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Modelling Integrated Dairy Systems In The UK: Towards Economic And Environmental Sustainability

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Abstract

This paper draws on the results of a multi-disciplinary research project funded by Defra[1] which has focussed on identifying and developing practical approaches by which the dairy sector can reduce inputs and diffuse pollution, whilst maintaining biodiversity, product quality, high animal health and welfare standards and market competitiveness. The pressures on UK dairying for change towards greater economic and environmental sustainability derive from the need to remain profitable in the face of low farm-gate prices, competition from the global market in the context of a wide range of environmental and animal welfare constraints that have increased considerably in number and stringency during recent years. The challenge is to identify and develop practices that, through the use of integrated systems, incorporate environmental objectives into profitable, modern farming. The research has explored the complex interaction 'surfaces' of multiple sustainability criteria in systems simulations using an interactive framework of modelling (N, P, methane and production economics) and objective scoring matrices (biodiversity, landscape features, product quality and animal health). As part of the SIMSDAIRY model[2], the EDMM (Economic Dairy Management Model) is an empirically-based model which simulates the revenue and costs attributed to dairy farming in the UK. At its core are a series of econometric relationships that replicate the underlying production and cost structures of dairy farm management. The results are presented and discussed in the context of recent market and policy developments in the milk supply sector.

Outline

Although UK dairy farming has evolved mainly in response to economic drivers, the industry is now being given environmental goals. Ways in which these economic and environmental pressures can be reconciled are needed in the form of more sustainable systems, which are based on integrated farming principles that can be implemented in a cost-effective manner. The policy context can be clearly stated, in that Defra has a requirement to both sustain and enhance the rural environment whilst promoting and developing the rural economy. The realisation of these two objectives need not be mutually exclusive, since it should be possible to identify and develop practices that, through integration of the agricultural system, incorporate environmental objectives into an economically sustainable farming business. In practice, however, the introduction of an integrated dairy production system requires research to explore a wide range of

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[1] Open Competition CTB0301: Integrated production systems for dairy farming.
[2] Developed jointly by the research consortium led by IGER North Wyke, including ADAS Consulting Ltd, Velcourt Group plc, LEAF, the University of Reading and Plant Research International, in addition to the University of Exeter.

alternatives, and to show that the negative environmental impact of production can be reduced or eliminated without having a negative effect on the economic viability of the farm. Such new approaches to production systems require developments that are inherently more environmentally and economically sustainable.

The research has made considerable advances in the development of methodologies for exploring the complex interactions between the various disparate sustainability criteria for UK dairy systems. These include novel methods of linking the N and P cycling models together and with indicators of economic performance and matrices for scoring the criteria for biodiversity, landscape, product quality and animal health. The modelling framework has potentially a much wider applicability than dairying systems. Methods of system optimisation for multiple goals have been developed from those already existing within the NGAUGE system to include the model-matrix linkages. The principles of integrated production have been applied in a new, systematic and rigorous manner to consider component combinations and approaches that are thought likely to confer the benefits that are sought. A range of improved system specifications have been produced that are scientifically and technically suitable for introduction over a range of situations. Moreover, an important activity has been the establishment of strong Knowledge Transfer (KT) links with the practicing dairy farmer so that the feasibility and practicality of introducing components of the new systems could be evaluated.

The use of reliable economic data by dairy farmers is an important part of the KT links, and knowing the costs of reductions in N emission, for example, is likely to influence their decision-making. Therefore, this paper focuses on the EDMM part of the SIMSDAIRY model, which uses econometric modelling of the relationships between milk production, input requirements and the cost functions, and is based on economic data of milk production that was originally collated by the University of Manchester in 2000/03[3]. The original survey data has been recalibrated to 2006 prices, and a number of alternative system scenarios are simulated in order to capture the range of likely responses by dairy farmers as they respond to economic pressures, whilst also considering changes to their production systems to meet specific environmental objectives. It is commonly recognized that dairy farmers counteract economic pressures in different ways, such as attempting to reduce production costs per litre by increasing production per cow and per hectare; reducing their costs per litre (with some output reduction) by lowering fixed costs; or by increasing income through producing higher value products and exploiting niche markets. However, each of these strategies has outcomes that are not necessary benign in either economic or environmental terms. For example, increasing income through organic milk and cheese production, using legumes as the source of nitrogen (N) is potentially just as environmentally troublesome as those based on inorganic N application, as there is less control of N supply and legumes have been shown to be more ‘leaky’ than grass. The results of such modelling are presented in this paper and discussed in the context of recent market and policy developments in the milk supply sector.

[3] See Colman et al. (2004) Economics of Milk Production: England and Wales 2002/03. The dataset behind this publication was made available to the Centre for Rural Research project members by Defra and is acknowledged with thanks.

Background and introduction

Although UK dairy farming has evolved mainly in response to economic drivers, the industry is now being given environmental goals. Ways in which these economic and environmental pressures can be reconciled are needed in the form of more sustainable systems, which are based on integrated farming principles that can be implemented in a cost-effective manner (van Calker *et al*, 2005). The policy context can be clearly stated, in that Defra has a requirement to both sustain and enhance the rural environment whilst promoting and developing the rural economy. The realisation of these two objectives need not be mutually exclusive, since it should be possible to identify and develop practices that, through integration of the agricultural system, incorporate environmental objectives into an economically sustainable farming business. In practice, however, the introduction of an integrated dairy production system requires research to explore a wide range of alternatives, and to show that the negative environmental impact of production can be reduced or eliminated without having a negative effect on the economic viability of the farm. Such new approaches to production systems require developments that are inherently more environmentally and economically sustainable.

The research programme on which this paper draws has made considerable advances in the development of methodologies for exploring the complex interactions between the various disparate sustainability criteria for UK dairy systems. These include novel methods of linking the nitrogen (N) and phosphorous (P) cycling models together and with indicators of economic performance and matrices for scoring the criteria for biodiversity, landscape, product quality and animal health. The modelling framework has potentially a much wider applicability than dairying systems. Methods of system optimisation for multiple goals have been developed from those already existing within the NGAUGE system to include the model-matrix linkages. The principles of integrated production have been applied in a new, systematic and rigorous manner to consider component combinations and approaches that are thought likely to confer the benefits that are sought. A range of improved system specifications have been produced that are scientifically and technically suitable for introduction over a range of situations. Moreover, an important activity has been the establishment of strong Knowledge Transfer (KT) links with the practicing dairy farmer so that the feasibility and practicality of introducing components of the new systems could be evaluated.

The use of reliable economic data by dairy farmers is an important part of the KT links, and knowing the costs of reductions in N emission, for example, is likely to influence their decision-making. Therefore, this paper focuses on the EDM model part of the $SIMS_{DAIRY}$ model, which uses linear regression modelling of the relationships between milk production, input requirements and the cost functions, and is based on economic data of milk production that was originally collated by the University of Manchester in 2000/03[4]. The original survey data has been recalibrated to 2006 prices, and a number of alternative system scenarios are simulated in order to capture the range of likely responses by dairy farmers as they respond to economic pressures, whilst also considering changes to their production systems to meet specific environmental objectives.

It is commonly recognized that dairy farmers counteract economic pressures in different ways, such as attempting to reduce production costs per litre by increasing production per cow and per hectare; reducing their costs per litre (with some output reduction) by lowering fixed costs; or by increasing income through producing higher value products and exploiting niche markets. However, each of these strategies has outcomes that are not necessary benign in either economic or environmental terms. For example, increasing income through organic milk and cheese production, using legumes as the source of nitrogen (N) is potentially just as environmentally troublesome as those based on inorganic N application, as there is less control of N supply and legumes have been shown to be more 'leaky' than grass. The results of such modelling are presented in this paper and discussed in the context of recent market and policy developments in the milk supply sector.

This remainder of this paper is structured as follows: after an outline of the research brief for the whole project the methodology adopted in developing the EDM model is set out in detail, together with the derivation of the production assumptions and cost/price parameters. The challenges posed by the integration of the three models - NGUAGE, PSYCHIC and EDM – into the composite $SIMS_{DAIRY}$ model are reviewed and the solutions adopted described. Finally, the paper concludes with a discussion of some of

[4] See Colman et al. (2004) Economics of Milk Production: England and Wales 2002/03. The dataset behind this publication was made available to the Centre for Rural Research project members by Defra and is acknowledged with thanks.

the issues associated with the development, validation and operation of this model, and considers the key areas where further development is required.

Overall research brief

In the research brief set out by Defra the research was defined within the department's requirement to 'sustain and enhance the rural environment whilst promoting and developing the rural economy' (Defra, 2003). There was an explicit presumption which underlay the identification and definition of the research need, namely that the realisation of these two objectives need not be mutually exclusive. Nevertheless, it was also clearly recognized that generally, with perhaps a few exceptions, intensive livestock production systems – specifically dairy farming and pig production – were not well structured to contribute environmental benefits *and* economic vitality. However, it was anticipated that it should be possible to develop practices that, through better integration of the technical, economic and environmental dimensions of the agricultural production systems concerned, incorporate environmental objectives into profitable, modern farming.

A key aim of the research was to show that the negative environmental impact of many current production systems can be reduced or eliminated without having a negative effect on the economic viability of the farm, thus underpinning the introduction of integrated production systems in practice. In particular, the brief called for an exploration of more environmentally-attuned dairy systems that maintained, if not enhanced, farm viability. Its pertinence can be gauged from the fact that during the period since the original research call a significant number of the larger and more profitable dairy herds have ceased production (Colman and Zhuang, 2005).

The Government has established dual policy aims for agriculture, for efficient and competitive agricultural systems that nevertheless sustain and enhance the environment through enabling the farming industry and the rural community as a whole to benefit from the integration of natural processes and cycles. It was recognized these can only be achieved through the identification of new approaches to production systems, and could be expected to require developments that are inherently more environmentally and economically sustainable. The two enterprises identified as presenting some of the greatest challenges for balancing efficient production with environmental impact were dairy production and outdoor pig breeding herds. In the research call (Defra 2003) it was proposed that one project in each of these areas should be funded, designed to assess the opportunities for promoting a more sustainable holistic approach. This paper is concerned with the work done in fulfillment of the contract for the dairy sector.

The overall research objective was to identify and develop practical approaches for the dairy sector to reduce inputs and diffuse pollution, whilst maintaining biodiversity, product quality, high animal health and welfare standards and the competitiveness of the dairy sector. The business context is that UK dairy producers are faced with the challenge of producing a high quality product within the constraints of quota, price, increasing environmental awareness and animal welfare concerns. Sustainable farming, optimising the use of resources through holistic approaches and evaluating practices by monitoring inputs and outputs and utilising natural nutrient cycles, has the potential to help farmers meet these multiple challenges.

Research was required to investigate how the principles of integrated production can be better applied to dairy farming to improve health and welfare standards and reduce costs and diffuse pollution whilst also enhancing economic efficiency and biodiversity. A number of possible approaches to achieve this were identified:

i) Improved stock management
ii) Selection of appropriate stock
iii) Enhancement of sward composition and management
iv) More precise management of nutrient application to grasslands
v) Alternative uses of low productivity areas of grassland

A combination of these were considered, together with other approaches, and the research focused on supporting conventional production systems (Defra's had a separate research programme specific to organic farming). Specific objectives of the research programme was to quantify the impact of the proposed new systems on the emissions of the following diffuse pollutants:

- Nitrates
- Nitrous oxide
- Methane
- Ammonia
- Phosphorus

Finally, the brief was that the research should be strategic in nature and, where appropriate, take a functional approach that addresses fundamental issues in a range of situations in the dairy industry. As the research ends there is a clear implementation plan to promote innovation through knowledge/technology transfer to the industry.

Methodology used in developing the EDM model

The purpose of the EDM model was to provide an economic component that could be integrated as part of the $\text{SIMS}_{\text{DAIRY}}$ model. As $\text{SIMS}_{\text{DAIRY}}$ simulates multiple interactions from different parts of the livestock production system, the economic variables associated with the dairy system are an important element. To this end, regression equations model the relationships between milk production, input requirements and cost functions to provide the necessary parameters to replicate the underlying structures of UK dairy farms. Data required for this modelling was based on economic data of milk production that was originally collected by Universities and Colleges under the aegis of Defra's Commissioned Work Programme and was collated by the University of Manchester in 2003/04; this was recalibrated to reflect 2006 prices throughout.[5] In total, data from 348 farms from across England and Wales were use to define the underlying production and cost relationships. Whilst this number was marginally less than the original reported in Colman *et al* (2004), the removal of outliers enabled normal distributions to be achieved for variables within the model. However, the exclusion of

[5] Recalibration of data occurred as the final stage of the integration process.

these cases, 21 in total, meant that some of the very largest dairy herds were lost from the analysis. Nevertheless, in the context of this project, it was crucial to enable the successful integration of empirical result from the EDM model into the $SIMS_{DAIRY}$ model that reasonably reflected the structure of the majority of dairy farms in England and Wales.

Certain parameters were stipulated that were integral to the linkages between EDM model and the nutrient optimisation system. These are detailed in Figure 1 with the asterisks indicating parameters that were either imputed directly or indirectly from the economics of milk production study data. Whilst the majority of these could be incorporated into the construct of the EDM model, they were clear omittance, particularly those parameters given under 'Manure Management'. In the original data collected from individual farms, information pertaining to manure management became subsumed into dairy specific items, such as labour, machinery, buildings, etc.[6]

Figure 1 Integral linkages between EDM model and the nutrient optimisation system of the $SIMS_{DAIRY}$ model

PRODUCE
Milk yield (L)*
Milk Quality (Protein in milk, Fat in milk, Milk enriched with omega-3 fatty acids, Bactoscan, Somatic cell count, Vitamins or any other beneficial components)

COWS
Number of cows*
Number of young cows**
Spring or autumn calving**
Breed*
Grazing time**
Feeds: concentrates bought*

FIELDS
Grassland (grass or and clover)*
Maize surface**
Total surface of the farm (seeds)**
Harvest of grass**
Harvest of maize**
Silage making**
Hay making**
Clover maintaining costs**
Fertilizer bought**
Fertilizer to grass*
Fertilizer to Maize**

[6] It could have been feasible to return to the original farm records to collect this data but the cost in terms of time and resources were not justifiable.

MANURE MANAGEMENT
Tank size (FYM or slurry)
Dirty water management
Cover or not cover of tanks
Slurry, FYM or Dirty water to grass (tractor)
Slurry, FYM or D water to maize (tractor)
Use of injector

GENERAL MANAGEMENT
Number of people working**
Vets or other subcontracted staff**
Subsidies for environmental practices**
Oil cost to run energy**
Hedging
Placing trees or valuable species

* Indicates variables that were directly imputed from regression equations.
** Indicates variables that were either directly or indirectly imputed from Manchester's study data.

In addition, parameters regarding milk quality were not imputed since analysis of the economic relationship between the price of milk and various attributes of the quality of milk were not proven.

Derivation of the production assumptions

Given the linkages between the EDM model and the nutrient optimisation system, two linear regression equations capture the assumptions that underlie the structural basis of dairy farming. The first assumes that milk production is maximised and that this is dependent on lactating cows and the feed they consume. Reasoning that cows graze some form of herbage to enable rudimentary milk production, the additional feeding of concentrates, particularly if this is scaled correctly to requirements at different stages of the lactation curve, will maximise milk yield. Milk production is therefore explained by:

$$Y_m = -\beta_{m0} + \beta_{m1} X_{m1} + \beta_{m2} X_{m2} + \varepsilon \qquad (1)$$

where $\mathbf{Y_m}$ is litres of milk produced annually produced; $\mathbf{X_{m1}}$ are the number of cows; and $\mathbf{X_{m2}}$ is tonnes of concentrate fed per cow over the same period. However, the number of cows kept on a farm will be dependent on the allocation of grassland (and for that matter the production of grass). Therefore, the second underlying equation is given by:

$$X_m = -\beta_{c0} + \beta_{c1} X_{c1} + \beta_{c2} X_{c2} + \beta_{c3} X_{c3} + \varepsilon \qquad (2)$$

where $\mathbf{Y_c}$ is the total number of cows; $\mathbf{X_{c1}}$ is the total area allocated to dairy herd; $\mathbf{X_{c2}}$, is the stocking rate of cows; and $\mathbf{X_{c3}}$, the available nitrogen kg ha^{-1} from artificially applied fertilizer. Therefore, it is hypothesised that the number of cows may be increased by altering (a) the total area of land allocated to dairy, (b) the stocking rate, (c) nitrogen applied, or (d) a combination of (a), (b) and (c). Within this equation, there is also a reciprocal dependency between the number of cows and the total area of land allocated to the dairy herd on a farm, which will in turn depends on the management techniques employed by the farmer. While equations (1) and (2) provide an empirical explanation of the structural basis of the EDM model, further assumptions are necessary to account for other important aspects of the milk production process. For instance, Rebeiro Filho *et al.* (2005) demonstrate that careful management of white clover is necessary if herbage intake is to increase milk production. Therefore, it is assumed that within equation (2) the application of nitrogen to maximise quality grass growth is an essential management technique that contributes to the production of milk and this is supplied from more than one source. Thus

$$N = N_s + N_c + N_a \tag{3}$$

where $\mathbf{N}$ is the total amount of nitrogen available for grass growth, which is derived from; $\mathbf{N_s}$, nitrogen available from slurry; $\mathbf{N_c}$, nitrogen converted from clover; and $\mathbf{N_a}$, nitrogen from artificial fertilizer.[7,8] It is assumed each day a typical dairy cow produced 42 litres of faeces and urine that is captured by slurry systems (Brockman 1988a). Therefore, over the period of one year, the amount of nitrogen available from slurry is the product of the number of dairy cows, their contribution to daily slurry, and the period of the year that the cow is not grazing outdoors. Thus:

$$N_s = Y_c \times \sum U_i \times \mathrm{N\ kg\ ha^{-1}} \tag{4}$$

where $\mathbf{Y_c}$ is the number of cows; $\mathbf{U_i}$ is the number of that the dairy cows spend under cover; and **N kg ha^{-1}** is amount of nitrogen available from slurry, which is assumed to be 2.5 kg of N kg ha^{-1} (Brockman 1988a). Nitrogen from clover, $\mathbf{N_c}$, is derived from the product of the score clover that is measured during the months of July and August as

[7] Arguably, a further source of nitrogen is that recycled by grazing animals but this has not been modelled.
[8] For organic farms nitrogen from artificial fertilizer is assumed to be zero.

this gives a guide to the overall value of clover in grazed swards, $\mathbf{C_i}$; and the amount of nitrogen that is available from each percentage of clover cover, **N kg ha^{-1}**. (Brockman 1988b). This gives:

$$N_c = \left(C_i \times \mathrm{N\ kg\ ha^{-1}}\right) \times 100 \quad (5)$$

Substituting equations 2 and 3 into equation 1, means that the annual total production of milk may be structurally described by:

$$Y_m = -\beta_{m0} + \beta_{m1}\left(-\beta_{c0} + \beta_{c1}X_{c1} + \beta_{c2}X_{c2} + \beta_{c3}X_{c3}\right) + \beta_{m2}\left(N_s + N_c + N_a\right) \quad (6)$$

Cost of milk production

Turning to the cost of milk production, log transformations are used to capture the shape of the cost curves for costs that are directly attributably to dairying (equation 7) and those that are more general in nature (equation 8). Furthermore, this alternative functional form of the regression equation enables normal distributions of costs to be attained as well as an expression of their cost elasticities. Thus the first of these cost functions is given by:

$$Y_m = f(C_{f1}, C_{f2}, C_{f3}) \quad (7)$$

where $\mathbf{C_{f1}}$ is the contribution of labour to fixed costs; $\mathbf{C_{f2}}$ is the contribution of machinery to fixed costs; and $\mathbf{C_{f3}}$ is the contribution of other factors to fixed costs. While a general cost function is given by:

$$C_g = f(C_{g1}, C_{g2}, C_{g3}) \quad (8)$$

where $\mathbf{C_g}$ is total general overhead costs; $\mathbf{C_{g1}}$ is the contribution of labour to general overhead costs; $\mathbf{C_{g2}}$ is the contribution of machinery to general overhead costs; and $\mathbf{C_{g3}}$ is the contribution of other factors to general overhead costs.

Similar to the production side of the EDM model, while the cost function create the structural base, other important assumption are necessary to compete the integration of the economic and nutrient optimisation system. The main one of these concerns the cost of herd replacement that is given by:

$$H_c = \sum H_o \times (\sum H_{vi} / \sum H_i) - \sum H_{vo} \tag{9}$$

where $\mathbf{H_c}$ is the total cost of herd replacement; $\mathbf{H_o}$ is the number of out going cows; $\mathbf{H_{vo}}$ is the value of out going cows; $\mathbf{H_i}$ is the number of incoming replacements; and $\mathbf{H_{vi}}$ is the value of incoming replacements. In the model, $\mathbf{H_o}$, is made up of two components – the number of cull cows and the number of other cows leaving the herd. This may be through private sales, death or some other reason. Similarly, $\mathbf{H_{vo}}$, has the same two components but this time relating to their respective values.

EDM model – *production aspects*

Regression equations (1) and (2) are used to derive the production structure of the EDM model identifying key variables terms of the model's specifications: the first determines the level of milk production as expressed by equation (1); and the second, establishes the number of cows on a farm, as stated by equation (2). Turning to the first of these, Table 1 shows that 94.3% of milk production can be explained by the number of dairy cows and the concentrate that they are feed. Each extra dairy cow added to the herd, when concentrate feed per cow is held constant will augment 7083 litres of milk to production, which is interpreted as a cow's annual milk yield, whereas increasing the tonnage of concentrate feed by one tonne will add over 100,000 litres of milk.

Table 1: Co-efficients of milk production

Variable	Coefficient β_i	Standard Error	t-statistic
Total milk production – All Breeds			***N=348***
Constant	-239738.7	16210.08	-15.69*
Dairy Cows	7083.44	110.70	64.54*
Concentrates fed per cow	108893.36	8425.33	13.63*
R^2			0.94
Adjusted R^2			0.94
Total milk production – British Friesian			***N=54***
Constant	-138816.01	31170.87	-4.45*
Dairy Cows	6191.29	247.85	24.98*
Concentrates fed per cow	65319.91	18541.36	3.52*
R^2			0.93
Adjusted R^2			0.93
Total milk production – Holstein			***N=80***
Constant	-229262.35	40319.39	-5.69*
Dairy Cows	7416.00	246.96	30.03*
Concentrates fed per cow	97007.17	18710.36	5.19*
R^2			0.94
Adjusted R^2			0.94
Total milk production – British Friesian Holstein X			***N=192***
Constant	-257634.02	22046.11	-11.69*
Dairy Cows	7099.35	138.74	51.17*
Concentrates fed per cow	119686.13	10250.52	11.68*
R^2			0.94
Adjusted R^2			0.94
Total milk production – Channel Island[1]			***N=22***
Constant	-139337.06	40582.50	-4.45*
Dairy Cows	6685.85	422.00	24.98*
Concentrates fed per cow	43594.59	34339.89	3.52†
R^2			0.97
Adjusted R^2			0.97

**Denotes significance at 1% level*

[1] This includes Jersey, Guernsey but also Ayrshire so is therefore not wholly Channel Island breeds

In reality, there are likely to be binding constraints on the addition of extra livestock, such as a maximum that can be potentially housed. Intensifying concentrate feed fed per cow *per se* may be related to the amount of pasture allowance (Bargo *et al*, 2002) and balancing the nutrient management to the requirements of individual dairy cows (Wu and Satter 2000). However, part of this may depend on the type of breed of the dairy cow and these are accounted for by using a dummy variale in equation (1) (where D_i=1 for the specific breed and D_i= 0 for other breeds).

From Table 1, four main breed categories are identified: British Friesian, Holstein, British Friesian Holstein Cross, and Channel Island breeds, which includes a few herds of non-Channel Island breeds such as Ayrshire. In each of these categories, over 93% of milk production can be explained by the number of cows and fed concentrates. However, the annual yield an additional dairy cow produces varies with a Holstein cow producing 1225 litres more than a British Friesian, as does the contribution of an additional tonne of feed, with the milk production of British Friesian Holstein cross seemingly most responsive and Channel Island the least responsive.

The area of pasture allocated to the dairy herd is the most important factor in the determination of the number of dairy cows in equation (2) and in Table 2 the information on grassland management co-efficients is set out for the principal breed groups used. Table 2 reports that 93.8% of the total number of dairy cows is explained by pasture allocation, nitrogen from artificial fertilizer applied to the grassland, and the intensity of stocking. For each additional hectare of land, 1.7 dairy cows may be augmented to dairy herd assuming other factors are held constant, while an additional 100 kg of nitrogen per hectare would increase grass growth to enable an additional four dairy cows, a similar number if stocking rates was adjusted by 0.1 LU/ha. Whilst these capture the main aspects grass land management that explains the number of dairy cows, rotational regimes and the nuance in the utilization of grass swards produced through fertilizer application and adjusting stocking rates can impinge on animal performance (Mayne *et al,* 1987). Again variations for each breed type illustrates that different resposnses to that allocation of hectage, nitrogen use and stocking rates.

Table 2: Comparison of grassland management co-efficients for different breeds

Variable	Coefficient β_i	Standard Error	t-statistic
Number of dairy cows – All Breeds			***N=348***
Constant	-81.06	3.14	-26.75*
Nitrogen Used	0.04	0.01	4.47*
Total hectares allocated to dairy herd	1.70	0.02	70.92*
Stocking rate	43.52	1.67	26.73*
R^2			0.94
Adjusted R^2			0.94
Number of dairy cows – British Friesian			***N=54***
Constant	-51.63	6.37	-8.101*
Nitrogen Used	0.01	0.2	0.218
Total hectares allocated to dairy herd	1.52	0.06	24.99*
Stocking rate	33.26	3.90	8.52*
R^2			0.93
Adjusted R^2			0.93
Number of dairy cows – Holstein			***N=80***
Constant	-95.23	7.206	-13.22*
Nitrogen Used	-0.02	0.02	-1.03
Total hectares allocated to dairy herd	1.69	0.05	36.09*
Stocking rate	57.18	4.08	14.03*
R^2			0.95
Adjusted R^2			0.95
Number of dairy cows – British Friesian Holstein X			***N=192***
Constant	-96.93	3.80	-25.51*
Nitrogen Used	0.04	0.01	3.70*
Total hectares allocated to dairy herd	1.77	0.03	59.53*
Stocking rate	50.42	1.98	25.50*
R^2			0.96
Adjusted R^2			0.96
Number of dairy cows – Channel Island[1]			***N=22***
Constant	-46.84	13.63	-3.39*
Nitrogen Used	0.12	0. 4	3.26*
Total hectares allocated to dairy herd	1.57	0.13	11.97*
Stocking rate	22.98	5.62	4.09*
R^2			0.94
Adjusted R^2			0.93

**Denotes significance at 1% level*

[1]This includes Jersey, Guernsey but also Ayrshire so is therefore not wholly Channel Island breeds

EDM model – *cost aspects*

As a clear relationship between the fixed costs and milk production were established from analysis of the Manchester data enabling the elasticities of fixed cost variables to be derived. From Table 3, it is seen that 81% of costs associated with dairying are determined by labour, machinery and buildings that are directly employed for the enterprise. As these variables are inelastic in nature (ln$\boldsymbol{\beta}$ < 1), a 1% increase in milk production would, for instance, only raise costs associated with specific dairy buildings by 0.59%. A caveat, in the case of buildings, is that the expansion of milk production would incur large discrete capital costs to replace or extend buildings to accommodate additional dairy cows rather than small incremental adjustments. Labour and machinery, on the other hand, may be less of an issue particularly if the supply of these is contracted out, the terms and conditions of which could be potentially attuned with relative ease.

Table 3: **Co-efficients of fixed costs**

Variable	Coefficient $ln\beta_i$	Standard Error	t-statistic
Cost of associated directly with milk production			
Constant	2.41	0.44	5.52*
Dairy and forage labour	0.35	0.06	5.81*
Dairy and forage machinery	0.20	0.04	4.87*
Specific dairy buildings[1]	0.59	0.04	16.33*
R^2			0.81
Adjusted R^2			0.81
General overhead costs			
Constant	2.02	0.44	4.61*
Labour overhead costs (£)	0.36	0.07	5.02*
Machinery overhead costs (£)	0.20	0.04	4.74*
General overhead and building costs	0.81	0.05	17.51*
R^2			0.73
Adjusted R^2			0.73

**Denotes significance at 1% level*
[1]Also includes *annualised charge and net farm rent*

Integration of EDM model into $SIMS_{DAIRY}$ and validation

With the main production and cost relationships established, it is possible to enable price coefficients to be externally controlled. For example, the price range attached to milk from the Manchester data was from 12.81p per litre to 28.73 pence per litre (ppl). However, using the mean value of the price co-efficients, as shown in Table 4, alongside the mean values for certain production co-efficients (the volume of concentrates feed per cow, cows per forage hectare and kilograms of nitrogen applied per hectare) creates a base model from which externally controlled variables can be altered. Variables that cannot be altered and are derived internally from the EDM modelling include the quantity of milk production, number of dairy cows, variable costs, fixed costs and net margin (NM). However, since the $SIMS_{DAIRY}$ model functions by optimizing all variables relative to each other it is necessary for the EDM model to create minimum and maximum values for coefficients of variables. By taking two standard deviations (2σ) from the mean this, in most cases, covers 95% of the probability distribution for each variable. Thus, $P(a< X<b)$, where ***a*** is -2σ and ***b*** is +2σ from the mean. In some cases however, ***a*** results in a negative value, which by definition of the model's specifications is infeasible. For example, total vet and medicines in the variable costs are negative in value at -2σ. As

such, variables with this restriction requires ***a*** takes the value of 0, and probability is reduced.

Table 4: **Price co-efficients used in EDM model**

	N	Minimum	Maximum	Mean
Price sold to milk buyer (ppl)	348	12.81	28.73	17.11
Price of concentrates (£/tonne)	348	69.00	245.00	125.86
Calf price (£/calf)	348	4.87	216.71	58.22
Cull cow price (£/cow)	342	0.00	526.00	300.32
Grass land fertilizer (£/ha)	348	0.00	190.00	68.16

The base results for the EDM model are expressed by the mean values in Table 5, while the optimization procedures of the $SIMS_{DAIRY}$ model ranges from the minimum to maximum values. As such, $SIMS_{DAIRY}$ model will not necessarily recreate the base line results in any of its runs as this is only one of many hundreds of possible permutations during the optimisation procedures. However, the integration of the EDM model into the $SIMS_{DAIRY}$ model is governed by the internal structure of the EDM model. From the base results, a gross margin (GM) is £601.61 and a negative NM of -£53.84 per cow is achieved whereas the $SIMS_{DAIRY}$ model could attain any value between £189.70 and £1013.52 per cow for GM and between -£651.54 and £543.85 per cow for NM.

As $SIMS_{DAIRY}$ simulates multiple interactions from different parts of the livestock production system it is necessary to validate its results. This is important on two fronts. First, to ensure the integration of the EDM model into the $SIMS_{DAIRY}$ model is error free and second, to certify that the results, given the large and more dynamic scale of the latter model, were consistent with the original EDM model that can be more closely controlled. In turn, the EDM model was cross referenced against the results from the Manchester study (Colman *et al,* 2004). From this process, it was apparent that the range offered by two standard deviations resulted in misleading economic outcomes from the $SIMS_{DAIRY}$ model. To rectify this, the range was restricted to one standard deviation of the mean, the effect of which reduced the incidence of minimum values in Table 5 taking the value of zero. In addition, only 68% of the original values used in the EDM model is available for the optimisation procedure in the $SIMS_{DAIRY}$ model, thus reducing the possibility of extreme outcomes.

Table 5: Output co-efficients from EDM modelling for use in $SIMS_{DAIRY}$†

	Min values	Max values	Mean values	P(a<X<b)
Total milk output £/cow	580.65	1614.24	1097.45	95%
Herd replace costs (£/cow)	-33.28	186.89	76.80	95%
Calves (£/cow)	5.90	103.59	54.74	95%
Total gross output (£/cow)	**572.10**	**1597.46**	**1084.78**	**95%**
Total concen. (£/cow)	69.50	388.66	229.08	95%
Total bulk feed (£/cow)	0.00	96.74	19.66	67%
Total bedding costs (£/cow)	0.00	46.00	17.41	87%
Total vet & medicines (£/cow)	0.00	76.07	36.48	94%
Total forage variable costs (£/cow)	16.03	153.85	84.94	95%
Total variable costs (£/cow)	**201.74**	**764.61**	**483.18**	**95%**
Gross margin in total (£/cow)	**189.70**	**1013.52**	**601.61**	**95%**
Total dairy specific labour (£/cow)	15.93	529.23	272.58	95%
Total forage labour (£/cow)	0.00	34.02	13.95	89%
Direct machinery and equipment (£/cow)	4.30	164.69	84.49	95%
Total forage machinery (£/cow)	0.00	60.04	23.13	87%
Total dairy specific buildings (£/cow)	0.00	94.38	26.88	77%
Annual charge for purchased quota (£/cow)	0.00	93.40	30.53	81%
Total net field rent (£/cow)	35.67	143.33	89.50	95%
Total fixed costs (£/cow)	**223.43**	**858.68**	**541.05**	**95%**
Labour overhead costs (£/cow)	0.00	73.06	35.89	95%
Machinery overhead costs (£/cow)	0.00	24.91	11.95	94%
Building overhead costs (£/cow)	0.00	18.39	4.83	74%
General overhead costs (£/cow)	23.06	100.41	61.73	95%
Total overhead costs (£/cow)	**46.38**	**182.42**	**114.40**	**95%**
Net margin after overheads (£/cow)	**-651.54**	**543.85**	**-53.84**	**95%**

†Totals may not sum correctly as not all variables are included.

Discussion

This paper has focussed on the issues involved in developing the EDM model as part of the integrated dairy systems $SIMS_{DAIRY}$ model developed in response to a Defra call for an integrated modelling approach to explore the characteristics of more sustainable dairy systems. The new environmental goals UK dairy farming require a more complex approach to dairy herd management than the solely economic drivers which have dominated its modern development. Crucially, it is essential that the ways in which this combination of economic and environmental pressures can be reconciled within the production cycle on the typical dairy farm are explored using realistic and preferably empirically-derived data. In this, the present research has benefited immensely from the availability of high quality economic data relating to a representative cross-sectional sample of dairy farms in England and Wales. The urgent need to develop more sustainable dairying systems, based on integrated farming principles that can be implemented in a cost-effective manner, underlines the policy and practical value of this research. However, the introduction of integrated dairy production systems requires the exploration of a wide range of alternatives, and the systems research needs to show that the negative environmental impact of production can be reduced or eliminated without necessarily having a negative effect on the economic viability of the farm. Such new approaches to production systems require developments that are inherently more environmentally and economically sustainable.

There are a number of issues relating to the development of the EDM model as well as its harmonisation within the $SIMS_{DAIRY}$ model. Perhaps the first aspect of the current model that should be addressed is the fact that there are some variables which are not modelled, and two of these deserve discussion. First, excellent though the Milk Costs Survey data were for the purposes of the modelling, there is insufficient information available to include any aspect of the manure handling practices on dairy farms. This is a serious omission in any model which aims to explore more environmentally sensitive dairying systems, but one which it proved impossible to rectify in the present research. To circumvent this, the $SIMS_{DAIRY}$ model uses imputed values for different manure handling systems. A second variable which was inadequately modelled was that of labour use, where the Milk Costs Survey data proved problematic at least partly due to the data recording conventions used. Again, since labour is the single largest cost item in milk production this situation is far from ideal. Despite these shortcomings, whilst the physically use of labour is not reflected in the model that is of use to the $SIMS_{DAIRY}$ model, the economic costs of labour provide a useful proxy.

A second important issue is the problem that was caused during the model development stage by the existence of outliers within the sample. These are valid sample results in terms of the original data but cause modelling difficulties in the present study. For instance, the mean number of cows is 104 per farm and the maximum cows recorded for a particular herd was 337 cows. Although in principle there should be no problem in modelling very large herds, the difficulty arises in the present model when outliers break the assumption of normality. As noted earlier, a decision was taken to exclude in total 21 farms that were in the original survey sample, but only four of these comprised the largest herds. As such, some of the extremely large herds are not represented within the model but these may have sectoral implications of changing production systems that are not fully explored. Having said that, it is also clear that the extreme types only represent a very small part of the total population of dairy herds and as such, the impact of this problem on the model results is not considered to be a major deficiency.

The full results from the integrated $SIMS_{DAIRY}$ model will be reported elsewhere, and this paper has deliberately focussed largely on the development methodological aspects of the EDM model. In principle, the challenge of a desk-based exploration of potentially more environmentally-sensitive farming systems, in this case for the dairy sector, has considerable merit, and the research reported here has proved that valuable insights can be gained in this way. The next stage has to be further improvement and refinement of the model, its extension to other farming systems and, crucially, its use in an extension and KT context.

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