the latter being determined by seasonal and social factors and the former being determined only by social factors. The amount of labour required for animal work is determined by the number of stock and the animal workrate coefficients, again taken from Nix (1996). Casual labour is not available for stock operations or specialised field operations such as combining.

3.2. Dairy component

The dairy herd consists of cows, heifers and calves and the model assumes an autumn calving pattern. Cows can have annual milk yields of 5000, 6000, 7000, 8000 or 9000 l (Table 1). Annual milk production is equal to the amount of quota owned plus quota leased in less quota leased out, with production resulting from the number of cows included at different yield levels.

Following Farrar and Franks (1998), herd replacement rate is assumed to increase as milk yield increases, to capture the higher culling rates necessary to maintain high yielding herds. For the respective yield levels of 5000–9000 l cow⁻¹, these are assumed to be 22.5, 24.5, 26.5, 28.5 and 30.5%. Cows can be replaced by heifers reared on the farm or by bought-in 2-year old ‘down-calving’ heifers. Cows are assumed to calve once a year, with 50% of calves being male and 50% female. Male calves are sold or retained for the beef production; female calves are sold or retained and reared as replacements for the dairy herd.

Table 1

Mean and maximum weekly milk yields for average annual milk yields used in the model

Yield cows ⁻¹ (l year ⁻¹)	Mean yield (l week ⁻¹)	Maximum yield (l week ⁻¹)
5000	96.45	160
6000	115.73	192
7000	135.03	224
8000	154.31	256
9000	173.60	288

The cow labour-workrates for milking are adjusted for different milking out time requirements of different yielding cows, assuming a 6/12 herringbone parlour and a 6000-l standard cow (Table 2). Thus, as milk-yield cow⁻¹ increases, the labour requirement for milking increases. Weekly milking time cannot exceed 35 h (equivalent to two 2.5-h milkings a day). Milk production is constrained by available quota; production can be increased by leasing-in quota or reduced by leasing-out quota as with current policy in the UK. The decision was taken not to model purchase and sale of quota, first because UK quota is attached to the holding rather than the producer and thus transactions tend to be limited to land-owners. Second, it was felt that the opportunity cost of holding quota was more appropriately modelled using leasing: indeed, some 10% of UK producers retain ownership of quota but lease it out annually, thus providing a significant pool of quota for the leasing market (Anon., 1997).

3.3. Beef component

Beef production is assumed to be an 18-month system; this is the most common lowland beef production system in the UK not involving specialised beef dams (Jenkins et al., 1998). In addition to male animals from the dairy herd, male calves can be bought in from outside the farm. Headage payments, payable on male animals only as part of the CAP's beef support system are paid at age 10 months, up to a maximum of 90 male calves.

Table 2

Mean and maximum milking out times (l week⁻¹), assuming a 6/12 herringbone type parlour^a

Yield (l cow ⁻¹)	Mean MOT (min cow ⁻¹)	Max. MOT (min cow ⁻¹)
5000	3.594	5.116
6000	3.879	5.589
7000	4.165	6.062
8000	4.450	6.535
9000	4.735	7.008

^a Total milking out time (MOT) in minutes per milking per cow = 2.75 + 0.207 × (weekly production in kg/14). Source: MAFF (1981).

3.4. Feed component

The model allows animals to be fed on farm-produced grass, silage, hay and barley or bought-in hay and concentrates. Stock weekly-energy- and weekly-protein-requirements are calculated from Alderman and Cottrill (1993) using a standard lactation curve to adjust for weekly milk yield at each yield level. Feed energy and protein content, assuming average quality feed and 15% wastage, are from the same source. Minimum stock diet quality (energy density) is estimated from recommended diets in Chadwick (1997): this restriction ensures that only feasible combinations of forage and concentrates are used to attain a given milk yield (i.e. to obtain higher yields cows must be fed not only more feed but feed of a higher energy density). For example, cows with an annual yield of 5000 l do not require concentrate supplements during the grazing season while 9000-l cows do. Provided these restrictions are met animals can be fed on any combination of available feedstuffs. Which combination is selected will depend on the relative costs of producing or buying each feedstuff. A further restriction is placed on calves, which cannot eat silage until 6 months old.

Forage can be provided from grazed permanent or temporary grass, two cuts of silage (May and July) and hay (cut once in June). Silage and hay 'aftermath' grazing are available from 4 weeks after the last cut. Stock are turned out onto available grassland from early April to early October. Weekly grass growth and yield is based on a double gaussian function fitted to a typical growth curve (Thomas and Young, 1982). The gaussian function is used as it captures the 'double peak' associated with grass growth in the UK — one in May/June and a smaller peak in September. Following Dowle and Armstrong (1990), a fertiliser response function is used to estimate dry matter yields with four levels of fertiliser applied four times annually; slurry applied between mid-March and the end of August is included in the nitrogen budget. Maximum annual grass yield, at the highest fertilisation level (400 kg ha⁻¹), is 11.45 t DM ha⁻¹. The three other points on the response curve are 250, 100 and 0 kg ha⁻¹ giving 80, 50 and 26% of the maximum yield respectively. The model

allows fertilisation of areas of grass at different rates (e.g. 10% of grazing grass could be fertilised at 400 kg ha⁻¹, 20% at 250 kg ha⁻¹, and 70% at 100 kg ha⁻¹). For hay and silage the amount of dry matter conserved is dependent on the cumulative grass growth until cutting time for each fertilisation level, later cutting produces greater yields. Wastage of grass is assumed to be 10% if grass is cut for silage and 15% if cut for hay.

The capacity to substitute different feedstuffs gives the model the necessary flexibility to respond to changes in output and input prices. For example, as nitrogen prices fall, the additional grass produced can substitute for concentrate at a given yield cow⁻¹. Under the same scenario, the model can also increase the number of stock carried ha⁻¹ subject to other constraints. However, in practice, due to poaching, milk yield cow⁻¹ will decline as stocking rate increases (Thomas and Young, 1982). Therefore, total stocking rate is constrained not to exceed two livestock units on the proportion of land available for grazing; livestock units animal⁻¹ are as given in Nix (1996).

3.5. Machinery and labour costs

Owned machine operating costs (fuel and repairs) and annual ownership costs (depreciation, interest, tax, insurance) were calculated from Nix (1996). Ownership costs are specified for tractors, trailers, grass conservation equipment, fertiliser and spray application equipment, cultivation and drilling equipment and combined harvesters. Fuel and repair costs were assumed to be linearly related to machine usage. All field activities can be contracted out up to a maximum of two contractors for each operation each week; silage and hay conservation, if contracted out, must be contracted out in entirety. Annual labour costs were also taken from Nix (1996). Other costs within the model (e.g. parlour equipment and cattle housing) are assumed to remain fixed.

3.6. Objective function

The objective function is the maximisation of farm net margin, i.e. total annual output net of variable, labour (full-time and casual)

and machinery (owned and contract) costs of production.

In total, the model has 9674 columns and 5881 rows, making it substantially larger than the LP models discussed in Section 2. Model size reflects the detailed specification of physical relationships between different levels of nitrogen and available forage (and, therefore, stocking rate), levels of different feeds and milk yield, milking out times, breeding herd depreciation, alternative sources of labour and machinery, integration of labour and machinery constraints and distinction between indoor and outdoor tasks. Furthermore, all production relationships are specified on a weekly basis, thus enabling changes in resource availability and use over the farming year to be fully represented.

The model matrix was generated with MP-MODEL and solved with MP-OPT (DASH, 1997). MP-MODEL matrix generation code is available, on request, from the authors. Results were recorded and are presented and discussed in the following section.

4. Results and discussion

The model was run with price levels for milk, quota-leasing, nitrogen fertiliser and concentrate set at average levels for sample farms in the ‘‘Highest Quartile Net Margin per Hectare’’ category in the Farrar and Franks’ survey, under the assumption that these higher performing farmers would better represent technically efficient levels of production. Model results and for the sample farms are shown in Table 3.

The model chooses the maximum number of cows possible (given the stocking rate limit) at the highest possible yield level. This results in greater concentrate use and herd depreciation than the survey figures. The model chooses silage rather than hay as a method of grass conservation; however, less silage is fed than on the survey farms, with more nitrogen being included to grow ‘fresh’ grass (10.8 t cow⁻¹, assuming a dry matter content of 20%). Overall, the results typify a higher input–output system than the survey figures; a priori we would expect this given the technically optimal

Table 3

Comparison of model results with highest quartile net margin ha⁻¹ farms from a survey of dairy farms in England and Wales^a

Variable	Model	Top 25% net margin
Grassland area (ha) ^b	75	73.37
No. of cows	92	119.7
Total milk (l)	827,436	775,297
Milk yield (l cow ⁻¹)	9000	6477
Milk price (£ l ⁻¹) ^b	£0.2535	£0.2535
Lease-quota price (£ l ⁻¹) ^b	£0.113	£0.113
Total quota (l) ^b	774,522	774,522
Quota leased in (l)	52,914	775
Concentrate (t cow ⁻¹)	3.84	1.71
Silage (t cow ⁻¹)	6.93	9.7
Concentrate per litre milk (kg l ⁻¹)	0.43	0.26
Stocking rate (cows ha ⁻¹)	2.0	2.02
Nitrogen (kg ha ⁻¹)	278	226
Replacement rate (%)	30.5	28.3

^a Farrar and Franks, 1998 (p. 153).

^b Pre-set in the model.

feed input–output relationships defined in the model.

4.1. Changes in the milk/quota-leasing price ratio

Table 4 shows the results of varying the milk price from £0.14 to £0.25 l⁻¹ with concentrate, nitrogen and quota-leasing set at baseline (Nix, 1996) levels of £0.133 kg⁻¹ dry matter, £0.39 kg⁻¹ and £0.08 l⁻¹, respectively. This gives a range of milk to quota-leasing price ratios of 1.8–3.1. Full time labour is initially set at one full-time worker; all other integer inputs are variable.

As expected, increasing milk price increases the number of dairy cows, the yield cow⁻¹ and hence total milk output. Forage intake (grass and silage) declines from 4.91 to 3.96 t cow⁻¹; concentrate use increases from 0.93 to 3.32 t cow⁻¹. Nitrogen applied ha⁻¹ increases as stocking rate increases up to the limit of 2 livestock units ha⁻¹. The restriction on labour available, together with the increased milking time required for higher yielding cows, makes it more profitable to switch to contract silaging of grass, thus allowing a greater number of higher yielding cows to be milked as price increases. To accommodate the increased number of dairy cows within the stocking rate

Table 4
Model results with varying milk price

Milk price margin (£l ⁻¹) ratio (£)	Stocking No. of animals					Milk (t)	Quota (t)	Food per cow (t)	Fertiliser/ha (t)	Area (ha)	Labour (h)	Contract									
	5000 cows	6000 cows	7000 cows	8000 cows	9000 cows							Grazing	Overtime	Casual							
	cows					Calves	Beef Heifers	Grass Silage	Concentrate												
0.14	1.8	31,526	1.32	25	0	0	0	96	90	6	125,000	-421,575	2.86	2.05	0.93	0.164	56.3	23.7	6	0	53
0.15	1.9	33,118	1.60	48	0	0	0	81	70	11	240,000	-306,575	2.67	2.15	0.96	0.203	52.5	27.5	30	0	124
0.16	2.0	36,642	1.89	0	73	0	0	63	45	18	438,000	-108,575	2.78	2.10	1.39	0.262	49.3	30.7	61	64	182
0.17	2.1	41,022	1.89	0	73	0	0	63	45	18	438,000	-108,575	2.78	2.10	1.39	0.262	49.3	30.7	61	64	182
0.18	2.3	45,635	1.95	0	78	0	0	59	40	19	468,000	-78,575	2.77	2.10	1.39	0.273	48.7	31.3	64	83	194
0.19	2.4	51,668	1.98	0	11	0	0	87	29	0	849,000	302,425	2.28	1.79	3.11	0.272	51.8	28.2	67	0	535
0.20	2.5	60,481	1.99	0	0	0	0	98	30	0	882,000	335,425	2.24	1.74	3.31	0.280	52.2	27.8	89	0	528
0.21	2.6	69,301	1.99	0	0	0	0	98	30	0	882,000	335,425	2.24	1.74	3.31	0.280	52.2	27.8	89	0	528
0.22	2.8	78,121	1.99	0	0	0	0	98	30	0	882,000	335,425	2.24	1.74	3.31	0.280	52.2	27.8	89	0	528
0.23	2.9	87,101	2.00	0	0	0	0	112	17	0	1,008,000	461,425	2.20	1.76	3.32	0.277	51.4	28.6	90	0	544
0.24	3.0	97,181	2.00	0	0	0	0	112	17	0	1,008,000	461,425	2.20	1.76	3.32	0.277	51.4	28.6	90	0	544
0.25	3.1	107,261	2.00	0	0	0	0	112	17	0	1,008,000	461,425	2.20	1.76	3.32	0.277	51.4	28.6	90	0	544

limit, the model buys in half the required replacement heifers (at a replacement rate of 0.305) at milk prices over £0.22 l⁻¹. The only change in integer input levels occurs between £0.17 and £0.18 l⁻¹, with the model buying in contract machinery and labour for all silaging operations at £0.18 l⁻¹ and above. This again enables farm-supplied labour to satisfy the greater milking out time requirements of higher yielding cows.

The model leases out quota over the milk price range £0.18–0.14 l⁻¹. A milk to quota-leasing price ratio of £0.18–0.08 is typical of current (1999) market conditions in the UK, at this ratio 14% of the available quota is leased out. Removing the capacity to lease out quota over this price range incurs an opportunity cost of between £6362 and £11,745 in net margin (Table 5); without the availability of leasing the model meets the farm's quota through 91 '6000' l cows at each price level. Allowing the amount of full-time paid labour to vary and comparing net margins (Table 6) shows that there is a further penalty, increasing as the milk to quota-leasing price ratio falls, in not adjusting the full-time labour input.

To explore the extent to which input substitution is possible, the model was run with only one choice of dairy cow (6000 l). Over the milk price range of £0.14–0.25 l⁻¹, concentrate use increases by a small amount, from 1.32 to 1.44 t⁻¹ (equivalent to an increase in concentrate cost of £176–192 cow⁻¹). Forage intake declines from 5.02 to 4.84 t of dry matter cow⁻¹ and fertiliser use increases from 159 to 305 kg ha⁻¹ as stocking rate increases. Restricting yield cow⁻¹ to 6000 l thus limits the possibility of substitution between grass and concentrates as price ratios change; this restricts the extent to which the model can profitably adjust to changing price ratios. At a milk price of £0.25 l⁻¹, the reduction in net margin is £19,772, or 18.4% compared to the unrestricted case. Restricting the model to choose from only 9000-l cows at a milk price of £0.14 l⁻¹ reduces net margin by £22,273, or 71% compared to the unrestricted case. Thus, there are substantial financial penalties in not adjusting yield cow⁻¹ to changing relative prices, particularly for high yielding herds in a situation of falling relative milk output prices.

Table 5
Results with and without availability of quota-leasing

Milk price (£ l ⁻¹)	Net margin with leasing (£)	Net margin without leasing (£)	Difference (£)
0.18	45,635	39,273	6362
0.17	41,022	30,701	10,321
0.16	36,642	25,241	11,401
0.15	33,118	22,893	10,225
0.14	31,526	19,781	11,745

Table 6
Results with and without availability of full-time labour

Milk price (£ l ⁻¹)	Net margin with no full-time labour (£)	Net margin with hired labour = 1 (£)	Difference (£)
0.18	51,940	47,398	4542
0.17	48,441	41,732	6709
0.16	46,221	37,292	8929
0.15	44,651	33,375	11,276
0.14	44,404	31,526	12,878

The above analysis assumes that quota-leasing prices remain unchanged as milk prices fall: historically, UK quota-leasing prices have moved in the same direction as milk prices. The results in Table 4 show that under baseline conditions for concentrate and nitrogen prices, a margin between milk price and quota-leasing price of £0.11 l⁻¹ is sufficient to favour cows producing 9000 l head⁻¹. Thus, assuming this margin to be maintained, a milk price of £0.14 l⁻¹ and, therefore, a leasing price of £0.03 l⁻¹ would result in 87 '9000'-l cows being chosen by the model, although at a much reduced net margin.

4.2. Variation in nitrogen and concentrate prices

Net margin and mix of beef and dairy animals are less responsive to changes in nitrogen price (Table 7). Due to their lower forage requirements, beef animals substitute for dairy animals as the cost of producing grass increases and stocking rate falls by a small amount. Dairy cow forage consumption shifts towards silage and away from grazing, total forage consumption declines from 5.01 to 4.84 t cow⁻¹ and concentrate use

cow⁻¹ increases. For concentrates, an increase in price from £110 to £125 shifts production from 9000-l cows to 6000-l cows (Table 8), with an accompanying increase in forage use and nitrogen applied per hectare. Results are stable for concentrate prices between £130 and £145, after which the model substitutes beef cows for dairy cows.

Although the model allows production of home-grown cereal feed, it has not so far allowed for bought-in cereals — for example feed barley — to form part of the cows' diet. If we assume that the 15% reduction in intervention support, proposed as part of Agenda 2000, will lead to a 15% fall in feed cereal prices from the £73 t⁻¹ typical of the 1998–99 marketing year, we arrive at a price of £63 t⁻¹. Running the model with the option of buying in feed barley at this price, with concentrate price held at £110 tonne⁻¹ and a milk to quota-leasing price ratio of 2.3, results in a net margin £26,000 greater than the equivalent run without availability of barley (Table 8). More cows at 9000 l are included in the model solution and more milk is produced. Less concentrate is fed to each cow; however, nitrogen application increases to the maximum possible amount allowed by the model (400 kg ha⁻¹) and more grass and silage are fed to each cow. Thus, as cereal prices fall, utilisation of forage, particularly silage, increases (under *ceteris paribus* conditions). The explanation for this lies with the lower metabolisable protein content of barley compared to silage (82 and 99 g kg⁻¹, respectively). Hence, the increased use of barley in the model is balanced by an increase in use of silage. If we allow the model to buy-in a protein-based feed such as rapeseed meal, nitrogen application falls to a more typical 223 kg ha⁻¹.

5. Summary and conclusions

It is important to emphasise that the results are dependent on the assumptions on which the model has been constructed, particularly the assumption of technical efficiency in relation to protein and energy requirements at each milk yield level. However, the incorporation of variable feed input and milk output levels, substitution between feed inputs, variation in nitrogen use and stocking rate

Table 7
Model results with varying fertiliser price

Fertiliser price (£ kg ⁻¹)	No. of animals										Fertiliser/ha (t)	Area (ha)	Labour (h)							
	5000 cows		7000 cows		8000 cows		9000 cows		10000 cows				Grazing Silage	Overtime	Casual	Contract				
	Calves	Beef	Heifers	Milk (t)	Quota (t)	Food per cow (t)	Grazing Silage	Concentrate												
0.29	45,293	1.94	0	79	0	0	58	39	19	474,000	-72,575	2.98	2.03	1.35	0.303	49.3	30.7	63	86	182
0.31	44,907	1.94	0	79	0	0	58	39	19	474,000	-72,575	2.98	2.03	1.35	0.303	49.3	30.7	63	86	182
0.33	44,644	1.95	0	78	0	0	59	40	19	468,000	-78,575	2.79	2.10	1.39	0.275	48.8	31.2	64	83	193
0.35	44,303	1.95	0	78	0	0	59	40	19	468,000	-78,575	2.79	2.10	1.39	0.275	48.8	31.2	64	83	193
0.37	43,962	1.95	0	78	0	0	59	40	19	468,000	-78,575	2.78	2.10	1.39	0.274	48.7	31.3	64	83	193
0.39	43,622	1.95	0	78	0	0	59	40	19	468,000	-78,575	2.77	2.10	1.39	0.273	48.7	31.3	64	83	194
0.41	43,286	1.95	0	78	0	0	59	40	19	468,000	-78,575	2.75	2.11	1.39	0.271	48.6	31.4	64	83	196
0.43	42,952	1.95	0	78	0	0	59	40	19	468,000	-78,575	2.74	2.11	1.40	0.270	48.5	31.5	64	83	196
0.45	42,587	1.95	0	77	0	0	60	41	19	462,000	-84,575	2.73	2.12	1.40	0.266	48.5	31.5	64	79	197
0.47	42,239	1.90	0	73	0	0	63	45	18	438,000	-108,575	2.72	2.12	1.40	0.256	49.0	31.0	61	64	188
0.49	41,926	1.90	0	73	0	0	63	45	18	438,000	-108,575	2.72	2.12	1.40	0.256	49.0	31.0	61	64	188

Table 8
Model results with varying concentrate price

Concentrate price (£ kt ⁻¹)	No. of animals										Fertiliser/ha (t)	Area (ha)	Labour (h)								
	5000 cows		7000 cows		8000 cows		9000 cows		10000 cows				Grazing Silage	Overtime	Casual	Contract					
	Calves	Beef	Heifers	Milk (t)	Quota (t)	Food per cow (t)	Grazing Silage	Concentrate													
110	49,216	1.95	0	0	0	0	89	41	14	27	801,000	254,425	2.25	1.73	3.31	0.252	51.8	28.2	136	97	135
115	47,273	1.90	0	36	0	0	42	55	33	22	594,000	47,425	2.47	1.92	2.43	0.258	51.0	29.0	60	92	151
120	46,177	1.95	0	74	0	5	0	58	39	19	484,000	-62,575	2.74	2.08	1.47	0.274	48.8	31.2	64	87	192
125	45,320	1.95	0	78	0	0	59	40	19	468,000	-78,575	2.76	2.10	1.39	0.272	48.7	31.3	64	83	194	
130	44,321	1.95	0	78	0	0	59	40	19	468,000	-78,575	2.76	2.10	1.39	0.272	48.7	31.3	64	83	194	
133.5	43,622	1.95	0	78	0	0	59	40	19	468,000	-78,575	2.77	2.10	1.39	0.273	48.7	31.3	64	83	194	
135	43,323	1.95	0	78	0	0	59	40	19	468,000	-78,575	2.78	2.10	1.39	0.274	48.7	31.3	64	83	193	
140	42,325	1.95	0	78	0	0	59	40	19	468,000	-78,575	2.78	2.10	1.39	0.274	48.7	31.3	64	83	193	
145	41,328	1.95	0	78	0	0	59	40	19	468,000	-79,575	2.78	2.10	1.39	0.274	48.7	31.3	64	83	193	
150	40,301	1.90	0	74	0	0	62	44	18	444,000	-102,575	2.78	2.10	1.39	0.264	49.2	3.8	60	68	184	
110 ^a	75,312	1.96	0	0	0	0	94	27	0	27	846,000	299,425	3.18	2.32	2.52 ^b	0.4	46.7	33.3	88	97	231

^a Barley available at £63 per tonne.

^b Of which, 2.24 t is barley.

and variable levels of labour and machinery does allow a comprehensive range of adaptation strategies to be modelled. If attention is directed to the *changes* that occur across Tables 4, 7 and 8, rather than absolute values at each price ratio, we can draw the following conclusions. The results demonstrate the sensitivity of UK dairy profitability to reductions in the price of milk relative to input prices and the type of response that is possible whilst meeting stock energy and protein requirements at different yield levels. With concentrate, nitrogen and quota-leasing prices of £0.133 kg⁻¹, £0.39 kg⁻¹ and £0.08 l⁻¹, respectively, as milk prices fall below £0.18 l⁻¹, there exists a large profit incentive to lease out quota, reduce the number of dairy cows, milk output cow⁻¹, concentrate fed and the amount of full-time labour. Under the assumed dietary requirements and feed availability used in the model, the scope for maintaining a given yield and adjusting the relative amount of concentrate and forage fed cow⁻¹ in response to lower milk prices is more limited, particularly for high yielding cows. The corollary of this is that the penalty for maintaining relatively low yields as milk price increases is high: nearly £20,000 at £0.25 l⁻¹ and a fixed yield of 6000 l cow⁻¹.

Current (1999) margins between milk and quota-leasing prices are in the region of £0.11 l⁻¹: model results show that a smaller margin (higher leasing price or lower milk price) shifts production towards a lower input–output system. However, a £0.11 l⁻¹ margin combined with lower concentrate prices favours a high input–output system. With cereal-based feedstuffs becoming less expensive under Agenda 2000, and reform of the EU dairy regime being postponed until 2005, technically efficient farmers in the UK will maintain profitability by continuing with strategies based on high-yielding cows being fed high levels of concentrate feeds. As one of the major themes of the next round of World Trade Organisation negotiations will be continued reduction in agricultural protection, it is interesting to consider how technically efficient UK dairy farmers would respond to wider reform of the EU dairy regime; specifically the removal of production quotas and world market prices for milk. Providing the world market

price for milk (currently £0.16 l⁻¹, Milk Development Council, 1998) remains at or above £0.11 l⁻¹ technically efficient UK dairy farmers would find it profitable to continue with a high input–output system, albeit at a much reduced net margin, as the return to quota falls to zero. This suggests that these farmers would be able to compete with farmers in major milk product-exporting countries such as New Zealand.

Finally, although a full specification of a UK dairy farm has been attempted here, there still remain further interesting possibilities for future research. With respect to dairy production, the interaction between stocking rates and grass growth and yield and hence individual animal performance requires further work. More generally, farm economic models require better information on the available weekly hours for animal grazing and field operations: linking economic models with models describing crop growth and soil workability at different times of the year would be a significant development.

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Appendix

Notation

CROP _{bc}	number of ha of crop c ($c = 1 \dots 6$) in each block b ($b = 1 \dots 4$)
FREE _{bc}	number of ha free in block b rotated against crop c in block $b + 1$
CCOEF _{ca}	work rate for activity a ($a = 1 \dots 23$) of crop c (h ha ⁻¹)
CLAB _{caw} , CONT _{caw}	hours of labour and contract labour used for activity a of crop c in week w ($w = 1 \dots 52$)
LAND _{ca} , NOLAND _{ca}	switch for activity a of crop c that uses land or no land

WLAND _{caw}	ha of land used for activity a of crop c in week w	GCROP _{c}	switch that defines crop c as a grazing crop
SLAB _{sw}	hours of labour used for stock s ($s = 1 \dots 8$) in week w	GPROP _{c}	proportion of grazing crop c used for grazing
STOCK _{s}	number of stock s	MILK	annual milk production (1)
SCOEF _{sw}	hours of labour required by stock s in week w	MILKQ,	litres of milk quota owned,
SLUR _{w} ,	weekly labour and contract	LEQ, UNQ	leased in and leased out
SCONT _{w}	labour used for slurry spreading in week w	MILKT _{sw}	hours taken to milk stock s in week w
FSLACK _{w} ,	unused field and stock labour	FGRASS _{l_c}	ha of crop c fertilised at level 1 ($1 = 1 \dots 4$)
ASLACK _{w}	in week w	TFOOD _{s$f$$w$} ,	total kg dry matter of food
OT _{w} , FOT _{w} ,	total, field, stock and barn	GFOOD _{fw} ,	f ($f = 1 \dots 6$), grown and
SOT _{w} , BOT _{w}	overtime in week w	BFOOD _{fw}	bought in week w and fed to stock s
CAS _{w} , FCAS _{w} ,	total, field and barn casual	GTIME _{cw}	crop c in week w available for grazing
BCAS _{w}	labour in week w	GYIELD _{1w} ,	kg/ha DM grass yield and
FARMFT _{w} ,	available farmer fieldtime and	GCUMY _{1w}	cumulative yield in week w at fertilisation level 1
FARMST w	stocktime in week w	HAYLAB _{1w}	hours cutting hay fertilised at level 1 in week w
LABFT _{w} ,	available labourer fieldtime	TSLUR _{s} ,	total slurry produced by stock s and used for fertilisation
LABST _{w}	and stocktime in week w	GSLUR	weeks in which slurry can be used for fertilisation
MAVAIL _{w} ,	available machine time and	USPRE _{w}	kg nitrogen bought, and rate of application at rate 1
OTAVAIL _{w}	overtime in week w	NBUY,	stock s energy, protein and
MTIME _{wm}	machine time for machine m ($m = 1 \dots 14$) used in week w	FRATE ₁	dry matter requirement in week w
MNUM _{m}	number of machines m owned	ENREQ _{sw} ,	food f energy, protein and
MOPR _{m}	number of operators required	MPREQ _{sw} ,	dry matter contents
MUSE _{cam} ,	machines m required for	DMREQ _{sw}	
MSLUR _{m}	activity a of crop c or slurry spreading	FOODMJ _{f} ,	
MFRAC _{cam}	fraction of activity a of crop c that requires machine m	FOODMP _{f} ,	
ROT _{bcp}	switch that allows crop c in block b to follow previous crop p ($p = 1 \dots 6$)	FOODDM _{f}	
SACROP _{c}	switch that specifies crop c as a set-aside crop	MDREQ _{s}	stock s energy density requirement
BHEIF,	heifers, 1-week-old male		
BMCALFIW,	calves, 1-year-old male calves		
BWALFIY	bought in		
MCALF,	male and female calves retained		
FCALF			
SMCALF,	male and female calves sold		
SFCALF			
LU _{s}	livestock unit of stock s		
RR _{s}	replacement rate of stock s		
THEAD,	total beef head payment,		
HEAD	payment per head		

Land and labour

Land is allocated only to the crop activities that require land, determined by the LAND switch (values 0 or 1). The slack variables, FSLACK and SSLACK, transfer unused labour from field activities to animal activities and from animal activities to barn activities, respectively.

$$\sum_{c=1}^6 \text{CROP}_{bc} + \sum_{c=1}^6 \text{FREE}_{bc} = 20 \quad \forall b \quad (1)$$

$$\begin{aligned} &\text{CLAB}_{caw} \times \text{LAND}_{ca} + \text{CONT}_{caw} \\ &\times \text{LAND}_{ca} = \text{CCOEF}_{ca} \\ &\times \text{WLAND}_{caw} \quad \forall c, a, w \end{aligned} \quad (2)$$

$$\sum_{c=1}^6 \sum_{a=1}^{23} \text{WLAND}_{caw} \leq 80 - \sum_{b=1}^4 \sum_{c=1}^6 \text{FREE}_{bc} \quad \forall w \quad (3)$$

$$\begin{aligned} &\sum_{w=1}^{52} \text{CLAB}_{caw} + \sum_{w=1}^{52} \text{CONT}_{caw} = \\ &\sum_{b=1}^4 \text{CROP}_{bc} \times \text{CCOEF}_{ca} \quad \forall c, a \end{aligned} \quad (4)$$

$$\text{SLAB}_{sw} = \text{STOCK}_s \times \text{SCOEF}_{sw} \quad \forall s, w \quad (5)$$

$$\begin{aligned} &\sum_{c=1}^6 \sum_{a=1}^{23} \text{CLAB}_{caw} \times \text{LAND}_{ca} + \\ &\text{FSLACK}_w + \text{SLUR}_w = \text{FARMFT}_w + \\ &\text{LABFT}_w + \text{FOT}_w + \text{FCAS}_w \quad \forall w \end{aligned} \quad (6)$$

$$\begin{aligned} &\sum_{s=1}^8 \text{SLAB}_{sw} + \text{SSLACK}_w \\ &= \text{FARMST}_w + \text{LABST}_w + \text{FSLACK}_w \quad \forall w \end{aligned} \quad (7)$$

$$\begin{aligned} &\sum_{c=1}^6 \sum_{a=1}^{23} \text{CLAB}_{caw} \times \text{NOLAND}_{c,a} \\ &\leq \text{SSLACK}_w + \text{BOT}_w + \text{BCAS}_w \quad \forall w \end{aligned} \quad (8)$$

$$\text{CONT}_{caw} \leq 2 \times \text{MAVAIL}_w \quad \forall c, a, w \quad (9)$$

$$\text{OT}_w = \text{FOT}_w + \text{SOT}_w + \text{BOT}_w \quad \forall w \quad (10)$$

$$\text{OT}_w \leq \text{OTAVAIL}_w \quad \forall w \quad (11)$$

$$\text{CAS}_w = \text{FCAS}_w + \text{BCAS}_w \quad (12)$$

Machinery

The MFRAC variable allows a fixed workrate to be used for operations that consist of more than one machine; e.g. harvesting winter barley consists of both combining equipment and grain transportation equipment. MFRAC variable determines the proportion of the overall labour workrate required for each type of machine (e.g. out of 2.1 h required for barley harvesting, 0.6 are required for combining, giving a combine MFRAC value of 0.286).

$$\begin{aligned} \text{MTIME}_{wm} &= \sum_{c=1}^6 \sum_{a=1}^{23} \text{CLAB}_{caw} \times \text{MUSE}_{cam} \\ &\times \text{MFRAC}_{cam} + \text{SLUR}_w \\ &\times \text{MSLUR}_m \quad \forall w, m \end{aligned} \quad (13)$$

$$\begin{aligned} &\sum_{m=1}^{16} \text{MTIME}_{wm} \times \text{MOPR}_m = \text{FARMFT}_w \\ &+ \text{LABFT}_w + \text{FOT}_w - \text{FSLACK}_w \quad \forall w \end{aligned} \quad (14)$$

$$\text{MTIME}_{wm} \leq \text{MNUM}_m \times \text{MAVAIL}_w \quad \forall w, m \quad (15)$$

Rotations (e.g. for block 2)

The ROT constant (values 0 and 1) specifies which crops can be grown in which block, and which crop they can follow.

$$\begin{aligned} \text{CROP}_{2c} &\leq \sum_{p=1}^6 \text{CROP}_{1p} \times \text{ROT}_{2cp} \\ &+ \text{FREE}_{1c} \quad \forall c \end{aligned} \quad (16)$$

Milk production, quota and time

$$\begin{aligned} \text{MILK} &= \text{STOCK}_1 \times 5000 + \text{STOCK}_2 \times \\ &6000 + \text{STOCK}_3 \times 7000 + \text{STOCK}_4 \times \\ &8000 + \text{STOCK}_5 \times 9000 \end{aligned} \quad (17)$$

$$\text{MILK} = \text{MILKQ} + \text{LEQ} - \text{UNQ} \quad (18)$$

$$\sum_{s=1}^6 \text{STOCK}_s \times \text{MILK}_{sw} \leq 35 \quad \forall w \quad (19)$$

Cow replacement and stocking rate

$$\text{STOCK}_7 + \text{BHEIF} \geq \sum_{s=1}^5 \text{STOCK}_s \times \text{RR}_s \quad (20)$$

$$\text{FCALF} = \text{STOCK}_7 \quad (21)$$

$$\text{MCALF} + \text{BMCALF1Y} = \text{STOCK}_8 \quad (22)$$

$$\text{MCALF} + \text{SMCALF} = \sum_{s=1}^5 \text{STOCK}_s \times \quad (23)$$

$$0.5 + \text{STOCK}_7 \times 0.5 + \text{BMCALF1W}$$

$$\text{FCALF} + \text{SFCALF} = \sum_{s=1}^5 \text{STOCK}_s \times 0.5 \quad (24)$$

$$+ \text{STOCK}_7 \times 0.5$$

$$\text{STOCK}_6 = \text{MCALF} + \text{FCALF} \quad (25)$$

$$\sum_{s=1}^6 \text{STOCK}_s \times \text{LU}_s \leq \sum_{b=1}^4 \sum_{c=1}^4 \text{CROP}_{bc} \quad (26)$$

$$\times \text{GPROP}_c \times 2$$

Beef headage payments

$$\text{THEAD} \times \text{STOCK}_8 \times \text{HEAD} \quad (27)$$

$$\text{THEAD} \leq \text{HEAD} \times 90 \quad (28)$$

Grass production

The GTIME constant (values 0 or 1) ensures that grass for grazing is only available during specified periods.

$$\sum_{b=1}^4 \text{CROP}_{bc} = \sum_{l=1}^4 \text{FGRASS}_{lc} \quad c = 1, 2, 3, 4 \quad (29)$$

$$\text{GFOOD}_{1w} + \text{SURPG}_w$$

$$= \sum_{l=1}^4 \sum_{c=1}^4 \text{FGRASS}_{lc} \times \text{GTIME}_{cw} \quad (30)$$

$$\times \text{GYIELD}_{lw} \times 0.95 \quad \forall w$$

Forage production (e.g. for hay)

$$\sum_{l=1}^4 \text{HAYLAB}_{lw} = \text{CLAB}_{27w} + \text{CONT}_{27w} \quad \forall w \quad (31)$$

$$\text{FGRASS}_{l2} \times \text{CCOEF}_{27} = \sum_{w=1}^{52} \text{HAYLAB}_{lw} \quad \forall l \quad (32)$$

$$\sum_{w=1}^{52} \text{GFOOD}_{2w} \times \text{CCOEF}_{27} \quad (33)$$

$$\leq \sum_{l=1}^4 \sum_{w=1}^{52} \text{HAYLAB}_{lw} \times \text{GCUMY}_{lw} \times 0.85$$

Slurry production and nitrogen budget

$$\sum_{w=1}^{52} \text{SLUR}_w \times 4 + \sum_{w=1}^{52} \text{SCONT}_w \times 4 \quad (34)$$

$$= \sum_{s=1}^8 \text{STOCK}_s \times \text{TSLUR}_s$$

$$\sum_{w=1}^{52} \text{SLUR}_w \times \text{USPRE}_w \times 4 + \sum_{w=1}^{52} \text{SCONT}_w \quad (35)$$

$$\times \text{USPRE}_w \times 4 = \text{GSLUR}$$

$$\text{NBUY} = \sum_{l=1}^4 \sum_{c=1}^6 \text{FGRASS}_{lc} \times \text{FRATE}_l \quad (36)$$

$$- \text{GSLUR} \times 0.005 \times 1000$$

Feedstuffs fed to animals

$$\sum_{s=1}^8 \text{TFOOD}_{sfw} \leq \text{BFOOD}_{fw} + \text{GFOOD}_{fw} \quad \forall f, w \quad (37)$$

$$\text{STOCK}_s \times \text{ENREQ}_{sw} \times 1.05 \leq \sum_{f=1}^6 \text{TFOOD}_{sfw} \times \text{FOODMJ}_f \times 0.85 \quad \forall s, w \quad (38)$$

$$\text{STOCK}_s \times \text{MPREQ}_{sw} \times 1.05 \leq \sum_{f=1}^6 \text{TFOOD}_{sfw} \times \text{FOODMP}_f \times 0.85 \quad \forall s, w \quad (39)$$

$$\text{STOCK}_s \times \text{DMREQ}_{sw} \times 1.05 \leq \sum_{f=1}^6 \text{TFOOD}_{sfw} \times \text{FOODDM}_f \times 0.85 \quad \forall s, w \quad (40)$$

$$\sum_{f=1}^6 \text{TFOOD}_{sfw} \times \text{FOODMJ}_f \geq \sum_{f=1}^6 \text{TFOOD}_{sfw} \times \text{MDREQ}_s \quad \forall s, w \quad (41)$$

Cash crops grown for feed

$$\sum_{w=1}^{52} \text{GFOOD}_{5w} = \text{FEED}_5 \times \text{CYIELD}_5 \times \text{DM}_5 \times 1000 \quad (42)$$

$$\sum_{b=1}^4 \text{CROP}_{b5} = \text{FEED}_5 + \text{SELL}_5 \quad (43)$$

Objective function

The objective is the maximisation of net farm margin. SGM is cash crop gross margin, FVC feed crop variable cost, CMILK milk price, CQ quota-leasing price, STGM stock gross margins excluding milk, calf, and forage costs, CBMC1W the price of

a 1-week-old male beef calf, CBMC1Y the price of a 1-year-old male beef calf, CSMC1W the price of a 1-week-old male dairy calf, CSFC1W the price of a 1-week-old female dairy calf, CH the price of a down-calved heifer, FC feed cost, NC nitrogen cost, COT overtime cost, CCAS casual labour cost, CCONT contractor cost, CSCONT slurry contractor cost, MCOST annual machine ownership cost and HFREP hourly machine running cost.

$$\begin{aligned} & \sum_{c=1}^6 \text{SELL}_c \times \text{SGM}_c + \text{MILK} \times \text{CMILK} \\ & + \text{UNQ} \times \text{CQ} - \text{LEQ} \times \text{CQ} + \sum_{s=1}^8 \text{STOCK}_s \\ & \times \text{STGM}_s + \text{THREAD} - \text{BMCALF1W} \\ & \times \text{CBMC1W} \\ & - \text{BMCALF1Y} \times \text{CBMC1Y} + \text{SMCALF} \\ & \times \text{CSMC1W} + \text{SFCALF} \times \text{CSFC1W} \\ & - \text{BHEIF} \times \text{CH} - \sum_{f=1}^6 \sum_{w=1}^{52} \text{BFOOD}_{fw} \times \text{FC}_f \\ & - \text{NBUY} \times \text{NC} - \text{CLAB} - \sum_{w=1}^{52} \text{OT}_w \times \text{COT} \\ & - \sum_{w=1}^{52} \text{CAS}_w \times \text{CCAS} - \sum_{c=1}^6 \sum_{a=1}^{23} \sum_{w=1}^{52} \text{CONT}_{caw} \\ & \times \text{CCONT}_{caw} - \sum_{w=1}^{52} \text{SCONT}_w \times \text{CSCONT} \\ & - \sum_{m=1}^{14} \text{MNUM}_m \times \text{MCOST}_m \\ & - \sum_{w=1}^{52} \sum_{m=1}^{14} \text{MTIME}_{wm} \times \text{HFREP}_m \quad (44) \end{aligned}$$

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