Improving the Sustainability of Dairy Farming within Northern Ireland

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Welcome

Welcome to our second seminar of 2010 for dairy specialists.

Having allocated funds for research projects on behalf of the local farming industry, AgriSearch is very keen to see the results of that research work disseminated to farmers within Northern Ireland.

The people invited to this seminar are in contact with dairy farmers during the course of their day-to-day work, or are involved in making policy decisions which can have a considerable impact on dairy farming within Northern Ireland. We believe that you can perform a vital role in helping to make farmers aware of the research results and promoting the uptake of advice that stems from the research.

This is all directed at the goal of a more efficient industry, which will be more competitive in the market. This is ultimately in the best interests of the people who work in the sector and in the wider economy of Northern Ireland.

On behalf of AgriSearch, I wish to thank the scientists at the Agri-Food and Biosciences Institute (AFBI) Hillsborough who have put together this technical seminar and AFBI for the use of the facilities.

James Campbell

AgriSearch chairman

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Robust Milk Production Systems for Northern Ireland

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Introduction

The European dairy industry faces an increasingly uncertain world. For example, there is uncertainty about subsidy payment levels and compliance conditions, global competition, price variability, consumer demand, carbon footprints, water quality, biodiversity, landscapes, animal welfare, and food safety, etc. The future is uncertain because it cannot be reliably predicted; therefore the industry must adopt production systems that will be financially robust over a wide range of possible circumstances. Adding to the uncertainty is a lack of consensus regarding the specific characteristics of these sustainable production systems. In this interdisciplinary research project we developed a profit maximising whole-farm model and employ it to identify robust milk production systems for Northern Ireland under varying market, policy and farm family conditions. The milk production systems incorporated into the model involve variations in date of calving, quantity of concentrate fed, and nature of forage utilised. The model also incorporates a disaggregated specification of time use within farm households and links intra-household resource allocation to the process of agricultural technology adoption. This work illustrates how profit maximising whole-farm models can play a decision support role in helping farmers, agricultural researchers, agribusiness advisers and agricultural policy makers to identify economically sustainable agricultural production systems.

Description of Production Systems Evaluated

The model currently contains seventeen dairy system options. These systems range from 5,000 to 10,000 litre annual yields, including both spring, autumn and non-seasonal calving options, and systems with winter rations based on grass silage only or both grass and maize silage. Milk supply pattern and quality are assumed to vary with calving date and diet. The dairy systems outlined in this paper aim to represent the average input-output parameters for a broad range of Northern Ireland milk production systems. There are six seasonal grass silage systems (i.e. where grass silage is the only winter forage used), namely, three spring-calving systems with average milk production per cow of 5,000, 6,000 and 7,000 litres, and three autumn-calving systems with 6,000, 7,000 and 8,000 litre yields. There are also three seasonal autumn calving systems that involve mixed forage diets (grass and maize silage) during the winter with 6,000, 7,000, and 8,000 litre yields. Finally, there are six non-seasonal calving confinement systems, four of these based on grass silage as the only forage with 7,000, 8,000, 9,000, and 10,000 litre yields, and four involving mixed forages (grass plus maize silage) with again 7,000, 8,000, 9,000, and 10,000 litre yields. Inputs of silage, grazing and concentrates are calculated for each of these seventeen model systems. Typical Northern Ireland conditions are assumed for grass and maize silage quality, grazing management, and genetic merit of cows. Standard lactation curves for Northern Ireland dairy cows are used (Lennox, 1992) with average daily milk yields calculated for each month. Cows in the autumn-calving systems are assumed to calve on 15 November, have a 305-day lactation, go to grass on 15 April, are dried off on 15 September and are housed on 15 October. Cows in the spring-calving systems are assumed to calve on 15 March, have a 305-day lactation, go to grass on 15 April, are housed on 15 October and are dried off in mid January. It is assumed that cows in the non-seasonal confinement systems are housed for most of the time with only limited use of grazing. Grazed grass is only utilised by those cows whose late lactation and dry period coincides with the 15 April to 15 October grazing season.

The cows are assumed to average 575 kg live weight in the 5,000 and 6,000 litre systems, 600 kg live weight in the 7,000 and 8,000 litre systems, and 625 kg live weight in the 9,000 and 10,000 litre systems. In the seasonal calving systems, conception is assumed to take place 85 days into lactation, with a gestation length of 280 days and calving interval of 365 days. Calving interval is a less critical factor in the high yielding non-seasonal calving systems and may extend to around 400 days. Annual replacement rates are assumed to be 23% for the 5,000 litre system, 26% for the 6,000 litre systems, 25% for the 7,000 and 8,000 litre systems, 26% for the 9,000 litre systems, and 27% for the 10,000 litre systems. Culling rates are assumed to be 4% below replacement rates.

Concentrates fed per cow

Using a combined FBS data file for the six-year timeframe 2003-'04 – 2008-'09, we tested a number of different regression models aimed at exploring the relationship between average yield per cow and the level of concentrates fed per cow (kg fresh weight). A linear regression model represented the most statistically significant relationship between average yield and concentrates fed per cow:

$$\text{Average yield per cow (l)} = 3{,}537.84 + 1.419\ (\text{concentrates fed per cow (kg)})$$

Both estimated coefficients are highly significant, ($P<0.01$). R-squared for the equation is a rather modest 0.52, suggesting that there are a number of other factors, in addition to level of concentrates fed, which affect litres of milk produced per cow.

The estimated equation was employed to calculate the level of concentrates fed per cow for each of the systems. Because the equation was estimated using survey level data it was necessary to employ the analysis contained in Anderson and Mayne (2006) to calculated concentrate intakes that are differentiated by seasonal or non-seasonal calving, summer grazing or confinement, and grass silage or grass-maize silage diets (Table 1).

Table 1 Breakdown of concentrate inputs per cow during the housed and grazing periods with each of the 17 model systems

System		Concentrates when housed (kg DM)	Concentrates when grazing (kg DM)
S5	Spring – grass silage – 5,000 L	689	172
S6	Spring – grass silage – 6,000 L	843	611
S7	Spring – grass silage – 7,000 L	982	1064
A6	Autumn – grass silage – 6,000 L	1330	235
A7	Autumn – grass silage – 7,000 L	1693	506
A8	Autumn – grass silage – 8,000 L	2068	765
AM6	Autumn – grass + maize silage – 6,000 L	1277	225
AM7	Autumn – grass + maize silage – 7,000 L	1604	507
AM8	Autumn – grass + maize silage – 8,000 L	1958	762
NS7	Non-seasonal - grass silage – 7,000 L	1869	330
NS8	Non-seasonal - grass silage – 8,000 L	2408	425
NS9	Non-seasonal - grass silage – 9,000 L	2947	520
NS10	Non-seasonal - grass silage – 10,000 L	3486	615
AM7	Non-seasonal - grass + maize silage – 7,000 L	1755	334
AM8	Non-seasonal - grass + maize silage – 8,000 L	2261	431
AM9	Non-seasonal - grass + maize silage – 9,000 L	2767	527
NSM10	Non-seasonal - grass + maize silage – 10,000 L	3273	623

Labour requirements

A linear multiple regression model was employed to investigate the relationship between '*dairy herd labour*' and two explanatory variables '*average yield per cow - litres*' and the '*average number of dairy cows in herd.* The multiple regression model was estimated using FBS data over a six-year timeframe from 2003-04 to 2008-09. The results for the model are as follows:

$$\text{Dairy herd labour (hrs)} = 1{,}017.953 + 0.071\,(\text{average yield per cow (l)}) + 21.187\,(\text{average number of dairy cows (head)})$$

The constant, yield and herd size coefficients are significant at the 0.01, 0.05, and 0.01 levels respectively. R-squared for the equation is 0.65 indicating that the model is a reasonably good fit for the data. Subsequently, the estimated equation was used to calculate the level of labour required per cow in each the dairy systems (see Table 2).

Table 2 Labour requirements per cow for each of the 17 model systems

System		Labour (hrs/cow)
S5	Spring – grass silage – 5,000 L	39.5
S6	Spring – grass silage – 6,000 L	40.4
S7	Spring – grass silage – 7,000 L	41.4
A6	Autumn – grass silage – 6,000 L	40.4
A7	Autumn – grass silage – 7,000 L	41.4
A8	Autumn – grass silage – 8,000 L	42.3
AM6	Autumn – grass + maize silage – 6,000 L	40.4
AM7	Autumn – grass + maize silage – 7,000 L	41.4
AM8	Autumn – grass + maize silage – 8,000 L	42.3
NS7	Non-seasonal - grass silage – 7,000 L	45.5
NS8	Non-seasonal - grass silage – 8,000 L	46.6
NS9	Non-seasonal - grass silage – 9,000 L	47.6
NS10	Non-seasonal - grass silage – 10,000 L	48.6
AM7	Non-seasonal - grass + maize silage – 7,000 L	45.5
AM8	Non-seasonal - grass + maize silage – 8,000 L	46.6
AM9	Non-seasonal - grass + maize silage – 9,000 L	47.6
NSM10	Non-seasonal - grass + maize silage – 10,000 L	48.6

Overhead costs

Using FBS data for the year 2008-09, we estimated a linear multiple regression model that quantified the relationship between ‘dairy herd overhead costs’ with ‘average number of dairy cows in herd’ and ‘average yield’. The following model was chosen as it represented the best option in terms of economic consistency, model tractability and statistical significance. The estimated equation is as follows:

$$\text{Dairy overhead costs (£)} = -13{,}912.08 + 369.39\ (\text{number of dairy cows (head)}) + 2.39\ (\text{average yield per cow (l)})$$

The constant, herd size and yield coefficients are significant at the 0.01, 0.01, and 0.05 levels respectively. R-squared for the equation is 0.85 indicating that the model is a very good fit for the data. Subsequently, the estimated equation was used to calculate the level of overhead costs per cow incurred in operating each of the dairy systems (see Table 3).

Table 3 Overhead costs per cow for each of the 17 model systems

System		Overheads (£/cow)
S5	Spring – grass silage – 5,000 L	343
S6	Spring – grass silage – 6,000 L	375
S7	Spring – grass silage – 7,000 L	407
A6	Autumn – grass silage – 6,000 L	375
A7	Autumn – grass silage – 7,000 L	407
A8	Autumn – grass silage – 8,000 L	439
AM6	Autumn – grass + maize silage – 6,000 L	375
AM7	Autumn – grass + maize silage – 7,000 L	407
AM8	Autumn – grass + maize silage – 8,000 L	439
NS7	Non-seasonal - grass silage – 7,000 L	488
NS8	Non-seasonal - grass silage – 8,000 L	527
NS9	Non-seasonal - grass silage – 9,000 L	565
NS10	Non-seasonal - grass silage – 10,000 L	603
AM7	Non-seasonal - grass + maize silage – 7,000 L	488
AM8	Non-seasonal - grass + maize silage – 8,000 L	527
AM9	Non-seasonal - grass + maize silage – 9,000 L	565
NSM10	Non-seasonal - grass + maize silage – 10,000 L	603

Forage intakes

Total dry matter intakes of grass silage, maize silage and grazed grass are based on the dairy production systems reported in Anderson and Mayne (2006). The feed inputs required to support target daily milk yields for each system during the housed period were estimated in Anderson and Mayne (2006) using the Feed into Milk (FiM) model (Offer *et al*., 2002). Anderson and Mayne (2006) also assumed typical grazing management, which is taken to be a paddock grazing system with some supplementation with a grazing concentrate as necessary. Grazed grass utilisation was assumed to be 75%.

Protein and butterfat percentages for model systems

The average butterfat and protein percentages for the different model systems are based on estimates contained in Anderson and Mayne (2006). Both fat and protein percentages are assumed to vary with calving season, but only protein is assumed to vary with yield.

Costs of feed inputs

Concentrate and fertiliser prices, as well as the costs of producing silage and grazing, were taken from Farm Business Data (DARD). In order to mitigate for the quite large variation in absolute and relative prices resulting from recent market volatility for these key inputs, the baseline model was calibrated using five-year average prices for the various types of concentrates and fertiliser used.

Leasing of resources

It is assumed that additional land can be rented in the form of conacre. Additional capital can be borrowed on a Current Account and also on a Term Loan over a ten-year period (i.e. where all capital and interest is fully paid back at the end of ten years). Milk quota leasing price is assumed to be negligible. Finally, it is also assumed that extra labour can be hired in.

Alternative enterprises

Four alternative enterprises are included, namely, dairy heifer rearing, 24-month beef, lowland breeding ewes and spring barley. The revenues, variable costs, overhead costs and capital requirements associated with the alternative enterprises are taken from Farm Business Data (DARD). Labour requirements for alternative enterprises are from Nix (2001). The dairy heifer rearing enterprise, although grouped with the alternative enterprises, may not be considered as a true alternative enterprise, as there is no option for selling the reared heifers or buying in replacement heifers. Due to assumed differences in animal size - silage, grazing and concentrate requirements for heifers from the 5,000 and 6,000 litre systems are assumed to be lower than for heifers from the 7,000 and 8,000 litre systems, which in turn are assumed to be lower than for heifers from the 9,000 and 10,000 litre systems.

Milk Purchasing Contracts

The basic milk contract incorporated into the linear programming model employed in this study has four main parameters: (1) average annual base price, (2) seasonal base price variation, (3) butterfat bonus/penalty, and (4) protein bonus/penalty. It is assumed that other elements of the milk purchasing contract, such as hygienic quality, presence of added water or transport charges, are all system neutral.

Average annual base price

The average annual base price sets the basic level of milk prices received by milk producers in any given year. The level at which this annual base is set will have a very significant impact on milk producer profits, the quantity of milk produced by each individual producer, and the number of producers agreeing to supply any individual processor. In order to dampen the change in absolute and relative milk prices resulting from significant milk market volatility in recent years, the baseline model was calibrated using a five-year average milk price.

Seasonal base price variation

Milk buyers vary prices over the year both in response to the milk supply/demand situation, and to influence farmer decisions on calving profile and hence volume of milk supplied per month. Table 4 reports the variation in monthly milk prices over the five years (2005-2009). The monthly variation is expressed as a percentage deviation from the average yearly milk price. Table 4 indicates that on average the monthly price variation ranged from the lowest month (May) at minus 9.732% to the highest month (November) at plus 15.894%. Finally, based on results from Lennox (1992), the model calculates (using a matrix generator) the monthly milk supply in each system.

Table 4 Average Seasonal Adjustments in Monthly Base Prices (2005-2009)

Month	% monthly deviation*
January	-0.033
February	-2.844
March	-6.459
April	-9.170
May	-9.732
June	-8.235
July	-4.473
August	1.539
September	10.163
October	15.026
November	15.894
December	11.558

*The monthly variation is expressed as a percentage deviation from the yearly base price.

Butterfat bonus/penalty

In the basic contract incorporated in the model the bonus/penalty for butterfat is 0.018 pence per 0.01% deviation from a standard base quality of 4.00% butterfat.

Therefore, milk produced in any given month with a butterfat percentage less than 4.00% will have a penalty deducted from the relevant monthly base price, while milk with a butterfat percentage more than 4.00% will have a bonus added to the relevant monthly base price. Again, utilising results from Lennox (1992), the model calculates (using a matrix generator) the monthly butterfat percentage of milk in each system.

Protein bonus/penalty

In the basic contract incorporated in the model the bonus/penalty for protein is 0.032 pence per 0.01% deviation from a standard base quality of 3.18% protein. Again, milk produced in any given month with a protein % less than 3.18% will have a penalty deducted from the relevant monthly base price, while milk with a protein % more than 3.18% will have a bonus added to the relevant monthly base price. There are no payments or deductions for lactose. Results from Lennox (1992) were again utilised by the model to calculate (using a matrix generator) the monthly protein percentage of milk in each system.

Availability of resources

Estimates of owned land, working capital and milk quota for dairy herds of between 70 and 80 cows (average herd size 75 cows) were taken from the Farm Business Survey 2008-09 (DARD). FBS data includes 12 farms in this size bracket. The average land area owned by farmers with 75-cow dairy herds is 39.7 hectares. A total of £57,681 of own capital is assumed to be available to finance livestock, working capital, and machinery, with any additional capital requirements for these items needing to be borrowed. Average milk quota owned for this sample of farms is 378,052 litres. Dairy cow housing is not specifically recorded in FBS, but a maximum of 80 cow places has been assumed. Other cattle housing includes housing for heifer rearing and 24-month beef production, with a maximum of 40 places assumed in the model. Each other cattle housing place consists of housing for one animal between 1-12 months and one animal between 13-24 months, with these cattle places equally suitable for either 24-month beef production or heifer rearing. A total supply by farmer and spouse of 8,249 hours of labour was estimated from an AFBI survey of farm households. This total labour supply relates to all time spent by the farmer and spouse in farm work, off-farm employment (including self employment off-farm), childcare, caring for others (perhaps elderly, sick or disabled individuals) and home production activities. Home production includes cooking, cleaning, laundry, gardening, household shopping, and routine maintenance.

Model results

The coefficients discussed in Sections 2 and 3 were incorporated into a linear programming model. The model was solved using the GAMS/CPLEX mathematical programming software package (Brooke *et al*., 1998). GAMS (General Algebraic Modelling System) is a matrix generator that was originally developed to assist economists at the World Bank in the quantitative analysis of economic policy questions. It allows modellers to generate many of the model parameters automatically, which enables model simulations to be conducted quickly and accurately. Optimisation models created with GAMS must be solved with a programming algorithm, and CPLEX is used in this case.

The optimal system as milk prices change

Table 5 summarises the results of model simulations involving changes in milk price. These are annual base price changes, with monthly milk prices varying throughout the year according to the seasonal structure of monthly base prices being assumed. The model results reported in Table 5 show the optimal milk production system when the average annual base price is 16 ppl, 20 ppl and 24 ppl. In these model simulations it is assumed that the butterfat bonus/penalty equals 0.018 p per 0.01% deviation from a standard base quality of 4.00% butterfat; that the protein bonus/penalty equals 0.032 p per 0.01% deviation from a standard base quality of 3.18% protein; and that the seasonal adjustment in base prices follows the historic average presented in Table 4.

Table 5 Annual Milk Price Simulation[1]

	Annual Milk Price(pence per litre)		
	16	20	24
Optimal Dairy System	S7	AM8	AM8
Dairy Cows (head)	79	78	80
Dairy Heifer (head)	40	39	40
Farm Income[1] (£)	22,584	44,200	68,664

Note: 1. Excluding all subsidies

In Table 5 it is clear that with annual average milk prices ranging from 16 ppl to 24 ppl that the optimal milk production system is consistently shown to be a moderate input-moderate output system. That is, either a spring calving herd, yielding an average 7,000 litres per cow (i.e. S7), or an autumn calving herd, fed grass and maize silage, yielding an average 8,000 litres per cow (i.e. AM8). Annual farm income, excluding all subsidies, ranges from £22,584 to £68,664 as the milk price increases from 16 to 24 pence per litre.

Relative profitability of the alternative systems at 16, 20 and 24 ppl

Table 6 illustrates the relative profitability of the ten best systems at milk prices ranging from 16 p/litre to 24 p/litre. The values in brackets represent the increase in profit per cow (£/cow) required for that system to be equal in profitability with the optimum system. Two points are worthy of note. First, although spring systems are shown to be best when milk prices are low, the equivalent autumn calving systems are nevertheless not that far from the optimum even at these low prices. Second, as expected the higher yield systems, regardless of calving pattern, perform much better than lower yield systems when milk prices are high.

Table 6 Relative profitability of the ten best systems at milk prices of 16, 20 and 24 pence per litre

Rank Order at Milk Price of 16 p/litre (profit increase required to be optimum)		Rank Order at Milk Price of 20 p/litre (profit increase required to be optimum)		Rank Order at Milk Price of 24 p/litre (profit increase required to be optimum)	
1.	S7 (optimal system	1.	AM8 (optimal system	1.	AM8 (optimal system)
2.	S6 (-£9/cow)	2.	S7 (-£1/cow)	2.	NSM10 (-£1/cow)
3.	S5 (-£14/cow)	3.	A8 (-£14/cow)	3.	A8 (-£14/cow)
4.	AM8 (-£31/cow)	4.	AM7 (-£39/cow)	4.	NS10 (-£30/cow)
5.	AM7 (-£38/cow)	5.	S6 (-£40/cow)	5.	S7 (-£36/cow)
6.	AM6 (-£41/cow)	6.	A7 (-£51/cow)	6.	NSM9 (-£69/cow)
7.	A8 (-£46/cow)	7.	NSM10 (-£70/cow)	7.	AM7 (-£74/cow)
8.	A7 (-£51/cow)	8.	AM6 (-£72/cow)	8.	A7 (-£87/cow)
9.	A6 (-£51/cow)	9.	S5 (-£76/cow)	9.	NS9 (-£97/cow)
10.	NSM8 (-£144/cow)	10.	A6 (-£82/cow)	10.	S6 (-£110/cow)

Concentrate prices

Table 7 shows the effect of changes in concentrate prices on the optimal system. From Table 5 it is clear that, even when concentrate prices vary by plus or minus 20%, the optimal milk production system remains a moderate input-moderate output system. That is, either a spring calving herd yielding an average 7,000 litres per cow (i.e. S7), or an autumn calving herd, fed grass and maize silage, and yielding an average 8,000 litres per cow (i.e. AM8). However, although the optimal systems remain relatively stable as concentrate prices vary, in contrast, farm incomes change significantly.

Table 7 Effect of changes in concentrate price on optimum system (annual milk price @ 20 p/litre)

Concentrate prices	Optimum system	Dairy cows	Dairy heifers	Farm income[1]
-20%	AM8	80	40	53,867
Baseline	AM8	78	39	44,200
+20%	S7	79	40	36,916

Note: 1. Excluding all subsidies

Fertiliser prices

Table 8 shows the effect of changes in fertiliser prices on the optimal system. Although fertiliser prices are allowed to vary by plus or minus 20%, the optimal milk production system is a moderate input-moderate output system. That is, either a spring calving herd, yielding an average 7,000 litres per cow (i.e. S7), or an autumn calving herd, fed grass and maize silage, yielding an average 8,000 litres per cow (i.e. AM8). Farm incomes also remain relatively stable as fertiliser prices vary.

Table 8 Effect of changes in fertiliser prices on optimum systems (annual milk price @ 20p/litre)

Concentrate prices	Optimum system	Dairy cows	Dairy heifers	Farm income[1]
-20%	S7	79	40	45,657
Baseline	AM8	78	39	44,200

+20%	AM8	78	39	42,897

Note: 1. Excluding all subsidies

Conclusion

The results from this research indicates that the optimal dairy system for most Northern Ireland dairy farms is one that is somewhere between the extremes of those systems adopted in the US and NZ. Moderate input-moderate output milk production systems are shown to be robust over a wide range of milk, concentrate and fertiliser prices. Low input-low output (NZ style) and high input-high output (US style) systems are found to be less versatile.

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Recent developments in supplementation strategies for high-yielding dairy cows during the winter

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Introduction

Intensive genetic selection has resulted in a dramatic increase in the milk production potential of the modern Holstein-Friesian dairy cow. However, this increase in milk production potential has been accompanied until recently by a decline in functional traits including health, fertility and longevity. In addition, the observed increase in milk production in early lactation has not been matched by a proportionate increase in energy intake (Veerkamp *et al.,* 1995; Ingvartsen *et al.*, 1999). The resulting energy deficit, better known as negative energy balance (NEB; Figure 1), is manifest in the mobilisation of body tissue reserves. A positive correlation has been identified between milk production potential and loss of body condition during early lactation (Ruegg and Milton, 1995). Severe and prolonged periods of NEB can predispose the dairy cow to metabolic disorders, immunosuppression, reproductive failure, and behavioural abnormalities, all of which contribute to a decline in the cow's general well-being (Nielsen, 1999). Thus, minimising the extent and duration of NEB experienced by dairy cows would appear to be an important objective within dairy systems.

Reducing NEB in early lactation is difficult for cows with a high genetic merit for milk production. Nevertheless, the approach most often advocated to reduce NEB is to increase nutrient intake. This can be achieved by either increasing total dry matter intake or by increasing the nutrient density of the diet, although both approaches normally go hand-in-hand. While improved housing and feed barrier management may provide some scope by which to improve total food intake, improving diet quality (nutrient density of diet) is the approach which is likely to be most effective. The nutrient density of the diet can be improved by improving forage quality (high digestible grass silage/inclusion of maize silage), or by increasing concentrate feed levels. The latter approach has been widely adopted in Northern Ireland. This is highlighted in CAFRE benchmarking data which indicates that the average concentrate input of benchmarked dairy herds in Northern Ireland increased from 1.1 to 2.1 tonnes/cow/year between 1997/1998 and 2008/2009.

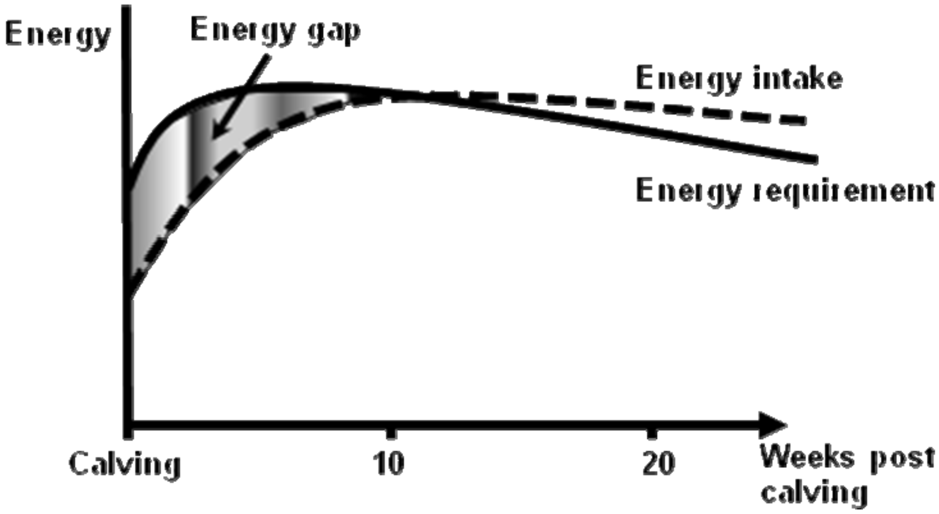

Figure 1 Relationship between energy intake and energy requirement during the first 25 weeks of lactation.

However, the move to dairy systems involving higher concentrate feed levels has raised a number of challenges and questions, such as: optimum strategies by which to increase concentrate inclusion levels in early lactation; at what part of lactation is the response to additional concentrates maximised; what is the optimal strategy by which to include concentrates in the diet; can the protein content of high concentrate diets be reduced; and can concentrate composition be used to modify energy balance and hormone levels to improve overall fertility. This paper will set out to address these issues, based primarily on the findings of recent research programmes undertaken at AFBI Hillsborough.

Strategies to increase concentrate feed level post-calving

With concentrate feed levels now much higher than in the past, optimum strategies by which to build up concentrate levels in the diet in early lactation need to be identified. This issue is highlighted in that within a short space of time, cows frequently move from a dry cow diet based on a medium quality silage and low concentrate supplementation to a lactating cow diet based on high quality forage and high levels of starchy concentrates. Furthermore, offering high concentrate diets can lead to rumen acidosis. Acidosis occurs when the rumen pH falls below 5.6 (normal pH is 6.5 to 7.0), resulting in impaired rumen function. In acute cases, normal rumen movement stops, and this will decrease fibre digestion and subsequently depress appetite and milk production. If this is left untreated, the changes in rumen pH alter rumen flora, with acid-producing bacteria becoming dominant. These bacteria produce more acid, which is absorbed through the rumen wall, causing metabolic acidosis, and this has the potential to cause death.

Introducing concentrates to the diet of fresh calved cows at a slow rate is likely to improve rumen function. In addition, there is some anecdotal evidence that a slow build-up in concentrate feed levels post-calving may reduce the extent of NEB experienced by the cow by delaying peak milk yield until closer to the time when maximum dry matter intakes have been achieved.

To address this issue a study was conducted to compare two very different strategies by which to increase concentrate feed levels in early lactation, namely a rapid build-up (RBU) or a delayed build-up (DBU) strategy. The slow build-up strategy was designed to slow the rate of increase in milk production in early lactation. Previous research at Hillsborough has highlighted that reducing milk production in early lactation can actually improve the energy status of the cow and reduce body reserve mobilisation. As discussed later in this paper, reduced milk production can be achieved by decreasing the protein content of the diet. Dietary protein supply is a key driver of milk production as the cow has a limited capacity to rely on body protein reserves to maintain a high level of milk production (Oldham, 1984). Reduced dietary protein levels can be achieved by reducing the protein content of the concentrate or by reducing concentrate inclusion levels in the diet. One potential benefit of the latter approach is higher forage intakes in early lactation, which may in turn improve rumen stability and total dry matter intake.

This study involved 60 winter-calving Holstein-Friesian dairy cows (multiparous), all of which were offered a basal diet containing 35% concentrate and 65% forage (grass silage and maize silage) on a dry matter basis (15% dietary protein content) post-calving. Cows were allocated to one of two post-calving feeding strategies, a rapid build up of concentrates (RBU) or a delayed build up of concentrates (DBU). Out-of-parlour feeders were used to allocate concentrates according to the two feeding strategies (RBU and DBU). With the rapid build-up treatment, concentrates offered through the out-of-parlour feeder were increased during the first 10 days of lactation (0-7 kg/cow/day). With the delayed build-up treatment cows were offered no concentrate via the out-of-parlour feeders until day 28 of lactation, and thereafter had their concentrates built up to 7 kg/cow/day over a 14-day period, so that maximum concentrate intake was achieved at day 42 post-calving. When cows were offered their full concentrate allocation the protein content of the diet was 18% on a dry matter basis (Figure 2). Cows remained on these two dietary treatments until day 150 of lactation.

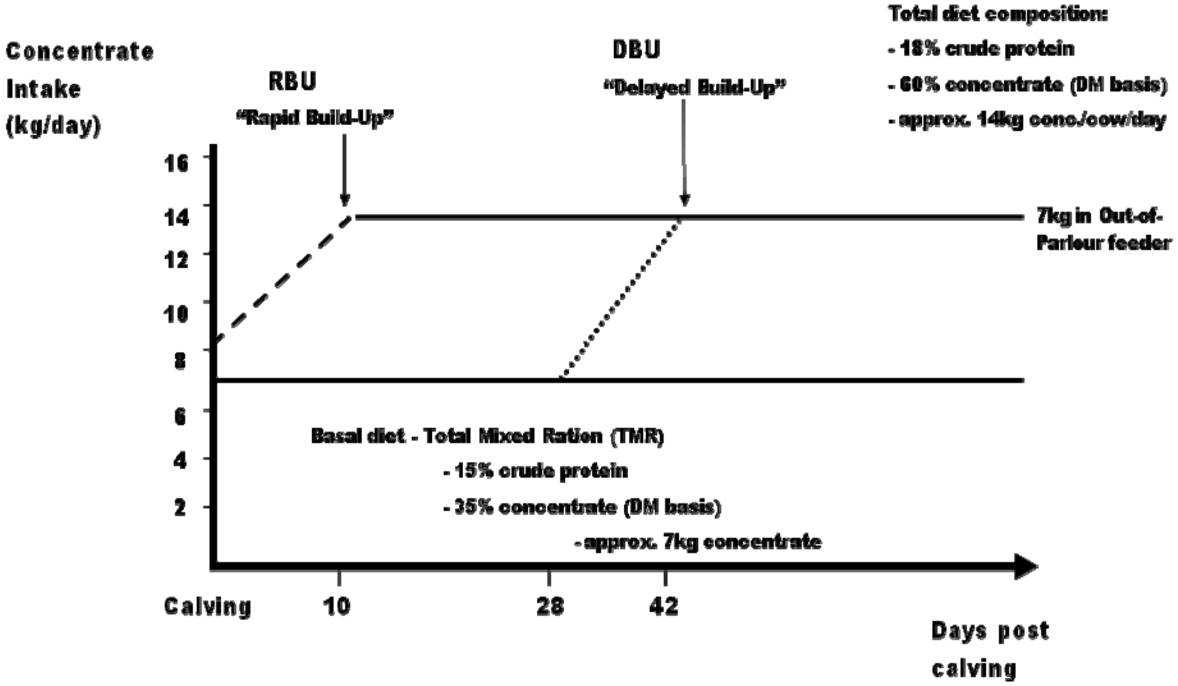

Figure 2 Schematic of concentrate allocation within the rapid (RBU) and delayed build-up (DBU) treatments.

Total dry matter intake was unaffected by concentrate build-up strategy (Table 1). However, forage intake was significantly higher (Figure 3) for cows allocated to DBU compared to those allocated to RBU, while concentrate intake was lower. Neither milk yield nor milk composition was affected by concentrate build-up strategy (Table 1). However, from weeks 3 to 7 post-calving, cows allocated to DBU produced 3.5 kg less milk per day than those allocated to RBU.

Table 1 The effect of concentrate allocation strategy (rapid build-up vs delayed build-up) on dry matter intake and milk production (mean for first 150 days of lactation), and on dairy cow fertility

	Concentrate build-up strategy		
	Rapid build-up (RBU)	Delayed build-up (DBU)	Significance[1]
Production			
Dry matter intake (kg/day)	20.5	21.4	NS
Forage intake (kg DM / day)	9.0	10.4	***
Concentrate intake (kg DM / day)	11.5	11.0	**
Milk yield (kg/day)	38.9	37.9	NS
Milk constituents			
Milk fat (g/kg)	40.5	41.6	NS
Milk protein (g/kg)	34.2	33.3	NS
Energy Balance (MJ / day)	-21.3	-6.3	NS
Fertility			
Pregnancy to 1st service (%)	41	36	NS
100 days in-calf rate (%)	63	64	NS
Overall pregnancy rate (%)	74	86	NS

[1] NS, P>0.05; *, P<0.05; **, P<0.01; ***, P<0.001

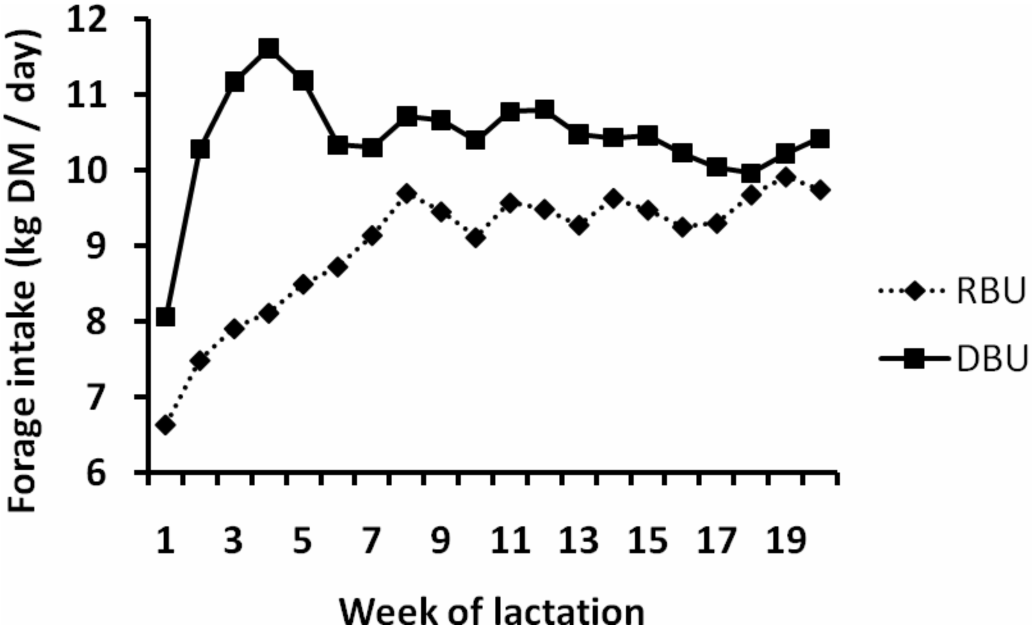

Figure 3 Forage intake during the first 140 days of lactation

Despite the lack of treatment effects on milk production, cows on DBU returned to positive energy balance earlier (week 7 post-calving) than those on RBU (week 19 post-calving). This effect can be attributed to improvements in dry matter intake throughout the experimental period and a lower milk yield during weeks 3-7 of lactation. Nevertheless, concentrate build-up strategy had no significant effect on any of the fertility parameters measured within this study (Table 1). There was, however, a numerically higher number of cows pregnant at the end of this breeding period with the delayed build-up feeding strategy.

Adopting a delayed concentrate build-up strategy in early lactation improved forage intake in early lactation, as well as overall intake, and had no detrimental effect on production performance. This resulted in an improved energy status of the cows on this treatment, and this should contribute to improved health and fertility. However, no significant effects on fertility were observed within this study.

How does the response to additional concentrates differ depending on when they are offered?

The previous study examined strategies for increasing concentrate feed levels in early lactation. However, there is relatively little information available on the response of dairy cows to increasing levels of concentrate supplementation during early to mid lactation. While historical data have indicated that the response to the inclusion of additional concentrates decreases with stage of lactation (Broster and Broster, 1983), no similar work has been undertaken using high-yielding dairy cows.

This issue was examined in a recent study at Hillsborough involving 80 winter-calving Holstein-Friesian dairy cows (40 primiparous and 40 multiparous). Post-calving all animals were offered a basal diet of grass silage, maize silage and concentrate (25, 25 and 50% of the diet on a dry matter basis, respectively) plus 1.0 kg concentrate/cow/day in the milking parlour. This diet was formulated to have a protein content of 180 g/kg dry matter. Cows were allocated to one of four treatments, namely a control treatment in which cows were offered the basal diet only, or treatments in which an additional 4.0 kg concentrate/cow/day was included into the diet at 2, 6 or 10 weeks post-calving.

During the first 29 weeks of lactation offering an additional 4.0 kg concentrate/cow/day from weeks 2, 6 or 10 post-calving had no effect on milk yield or milk composition, but resulted in a significant increase in total dry matter intake (Table 2). However, there was a trend for a greater milk yield response when supplementation commenced at week 2 (P=0.051) post-calving, compared to weeks 6 (P=0.135) or 10 (P=0.944) (Figure 4). The milk production response was then examined during each 4-week period after extra concentrates were introduced in the diet i.e. at weeks 1-4, 5-8, 9-12 etc. post inclusion. When analysed on this basis, concentrate inclusion at week 2 post-calving results in a significant increase in milk output (compared to the control treatment) during weeks 1-4 (P=0.014), 5-8 (P=0.008), and 9-12 (P=0.015) weeks post inclusion. However, when additional concentrates were offered at week 6 and 10 post-calving, no significant milk yield response was observed during any of the 4-week intervals examined.

Table 2 Effects of offering additional concentrates at 2, 6 and 10 weeks post-calving, on dry matter intake and milk production (day 1 to 203 of lactation)

	Treatment				
	Control	2	6	10	Significance[1]
Dry matter intake (kg/day)	17.1	19.7	19.1	19.1	**
Milk yield (kg/day)	32.1	33.8	33.5	33.2	NS
Milk constituents (g/kg)					
Fat	37.6	37.9	38.8	39.4	NS
Protein	32.5	32.6	32.7	32.4	NS
Lactose	50.3	49.5	50.0	49.7	NS
Fat + protein yield (kg/day)	2.22	2.38	2.36	2.36	NS
Liveweight (kg)	566	566	573	571	NS
Energy balance (MJ/day)	-58.4	-44.2	-34.8	-30.3	NS

[1] NS, P>0.05; **, P<0.01

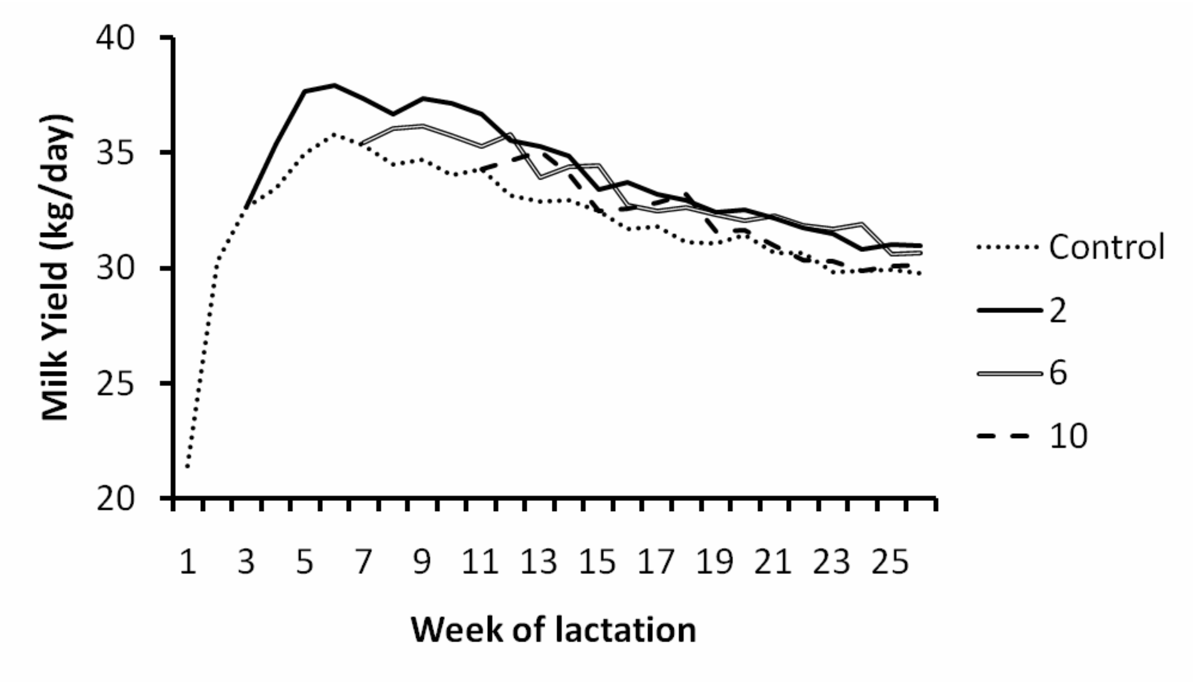

Figure 4 Effects of offering additional concentrate from weeks 2, 6 and 10 post-calving on average daily milk yield (kg/day)

The decreasing response to additional concentrates offered in late lactation appears to be reflected in changes in body tissue reserves. For example, there was a tendency for an improved energy balance (Table 2) in cows receiving additional concentrate later in lactation. This indicates that the responses of dairy cows to supplementation changes according to the stage of lactation when additional concentrates are offered. In early lactation, the additional nutrients consumed tended to be partitioned mainly towards extra milk, whereas after peak milk yield the additional nutrients consumed tended to be partitioned primarily to body tissue reserves.

Complete diet feeding vs out-of-parlour feeders: has the debate moved on?

Historically dairy cows within the UK were offered concentrates twice daily in the milking parlour. However, concentrate feed levels on many farms have increased considerably above the 8-10 kg/cow/day normally considered as the maximum for twice daily in-parlour feeding. Out-of-parlour feeders and complete diet mixer wagons have become increasingly popular methods of achieving higher concentrate intakes. One of the benefits claimed for both of these systems is the improved synchrony in the supply of dietary fermentable energy and nitrogen, with concentrates being consumed “little and often” throughout the day. Mixer wagons also offer an opportunity to incorporate by-product ingredients, which are often cheaper than cereals, into the ration.

However, there has been considerable debate in recent years as to the relative merits of complete diet feeding compared to the same quantity of concentrate being offered via out-of-parlour feeders. In a review of 14 studies involving comparisons of complete diet feeding and separate feeding of concentrates and silage, Ferris *et al.* (1998) concluded that improvements in milk yield were generally obtained when the proportion of concentrate in the diet was 0.6 or higher. However, many of these studies did not include high-yielding cows or grass silage-based diets. To address this issue a series of three studies were conducted at AFBI Hillsborough (Gordon *et al.,* 1995; Yan *et al*., 1998) in which the performance of cows offered concentrates, either through an out-of-parlour feeder or in the form of a TMR, was examined.

The results of these studies illustrated that only small improvements in animal performance and efficiency were achieved when concentrates were offered as a complete diet as opposed to being offered separately from the forage through out-of-parlour feeders (Table 3). In these three experiments the average concentrate proportion in the diet was 0.61 and the forage proportion of the diet consisted of good quality grass silage. In contrast to previous work, the results of this series of studies suggest that offering concentrates in the form of a complete diet, as opposed to being fed separately from the forage, actually decreased total dry matter intake by 3%. However, milk yield was increased by 6%, and milk fat concentrations reduced by 4% when cows were offered concentrates as a complete diet rather than separately from the forage.

Table 3 Responses to complete-diet feeding vs computerised out-of-parlour feeding of a concentrate supplement; weighted overall mean responses across three experiments (Ferris *et al.*, 1998)

	Silage DM intake (kg/day)	Concentrate DM intake (kg/day)	Total DM intake (kg/day)	Milk yield (kg/day)	Milk fat (g/kg)	Milk protein (g/kg)	Yield of fat plus protein (kg/day)
Weighted mean	7.5	11.5	19.0	32.7	39.8	33.9	2.40
Response to complete diet	-0.9	0.3	-0.6	1.9	-1.7	-0.1	0.05
Proportional response	-0.11	0.03	-0.03	0.06	-0.04	0.01	0.02

However, a valid criticism of these studies was the fact that with the out-of-parlour feeding treatment, the silage component of the diet was mixed using a mixer wagon prior to feeding, and fresh silage was offered daily. In practice when silage and concentrates are offered separately, the silage is likely to be offered in whole blocks or part blocks along a feed barrier, with fresh allocation gauged to last 3 to 4 days. To address the practical shortcomings associated with the earlier studies, two separate experiments were conducted to examine cow performance associated with two winter feeding systems, namely daily complete diet feeding vs separate feeding of the forage and concentrate components. The latter system was specifically designed to incorporate twice weekly feeding of whole blocks of silage (easy-feed system). In addition, an assessment of labour requirements associated with each of the two feeding systems was made.

Experiments 1 and 2 involved 64 and 86 Holstein-Friesian dairy cows, respectively, with the duration of these studies being 144 and 146 days, respectively. Concentrate feed levels in these studies were approximately 8.4 and 10.2 kg/cow/day, respectively. The forage component of the diet consisted of 33% maize silage and 66% grass silage (dry matter basis) in Experiment 1 and 30% maize silage and 70% grass silage (dry matter basis) in Experiment 2. The complete diet was prepared daily using a complete diet mixer wagon. The easy-feed system involved whole blocks of grass silage and maize silage being placed along a movable easy-feed barrier on two occasions per week. The design of the feed barrier allows cows to push the barrier out whilst eating their way through the forage. The concentrate portion of the ration was offered using out-of-parlour feeders.

In each of the two experiments, feeding system had no effect on food intake, milk production, milk composition or condition score of cows at the end of the winter period (Table 4), and this may reflect the fact that concentrate proportions in the diet on Experiments 1 and 2 were proportionally 0.48 and 0.54, respectively. In terms of labour, it took approximately 156 minutes per week to feed silage within the easy-feed system and approximately 210 minutes per week to feed with the complete diet system. This equates to 78 minutes twice weekly with the easy feed system and 30 minutes every day with the complete diet system.

Table 4 Effect of feeding system on average cow performance over the winter period in two separate experiments (Ferris *et al.,* 2006)

	Treatments		Significance
	Daily complete diet	Twice weekly easy-feed	
Experiment 1			
Dry matter intake (kg/day)	17.6	17.0	NS
Milk yield (kg/day)	28.4	29.6	NS
Milk fat (g/kg)	39.4	38.5	NS
Milk protein (g/kg)	33.5	34.1	NS
Milk fat plus protein (kg/day)	2.1	2.1	NS
Final live weight (kg)	539	532	NS
Final body condition score	2.4	2.3	NS
Experiment 2			
Dry matter intake (kg/day)	18.7	18.5	NS
Milk yield (kg/day)	30.0	30.6	NS
Milk fat (g/kg)	41.8	40.2	NS
Milk protein (g/kg)	33.9	33.9	NS
Milk fat plus protein (kg/day)	2.2	2.2	NS
Final live weight (kg)	561	556	NS
Final body condition score	2.5	2.5	NS

[1] NS, $P>0.05$

The results of this study demonstrate that a simple feeding system, in which the forage part of the diet is offered twice weekly, can result in similar performance to that of a more complex system involving daily feeding. Also, it is clear that mixed forages can be offered as alternate blocks at a feed barrier with good performance and reduced labour. However, this is heavily dependent on maintaining the integrity of the block when placing them at the feed barrier.

Can we reduce the protein content of the concentrates offered (at high concentrate levels)?

Dairy cows require protein for milk production, maintenance, growth, pregnancy and immune function, while protein supply is a key driver of food intake and milk production. These protein requirements are met directly from dietary protein, rumen microbial protein, and from the mobilisation of body tissue reserves. Within Northern Ireland the overall protein content of dairy cow diets is normally approximately 18% (dry matter basis). However, there is currently considerable interest in the use of lower protein diets for dairy cows. The reasons for this are as follows:

1) Protein ingredients tend to be the most expensive component of concentrate feeds.
2) Offering lower protein diets has been suggested as one option by which to improve cow fertility. As protein supply is a key driver of milk production, reducing the dietary protein content may provide a tool by which to 'reduce milk yield', while maintaining feed intake. This in theory should improve energy status, and as such, also improve fertility.
3) Dietary protein is used inefficiently by dairy cows, with approximately 70% of the protein (nitrogen) consumed ending up in manure. Nitrogen excretion is of significant environmental concern at present due to nitrogen losses to waterways (via leaching), which contributes to aquatic eutrophication. Nitrogen lost to the atmosphere as ammonia (via volatilisation), and nitrous oxide (via denitrification), contribute to terrestrial eutrophication and global warming, respectively. Research from AFBI Hillsborough has illustrated that nitrogen excretion in manure is highly correlated with dietary nitrogen intake (Yan *et al.,* 2006).

Thus while there may be clear benefits of offering lower protein diets, this strategy will only be acceptable if it can be achieved without a significant reduction in milk output, and without having a detrimental effect on cow health. To address this issue, a single lactation study was undertaken at AFBI Hillsborough involving 90 high-yielding Holstein-Friesian dairy cows (45 primiparous and 45 multiparous). These were allocated to diets containing one of three dietary protein concentrations (173, 144, or 114 g protein/kg dry matter) from calving until day 150 of lactation. All cows were offered a complete diet containing 55% concentrate and 45% forage (dry matter basis). The forage offered was a mixture of grass silage (27%) and maize silage (18%).

During the first 150 days of lactation, an increase in dietary protein concentration resulted in an increase in dry matter intake and milk yield (Table 5). Animals offered 114 g protein/kg dry matter produced milk with a higher milk fat concentration than animals offered diets containing 144 or 173 g protein/kg dry matter. There was no effect of diet on milk protein concentrations. In addition, the increase in dry matter intake at higher protein levels was not sufficient to supply the additional ME requirement associated with the higher milk output. Thus animals on the high protein diet experienced a more severe NEB than animals offered the medium and low protein diets.

The results presented so far relate to the first 150 days of lactation, and these have demonstrated that milk production is substantially reduced when cows are offered a diet with a protein content of 144 g/kg dry matter. However, it is known that the protein requirements of dairy cows decrease in later lactation. To allow this to be examined in more detail, half of the cows on the high protein diet were moved onto a medium protein diet after day 150 of lactation, while the remaining cows continued to be offered the high protein diet.

During mid to late lactation (day 151 to 305), decreasing the dietary protein concentration from 173 to 144 g/kg dry matter had no significant effect on milk yield or dry matter intake. This highlights that the efficiency of use of dietary nitrogen can be improved by feeding diets with lower protein concentrations (144 g protein/kg dry matter) without detrimental effects on production (Figure 5).

Table 5 Effects of dietary crude protein concentration on dry matter intake, milk yield and milk composition (fat, protein and lactose) during the first 150 days of lactation, and on fertility

	Dietary protein concentration (g/kg dry matter)			
	114	144	173	Significance[1]
Production				
Dry matter intake (kg/day)	16.5	18.0	18.6	***
Milk yield (kg/day)	25.4	31.8	35.4	***
Milk composition (g/kg)				
Fat	42.0	38.3	38.1	*
Protein	31.4	32.3	32.4	NS
Lactose	48.2	48.1	47.8	NS
Energy balance (MJ/day)	12.8	0.24	-11.1	**
Nitrogen efficiency (Milk N/Dietary N)	0.31	0.30	0.26	***
Fertility				
Pregnancy to 1st service (%)	35	30	28	NS
Pregnancy to 1st and 2nd service (%)	55	63	52	NS
100 day in-calf rate (%)	83	67	62	NS
Overall pregnancy rate (%)	100	93	87	NS

[1] NS, $P>0.05$; *, $P<0.05$; **, $P<0.01$; ***, $P<0.001$

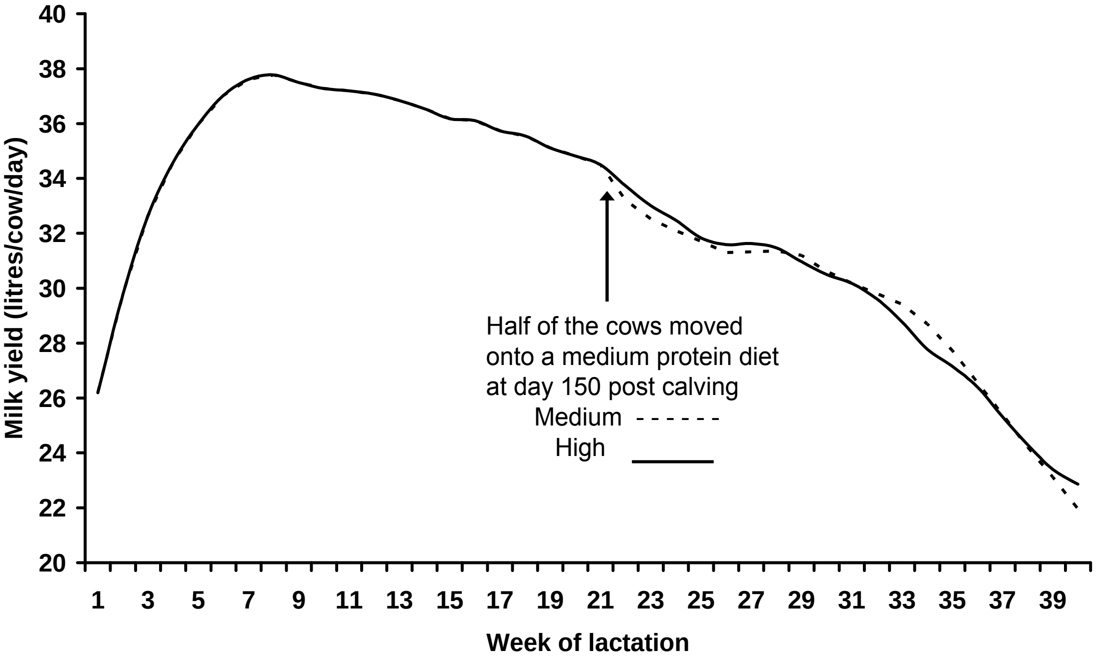

Figure 5 Effect of lowering the dietary protein content at day 151 of lactation (from 173 to 144 g protein/kg/dry matter) on milk production

Dietary protein concentration had no significant effect on any of the reproductive parameters assessed. However, animals receiving 114 g protein/kg dry matter tended to have a higher 100-day in-calf rate compared to animals receiving 144 and 173 g protein/kg dry matter (Table 5). Within a six month breeding period, 100% of cows became pregnant when allocated a diet containing 114 g protein/kg dry matter during the first 150 days of lactation, compared to 92.9% and 86.7% of cows receiving diets containing 144 and 173 g protein/kg dry matter respectively.

A protein content of 114 g/kg dry matter was inadequate. While the efficiency of nitrogen utilisation was improved with a protein content of 144 g/kg dry matter, there were substantial decreases in production. However, there is scope to reduce dietary protein levels to 144 g/kg dry matter after mid lactation without a loss in performance, but with the benefits of reduced feed costs.

Can the efficiency of nitrogen utilisation be improved by supplementing with specific amino acids?

The results of the previous study have demonstrated that diets containing 144 g protein/kg dry matter are inadequate in terms of maintaining high levels of cow performance. However, there is evidence that this decline in performance may not be due to an overall deficit of protein in the diet, but rather due to a shortage of one or two specific amino acids. The two amino acids that are normally most likely to be limiting in dairy cow diets are lysine and methionine. The optimal ratio of lysine to methionine in dairy cow diets has been identified as 3:1. While the majority of UK rations generally supply sufficient quantities of lysine, in most cases methionine is undersupplied. Methionine supplementation can be achieved using ruminally protected methionine.

To address this issue, 48 Holstein-Friesian dairy cows were allocated to one of two diets; control (180 g protein/kg dry matter) and low protein + methionine (150 g protein/kg dry matter with an additional supplement of 40 g/head/day of protected methionine). Diets consisted of 40% forage (16% maize silage, 24% grass silage) and 60% concentrates on a dry matter basis. Cows entered the experiment at calving and remained on the study until day 210 of lactation.

Offering a low protein diet supplemented with methionine was found to have no effect on either dry matter intake or milk yield compared to a control diet (Table 6). However, milk urea nitrogen was significantly lower in animals offered a low protein diet supplemented with methionine compared to a control diet, suggesting that milk was being used as an excretory route for excess nitrogen with the control diet. In addition, the efficiency of nitrogen utilisation was significantly higher when animals were offered the low protein + methionine treatment compared to the control treatment, a reflection of the lower nitrogen intakes associated with this treatment.

Table 6 Effect of supplementing a low protein diet with methionine on cow performance and the efficiency of nitrogen utilisation

	Treatment		
	Control	Low protein + methionine	Significance[1]
Dry matter intake (kg/day)	19.7	19.4	NS
Milk yield (kg/day)	32.9	32.6	NS
Milk Urea (mg/kg)	164	134	***
Nitrogen utilisation efficiency			
Nitrogen intake (g/day)	569	466	***
Milk nitrogen output (g/day)	180	180	NS
Milk nitrogen/nitrogen intake (g/g)	0.31	0.38	***

[1] NS, P>0.05; ***, P<0.001

These results indicate that there may be scope to reduce dietary protein levels without having a detrimental effect on cow performance, provided the diet is supplemented with appropriate limiting amino acids. This has the potential to improve the efficiency of nitrogen utilisation, and as such reduce nitrogen excretion by animals in faeces and urine.

Can dietary protein levels be used as a tool to manage the energy status of individual cows?

As already discussed, severe and prolonged periods of NEB are associated with poor reproductive performance in high-yielding dairy cows (Jorritsma *et al*., 2003) and has been associated with a delay in the onset of luteal activity (Jolly *et al*., 1995), an extended interval to first service (Butler *et al*., 1981) and decreased conception rates (Domecq *et al*., 1997). Thus it has often been suggested that reproductive performance could be improved by reducing the extent of NEB experienced by dairy cows.

A key outcome of a recent AFBI study was that when total dietary protein content was reduced from 180 to 150 g/kg dry matter of the total diet, total milk output was reduced, while dry matter intake was unaffected. The overall effect was an improvement in the energy status of the cow (Law *et al.*, 2009). While there was a significant reduction in milk yield within this study, this was associated with a reduced protein diet being offered for a 150-day period. However, it is possible that a lower protein diet could be offered for a shorter period of time to improve the energy status of the cow, without having a long term detrimental effect on cow performance.

To address this issue a study was undertaken in which a Control diet containing 180 g protein/kg dry matter was compared with an “Individual Cow” management treatment. In the latter treatment the energy balance of individual cows was calculated weekly and manipulated to reach a predefined energy balance trajectory. After calving, all cows on this individual cow management treatment were initially offered a diet containing 170 g protein/kg dry matter, plus 5.22 kg dry matter of a concentrate containing 170 g/kg dry matter in the parlour. Commencing 3 weeks after calving, the protein content of the parlour concentrate was altered, if required, in an attempt to maintain energy balance along a predefined trajectory. If the extent of NEB was greater than planned, the protein content of this concentrate was reduced to 140 g/kg dry matter until the energy balance was back on the predefined trajectory. Alternatively, if the extent of NEB was less than the predisposed trajectory, the protein content of the parlour concentrate was increased to 220 g/kg dry matter. This was continued until day 210 of lactation.

Cows on the individual cow treatment had a higher dry matter intake than those on the control treatment (Table 7). None of milk yield, milk fat or milk protein concentrations were affected by dietary treatment. Due to the increase in dry matter intake combined with the absence of a milk yield response, animals on the individual cow treatment had a significantly improved daily energy balance.

Table 7 The effect of managing individual cows to achieve a preset energy balance, compared to group management, on milk production and energy balance between 1 and 210 days of lactation

	Treatment		Significance[1]
	Control	Individual cow	
Production			
Dry matter intake (kg/day)	19.7	21.0	***
Milk yield (kg/day)	32.8	32.7	NS
Milk constituents			
Fat (g/kg)	37.7	39.4	NS
Protein (g/kg)	33.8	33.9	NS
Urea (mg/kg)	164	174	***
Mean liveweight (kg)	563	557	NS
DEB (MJ/day)	18.4	31.7	***
Reproduction			
Onset of cyclicity (day)	31.5	26.1	NS
Pregnancy to 1st and 2nd service (%)	61.9	60.0	NS
100 days in-calf rate (%)	71.4	79.2	NS
Overall pregnancy rate (%)	85.7	95.8	NS

[1] NS, $P>0.05$; ***, $P<0.001$

However, despite this improvement in energy balance, feeding strategy had no significant effect on any of the reproductive parameters examined (Table 7), although there was a trend for a higher conception rate with the individual cow management treatment.

Adjusting the protein content of the diet shows promise as a strategy by which the energy balance of dairy cows can be manipulated. Furthermore, low protein diets can be offered for relatively short periods of time during lactation without having a long term detrimental effect on cow performance. Although energy balance was improved in this experiment, no clear fertility benefits were identified.

Can we improve reproductive performance with specifically formulated concentrates?

It is considered unlikely that the decline in reproductive performance has a direct ‘genetic’ origin as conception rates in non-lactating Holstein-Friesian heifers have remained high (at 70-80%) during a period when milk production has increased by 218% (Beam and Butler, 1999). While a number of studies presented within this paper have examined the impact of nutritional strategies on dairy cow energy balance, and subsequent reproductive performance, there is increasing interest in the use of specific nutrients to target various aspects of the reproductive system. For example, diets high in starch have been shown to increase circulating concentrations of insulin (van Knegsel *et al*., 2007), thus promoting the resumption of ovarian activity and subsequent cyclicity (Gong *et al*., 2002), while diets high in dietary fat have been shown to be beneficial to embryo growth rate and subsequent survival (Fouladi-Nashta *et al*., 2007). Indeed the results of a recent study by Gong *et al*. (2002) indicate that the interval to the onset of cyclicity was reduced when cows were offered a diet high in starch during the first 50 days of lactation. However, work by Fouladi-Nashta *et al*. (2005) has shown that cows on a high starch diet (resulting in high circulating insulin levels) produced a significantly high number of poor quality oocytes (resulting in lower conception rates). The latter authors state that high plasma insulin levels are detrimental to oocyte quality and suggest that once cycling has commenced a high fat diet is beneficial to blastocyst growth rate in lactating dairy cows (Fouladi-Nashta *et al.*, 2007).

This issue was examined in a study at Hillsborough involving 48 dairy cows, with cows offered either a standard TMR containing 180 g protein/kg dry matter, or a “fertility improver” diet. With the latter, a high starch diet was offered during the first 50 days of lactation to encourage the commencement of cyclicity, followed by a low-starch/high-fat diet (supplemented with 750 g of protected fat per day, Megalac) between day 51 and day 120 of lactation. This latter diet was offered to avoid the detrimental effects of high insulin levels on oocyte quality (Fouladi-Nashta *et al*., 2005).

The diets offered had no effect on food intake, milk production or milk composition. In addition treatment had no effect on the interval to the onset of cyclicity, although, cows offered the fertility improver ration tended to cycle earlier than those offered the control diet (Table 8).

Table 8 The effect of offering a fertility improver ration on conception rate and oestrous cycle characteristics

	Treatment		Significance[1]
	Control	Fertility improver	
Onset of cyclicity (days)	31.5	21.7	NS
Pregnancy to 1st and 2nd service (%)	61.9	56.0	NS
100 day in-calf rate (%)	71.4	68.0	NS
Overall pregnancy rate (%)	85.7	88.0	NS

[1] NS, P>0.05; ***, P<0.001

Although the concept of offering high starch diets in early lactation (to reduce the interval from calving to commencement of cyclicity), followed by a high fat diet (to improve embryo quality) appears to be based on sound scientific principles, the results of the current experiment provide no evidence of an increase in overall conception rate with the fertility improver ration. It is possible that this lack of response was related to the relatively low numbers of cows on each of the diets, and that a different result may have been obtained if much larger group sizes had been used.

Future research

Feed costs, especially concentrates, represent approximately 70% of variable costs on Northern Irish dairy farms. During the last decade annual concentrate inputs have increased by approximately 1.0 tonne/cow, while the increase in milk output has been approximately 1000 kg/cow. This poor response highlights a high degree of inefficiency in concentrate use on dairy farms. Future research is required into the development of robust concentrate allocation strategies for dairy cows which optimise forage use, and ensure nutrient requirements are met across the range of cows within herds.

As technology advances, farms with automated weighing and milk quality monitoring systems will be able to more accurately predict cow energy status. However, farmers often fail to make use of much of this information and research is required to develop algorithms to best allow the farmer to utilise these data within precision management dairy system.

In dairy systems involving high concentrate inputs, the importance of grass silage quality on whole farm profitability may be greatly underestimated. Grass silage remains the key forage within most winter milk production systems, but quality remains extremely variable. Research is required to evaluate the importance of multi-cut silage systems within a whole farm systems context. Furthermore, the relationships between silage quality/concentrate use and whole farm profitability need to be established. This could be achieved by linking CAFRE Benchmarking data with silage quality/feed input data.

The transition period (4 weeks pre-calving to 4 weeks post-calving) is the most traumatic period in the annual cycle of the dairy cow. During this time the cow experiences severe physiological, hormonal, nutritional and metabolic stress. This is due in part to a rapid increase in milk production, and the inability of the cow to consume sufficient feed to meet her metabolic requirements. Previous research has shown that most infectious diseases and metabolic disorders occur during the transition period (Drackley, 1999), with a negative effect on cow performance (Wallace *et al*., 1996) and reproductive performance (Borsberry and Dobson, 1989) during the following lactation. Developing feeding strategies to improve the transition from the dry period to lactation is critical.

Conclusions

- Delaying concentrate build-up in early lactation improved forage intake, but had no significant effect on milk production. This delayed concentrate build-up regime improved the energy status of the cow, but did not significantly affect fertility.

- The introduction of additional concentrates into the diet in early lactation resulted in a large milk yield response. However, introducing additional concentrates into the diet later in lactation resulted in a poorer milk yield response, with a large part of the additional energy consumed being partitioned to body tissue reserves.

- Cow performance was unaffected when the concentrate and forage components of the diet were offered separately (the latter twice weekly at a moveable feed barrier), rather than being offered as a mixed ration.

- Reducing the dietary protein content of the diet from 173 g/kg dry matter to either 144 or 114 g/kg dry matter improved the efficiency of nitrogen utilisation but resulted in a substantial reduction in cow performance. However, there is scope to reduce dietary protein levels to 144 g/kg dry matter after mid lactation without a loss in performance, but with benefits of reduced feed costs.

- The use of rumen protected methionine may offer an opportunity to reduce dietary protein levels and improve N utilisation efficiency, without loss in performance.

- Dietary protein content can be used as a tool to manage energy balance. Cows whose energy status was managed to achieve a predefined energy balance had improved dry matter intake and energy status, although this had no effect on reproductive performance.

- Offering a fertility improver ration (high starch in early lactation and high fat in late lactation) tended to reduce the interval from calving to commencement of cyclicity, but resulted in no improvement in overall reproductive performance.

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Reducing dietary phosphorus inputs within dairy systems[†]

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Introduction

The two main inputs of phosphorus (P) to agricultural systems are P in inorganic fertilisers and P in concentrate feedstuffs. Agricultural P is obtained from phosphate rock, with China, the United States of America (USA), Morocco and the Russian Federation currently the world's main producers. However, world reserves of phosphate rock are finite, and at the present rate of use known reserves have a predicted lifespan of approximately 200 years (Richards and Dawson, 2008). Thus there is an increasing need to maximise the efficiency of use of this un-substitutable nutrient, and to minimise losses from agricultural systems.

However, in many agricultural regions, and at an individual farm level, there is a significant imbalance between P inputs and P outputs. For example, until relatively recently the agricultural P balance sheet for Northern Ireland (NI) (Foy *et al*., 2002) indicated a total P input of 18911 t/annum (9601 t/annum in inorganic fertiliser and 9310 t/annum in feeds), compared to an output (removed in milk, beef, sheep, 'pigs and poultry' and crop) of 6062 t/annum.

Although most surplus P accumulates within the soil, part of this P is at risk of being lost to the environment. In addition to representing a loss of valuable nutrients from agricultural systems, phosphates can cause the eutrophication of waterways (the enrichment of water by nutrients, especially compounds of nitrogen and P, whereby a body of water changes from a nutrient poor (oligotrophic) to a nutrient rich (eutrophic) state).

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Eutrophication has a number of adverse effects on water quality, including health risks associated with toxic algae and algal scums in drinking water supplies and recreational waters, damage to habitats leading to loss of species diversity, loss of fisheries, and undesirable aesthetic impacts such as odours, loss of transparency, and clogging by weeds, the latter reducing amenity value. Phosphorus is often the 'limiting nutrient' within these processes.

In many parts of the world dairy farming is a significant driver of P induced eutrophication. Problems exist in countries where grassland-based systems dominate, such as New Zealand and Ireland, and in countries where intensive dairy systems are more common, such as the USA and the Netherlands. However, as pressure on water resources continues to grow, all agricultural sectors, dairying included, will be forced to tackle this problem with increasing rigour. Within the European Union (EU), legislation designed to improve water quality is already in place. For example, restoring surface waters to good ecological status by 2015 (including reducing the trophic status) is a target within the Water Framework Directive, while, where it can be related to agricultural activities, action to control nutrient enrichment is also required under the Nitrates Directive**.**

Proportionally 0.58 of P exports to inland waters within NI are of agricultural origin (Smith *et al*., 2005). While the exact contribution of different agricultural sectors to this problem is unknown, the impact of dairying is likely to be significant due to the importance of the dairy sector within NI, and its relatively intensive nature. This was highlighted in a recent agricultural P balance sheet for NI which indicated that P in dairy feeds represented the second largest P input (3025 t P per annum), exceeded only by P in fertiliser (Foy *et al*., 2002). This feed P input exceeded the output of P in milk (1539 t of P per annum), so that even before inputs of P in fertiliser were considered, the average dairy farm was likely to be in P surplus. The analysis of 40 commercial concentrate feedstuffs collected from dairy farms around Northern Ireland at this time (2000 – 2001) highlighted one of the factors contributing to this situation, namely the high mean P content of these concentrates (7.1 g/kg DM: C.P. Ferris, unpublished data).

While improved management of P on farms will help reduce P loss to the environment, control measures must firstly seek to reduce farm-gate P surpluses. For dairy farmers, options by which farm-gate P surpluses can be reduced include reducing the quantity of P brought onto farms in fertiliser and feeds. With regards the latter, this may involve reducing stocking rates, utilising more home-produced concentrate feeds, feeding less concentrates/cow, or feeding concentrates with a lower P level. While the latter is recognised as one of the most promising options for reducing P surpluses, reducing P levels in dairy cow diets will clearly be unacceptable if animal performance, health, fertility and welfare are not compromised.

This paper will review the findings of ‘recent’ studies in which dairy cows have been offered diets containing different P levels, and will examine opportunities for reducing P levels in dairy cow diets, together with some of the practical implications of feeding rations containing lower P levels. Where possible, this paper will examine these issues within the context of grassland-based systems.

Phosphorus requirements and uncertainties

Approximately 80% of P within the dairy cow occurs in bones and teeth, principally as apatite salts and calcium phosphate (NRC, 2001). Phosphorus is also involved in acid-base buffer systems of blood and other body fluids, in cell differentiation, in all energy transactions, and as a component of cell walls and cell contents. Dairy cows also secrete large quantities of P in milk on a daily basis (approximately 0.9 g/kg of milk produced), thus greatly increasing their requirements compared to those of growing cattle. Rumen microbes also have a requirement for P (Bryant *et al*., 1959), and if this is not supplied via the diet, or from P recycled in saliva, microbial activity may be impaired.

The P requirements of dairy cows have been defined in many countries, including the United Kingdom (UK) (AFRC, 1991), USA (NRC, 2001), Germany (GfE, 1993) and the Netherlands (NCMN, 1973). Most P requirement systems adopt a factorial approach which sums the net P required for 'maintenance', growth, pregnancy and lactation, and then divides this by a true absorption coefficient, to obtain a total daily P requirement.

Valk *et al*. (2000) reviewed the calculated P requirements of lactating dairy cows using a number of these systems, and demonstrated that while there was reasonable agreement between systems in net P requirements for milk production, maintenance P requirements and true absorption coefficients varied widely between systems. The differing maintenance requirements are due in part to the different approaches adopted, with maintenance being a factor of cow live weight in some systems, and of dry matter (DM) intake in others. In addition, appropriate data were not always available when these systems were being developed. For example, within the current UK recommendations (AFRC, 1991), maintenance requirements for lactating dairy cows are based on unpublished data obtained from experiments involving sheep. Indeed, recognising the limitations of existing knowledge, and noting that many aspects of P nutrition and metabolism were not well understood, AFRC (1991) included a recommendation that dairy cow P requirements should be validated in long term feeding trials using roughage-based diets.

It is clear that the exact net P requirements of dairy cows are not known precisely, while the availability of P from many common feedstuffs is not well defined. As a consequence of these uncertainties, together with the perceived benefits, especially in relation to fertility, that farmers associate with feeding diets high in P content, there is evidence that nutritionists and farmers tend to feed P to dairy cows at levels in excess of existing recommendations.

Impact of reducing dietary phosphorus content on cow performance

During the last four decades a number of studies have examined the effect of dietary P level on dairy cow performance, with key details of some of these studies presented in Table 1. However, many of these studies were of a relatively short term nature (less than two years), which is of concern as cows have the ability to deplete phosphorus reserves for milk production over a number of lactations, thus deficiency symptoms may not arise in the short term.

Table 1 Details of some of the main studies published during the last 40 years in which dairy cows were offered diets containing different levels of dietary phosphorus

Reference	Main dietary components	Number of cows per treatment	Duration of study	Approximate lactation yield (kg)	Dietary P levels (g/kg DM)
Steevens *et al*. (1971)	Alfalfa hay, concentrates	16	Lactation 1 + 16 weeks of lactation 2	6 100	4.1 and 6.0
Carstairs *et al*. (1981)	Maize silage, concentrates	24	3 months	Unavailable	4.0 and 5.0
Kincaid *et al*. (1981)	Alfalfa hay, grass/alfalfa silage, concentrates	10	10 months	8 500	3.1 and 5.4
Call *et al*. (1987)	Alfalfa hay, corn, molasses, dried beet pulp, soya hulls	8-13	2 months pre-calving until 7-10 months post-calving	7 000	2.4, 3.2 and 4.2
Brodison *et al*. (1989)	Grass silage, concentrates (winter); grazed grass (summer)	35	3 years	5 000	Housed: 3.5 and 4.4, Grazing: 3.5 and 3.5
Brintrup *et al*. (1993)	Grass silage, maize silage, concentrates	26	2 years	7 500	3.3 and 3.9
Dhiman *et al.* (1995)	Alfalfa silage, maize silage, high moisture ear corn, soya bean, barley	23	3 months	Unavailable	3.9 and 6.5
Valk and Sĕbek (1999)	Grass silage, dried grass, maize silage, wet beet pulp, straw, concentrates	6-9	Week 17 of lactation 1, to the end of the dry period in lactation 2	9 000	2.4, 2.8 and 3.3
Wu *et al.* (2000)	Alfalfa silage, maize silage, high moisture ear corn, soyabean, beet pulp	8-9	1 year	11 000	3.1, 4.0 and 4.9
Wu and Satter (2000)	Alfalfa silage, maize silage, high moisture ear corn, soya (housed); maize silage, high moisture ear corn, soya, grazed grass (grazing period)	21	2 years	9 500	Housed: 3.8 and 4.8, Grazing: 3.1 and 4.4
Lopez *et al.* (2004)	Alfalfa silage, maize silage, high moisture ear corn, soyabean	123	5 - 6 months	Unavailable	3.7 and 5.7
Tallam *et al*. (2005)	Alfalfa hay and silage, corn silage, high moisture ground corn, soyabeans, concentrates	27	10 months	11 000	3.5 and 4.7
Odongo *et al*. (2007)	Corn silage, alfalfa silage, high moisture ear corn, grain mix	32	2 years	11,000	3.5 and 4.2
Ferris *et al*. (2010a)	Grass silage, maize silage, concentrates (winter) Grazed grass, concentrates (summer)	50 decreasing to 10	4 years (lactations 1 – 4)	7 500 increasing to 9 000	Housed: 3.6 and 4.9 Grazing: 3.6 and 4.2

In addition, the appropriateness of some of these studies from a UK perspective have been questioned due to the use of monosodium phosphate (a very available form of P which is rarely used in UK diets) as a P supplement, and the use of non grass/grass silage-based diets (Hemmingway, 2002). The latter is of concern as the availability of P from different feedstuffs (concentrates, maize silage, alfalfa silage, grazed grass) may vary, as reflected in the different true absorption coefficients adopted within feeding recommendations in different countries.

While low P diets have been examined previously in grassland-based systems (Brodison *et al*., 1989), this study involved relatively low yielding dairy cows (5,000 litres), compared to the industry norm at present. However, it was only recently that the recommendation made within AFRC (1991), namely 'validation in long term feeding trials using roughage-based diets', was addressed in a four-year experiment involving a grassland-based system (Ferris *et al*., 2010a and 2010b).

Nutrient utilisation and food intake

Rumen microbes have a requirement for P (Bryant *et al*., 1959), and if this is not supplied via the diet, or from P recycled in saliva, microbial activity may be impaired, and ration digestibility and food intake reduced. For example, P depletion has been associated with a reduction in microbial protein synthesis and organic matter digestibility in sheep and goats (Breves *et al*., 1985; Petri *et al*., 1988). However, in the majority of dairy cow production studies which involved measures of nutrient utilisation, ration digestibility was unaffected when low P diets, including one containing 2.4 g P/kg DM (Valk *et al.*, 2002), were offered. It is therefore likely that diets containing extremely low levels of dietary P are required before ration digestibility is impaired, with Satter (2003) suggesting that modern dairy cow diets never approach the low dietary P concentrations that can result in impaired microbial growth in the rumen.

However, reduced food intakes have been observed with cows offered low P diets in a number of studies. For example, Call *et al*. (1987) observed a reduction in food intake after a diet containing a very low P content (2.4 g P/kg DM) was offered for approximately six weeks. In a separate study (which commenced at week 17 of lactation) involving a similar diet (2.4 g P/kg DM), Valk and Sĕbek (1999) observed no reduction in food intake until the dry period at the end of lactation 1, with DM intake reduced during lactation 2 (Table 2) to such an extent that this treatment was discontinued. These studies clearly demonstrate a dietary P content of 2.4 g/kg DM to be inadequate, even during a single lactation. Reductions in food intake have also been observed with diets containing much higher P levels, namely 3.1 (Kincaid *et al*., 1981) and 3.5 g P/kg DM (Odongo *et al*., 2007), the latter involving primiparous cows.

In a number of other studies in which reductions in food intake were observed (Bortolussi *et al*., 1996; Milton and Ternouth, 1985), ration digestibility was unaffected by dietary P level. The latter authors have suggested that the reduction in food intake associated with low P diets may be mediated via a metabolic effect at a cellular level. However, intakes were unaffected in studies involving dietary P levels of between 2.8 and 3.3 g P/kg DM (Call *et al*., 1987; Brintrup *et al*., 1993; Valk and Sĕbek, 1999; and Wu *et al*., 2000), and during the winter period of a four-year study (Ferris *et al.,* 2010a) in which cows were offered diets containing approximately 3.6 g P/kg DM (Table 3).

Table 2 Dry matter intakes and milk yields of dairy cows offered diets containing three levels of dietary phosphorus (2.4, 2.8 and 3.3 g/kg DM) from week 17 of Year 1 until the end of lactation in Year 2 (Valk and Sĕbek, 1999)

Dietary P level (g/kg DM)		2.4	2.8	3.3	2.4	2.8	3.3
		Dry matter intake (kg/day)			Milk yield (kg/day)		
Year 1	Weeks 17-27	21.5	20.7	21.1	26.8	25.9	27.5
	Weeks 28-37	19.2	19.1	19.2	19.7	22.3	21.4
	Dry period	10.5	11.1	11.6			
Year 2	Weeks 2-11	20.8	24.6	25.3	37.9	43.7	44.1
	Weeks 12-21	21.9	24.0	24.7	29.9	37.5	37.1
	Weeks 22-31	*	21.5	20.8	*	30.5	28.9
	Weeks 32-42	*	19.8	19.5	*	24.9	22.1
	Dry period	*	10.2	11.5			

* Cows removed from treatment

Table 3 Effect of dietary P level over four successive lactations on dairy cow performance and fertility parameters (Ferris *et al*., 2010a and b)

		Mean dietary P level	
	Lactation No	3.6 g/kg DM	4.5 g/kg DM
Intake (kg DM/cow/day)†	1	17.6	17.4
	2	19.9	19.6
	3	20.8	19.8
	4	22.9	22.7
Lactation milk output (kg)	1	7521	7474
	2	8241	8419
	3	9177	9219
	4	9000	8976
Proportion of cows with luteal activity pre day 42 post-calving‡	1	0.60	0.64
	2	0.55	0.64
	3	0.60	0.49
	4	0.65	0.73
Conception to 1st + 2nd insemination (proportion basis)	1	0.74	0.67
	2	0.73	0.56
	3	0.59	0.69
	4	0.31	0.25

† winter period only

‡ based on milk progesterone analysis

Milk production

The reduction in feed intake observed by Call *et al*. (1987), Valk and Sĕbek (1999) and Kincaid *et al*. (1981) with diets containing 2.4, 2.4 and 3.1 g P/kg DM, was accompanied by a lower milk output. However the fall in milk production observed by Valk and Sĕbek (1999) was only observed after the diet was offered during a second lactation (Table 2), highlighting that body P reserves can sustain cows through considerable periods of P inadequacy. In the same study no reduction in milk production was observed with a dietary P level of 2.8 g P/kg DM during either of lactations 1 or 2, although this study excluded the first 17 weeks of lactation 1. In contrast, Call *et al*. (1987) observed a lower persistency of milk yield with diets containing 3.2 g P/kg DM, while Wu *et al*. (2000) observed a reduction in milk yield after cows had been offered a diet containing 3.1 g P/kg DM for 25 weeks, although intake was not affected in either of these studies. Ferris *et al*. (2010b) found milk production to be unaffected when a diet containing 3.6 g P/kg DM was offered over four successive lactations (Table 3), highlighting the long term adequacy of this level of P in sustaining milk yields of up to 9000 kg/lactation. Although it is likely that dietary P impacts on milk yield through a reduction in food intake, Valk and Sĕbek (1999) observed that the fall in milk yield preceded the decline in intake, perhaps also suggesting an effect of dietary P on milk synthesis at the cellular level. Nevertheless, Ferris *et al*. (unpublished data) observed no difference in the partial efficiency of lactation (kl) with cows offered diets differing in dietary P levels. In general, there is no evidence of a reduction in milk output in studies involving dietary P levels in excess of 3.3 g/kg DM (Table 1), although all but two of these studies (Brodison *et al*., 1989; Ferris *et al*., 2010a) were of less than two years in duration.

Body tissue reserves

When cows were offered diets containing 2.4 g P/kg DM, Call *et al.* (1987) observed a significant reduction in live weight after a 14-week period, while a trend towards a lower live weight was observed by Valk and Sĕbek (1999). However, in each of these studies the reduction in live weight was associated with other symptoms of P deficiency (reduced intakes and milk outputs). In contrast, Wu *et al.* (2000) observed no significant effect of dietary P level on either condition score or live weight during a single lactation study, despite a significant reduction in milk yield in late lactation with cows offered a low P diet. More recently Ferris *et al.* (2010a), observed a significant reduction in both condition score and live weight with a diet containing 3.6 g P/kg DM, despite no significant effect of diet on food intake or milk production. These differences only became apparent after cows had been managed on this diet for two full lactations, with the authors concluding that the effect was unlikely to have arisen as a direct consequence of the different dietary P levels imposed.

Cow health

The results from a number of studies (Valk and Sěbek, 1999; Wu and Satter, 2000; Lopez *et al*., 2004; Odongo *et al*., 2007; Ferris *et al*., 2010b) provide no evidence that dietary P level had an effect on incidences of mastitis. While Wu *et al.* (2000) and Odongo *et al*. (2007) observed a numerically higher incidence of hoof problems in cows offered a low P diet, Wu and Satter (2000) observed the reverse trend. However, over four successive lactations, Ferris *et al.* (2010b) observed that dietary P level had no effect on the incidence of lameness. Similarly, in a six-month study involving 247 cows, incidence of foot/leg problems did not differ between cows offered either a high or low P diet (Lopez *et al*., 2004). More recently, Mullarky *et al*. (2009) observed neither innate or cell-mediated immune responses of lactating dairy cows to differ when dietary P level was reduced from 5.2 to 3.4 g P/kg DM.

Reproductive performance

There is no doubt that the perception of a strong link between dietary P levels and dairy cow fertility is one of the key reasons why dairy cows are frequently fed diets containing high P levels. The origins of this perception have been traced by Ferguson and Sklan (2005), in a review of data published between 1920 and 1960, much of it based on field observations and survey work. However, in the vast majority of ‘recent’ studies in which the effect of dietary P level on cow fertility is presented (Call *et al*., 1987; Brodison *et al*., 1989; Brintrup *et al*., 1993; Valk and Sěbek, 1999; Wu and Satter, 2000; Wu *et al*., 2000; Ferris *et al.,* 2010b), fertility performance was largely unaffected by dietary P levels. Nevertheless, these studies were primarily designed to examine the impact of dietary P level on cow performance, and not fertility performance *per se*. Recognising that basic indices of ‘fertility success’ such as ‘conception rate’ are affected by a wide range of factors, including human ‘intervention’, a number of studies have examined the effect of dietary P level on physiological changes within the cow, including milk progesterone levels, oestrus behaviour and ovarian activity. For example, Lopez *et al*. (2004) using a radiotelemetric transmitter, observed that dietary P (3.8 and 4.8 g/kg DM) had no significant effect on the number of oestrus events recorded, the duration of the oestrus cycle, the duration of oestrus, the number of mounts within each oestrus or total mounting time within each oestrus. Similarly, using ultrasonography, Tallam *et al*. (2005) observed that dietary P (3.5 or 4.7 g P/kg DM) had no effect on days to first post-partum ovulation or the diameter of dominant and ovulating follicles, corpus luteum development, or blood progesterone concentrations during the voluntary weighting period. The latter supports the findings of Ferris *et al*. (2010b), who observed no difference in the proportion of cows showing luteal activity prior to day 42 post-calving (Table 3), the interval to commencement of luteal activity, and the peak progesterone level during the first oestrus cycle, with cows offered diets differing in P content.

Nevertheless, ‘cow numbers’ have been a limiting factor in virtually all studies, with Wu and Satter (2000) observing that approximately 250 cows per treatment would have been required in their study in order to detect a 10% difference in fertility parameters. Realising the limitations of examining fertility data from individual studies in isolation, these authors combined data from 13 individual experiments, involving a total of 785 cows, approximately 392 cows per P level. When reproductive performance was compared across low (3.2-4.0 g P/kg DM) and high (3.9-6.1 g P/kg DM) P diets, diet had no significant effect on days to first oestrus, days to first insemination, days open, number of services per conception, or pregnancy rate. Indeed, reproductive performance was unaffected in studies where dietary P concentrations of 2.4 g/kg DM were examined (Call *et al*., 1987; Valk and Sĕbek, 1999), despite a reduction in cow performance with these diets. This is in agreement with the findings of Ferguson and Sklan (2005), who modelled the relationships between dietary P and conception rates, and dietary P and pregnancy rates, across a range of studies. These authors concluded that dairy cattle can tolerate dietary P concentrations of between 2.0-3.0 g/kg DM, without reproductive performance being affected. In summary, it would appear that with most modern dairy cow diets containing moderate to high concentrate feed levels, dietary P in isolation is unlikely to be a causal effect of poor reproductive performance.

Blood metabolites

It is generally accepted that blood P concentrations do not provide a good indicator of P deficiency in ruminants (Forar *et al*., 1982). This was highlighted by Wu *et al*. (2000) who observed similar plasma P concentrations over a range of diets, despite a significant reduction in milk yield with cows offered a diet low in P. Nevertheless, reduced plasma P concentrations have frequently been observed with cows offered low P diets (Brodison *et al.*, 1989; Dhiman *et al*., 1995; Wu *et al*., 2000; Lopez *et al.,* 2004; Ferris *et al*., 2010a). In the latter study, which was conducted over four successive lactations, a significantly lower plasma P concentration was observed with cows offered a diet containing 3.6 g P/kg DM, compared to those offered a diet containing 4.5 g P/kg DM (Figure 1). The trend for plasma P concentrations to be lowest during the post-calving period, and to decline with increasing lactation number, was observed previously (Wu *et al*., 2000; Forar *et al*., 1982). However, it was only during weeks 2-6 of lactation 4 that P concentrations fell below the norm (1.44 mmol/l) for samples collected and analysed within NI (M. McCoy, personal communication). However, with extremely low P diets, plasma P concentrations may be a useful diagnostic tool, with Call *et al*. (1987) observing a significant reduction in plasma P concentrations (mean concentration over the lactation of 1.16 mmol/l) with a diet containing 2.4 g P/kg DM.

Bone reserves

The extent of P resorption from bone can be significant, with Wu *et al*. (2001) suggesting that a 600 kg dairy cow could mobilise between 600-1000 g P in early lactation. Indeed, there is no doubt that resorbed bone P has an important role to play in meeting the P requirements of dairy cows, especially in situations where dietary P is inadequate, with AFRC (1991) justifying the absence of a safety margin by suggesting that the skeleton should be relied upon to provide the necessary ‘elasticity’ between supply and demand. Similarly, Ekelund *et al.* (2006) suggested that it may be possible to reduce the dietary supply of P to dairy cows in early lactation by optimising naturally occurring bone resorption.

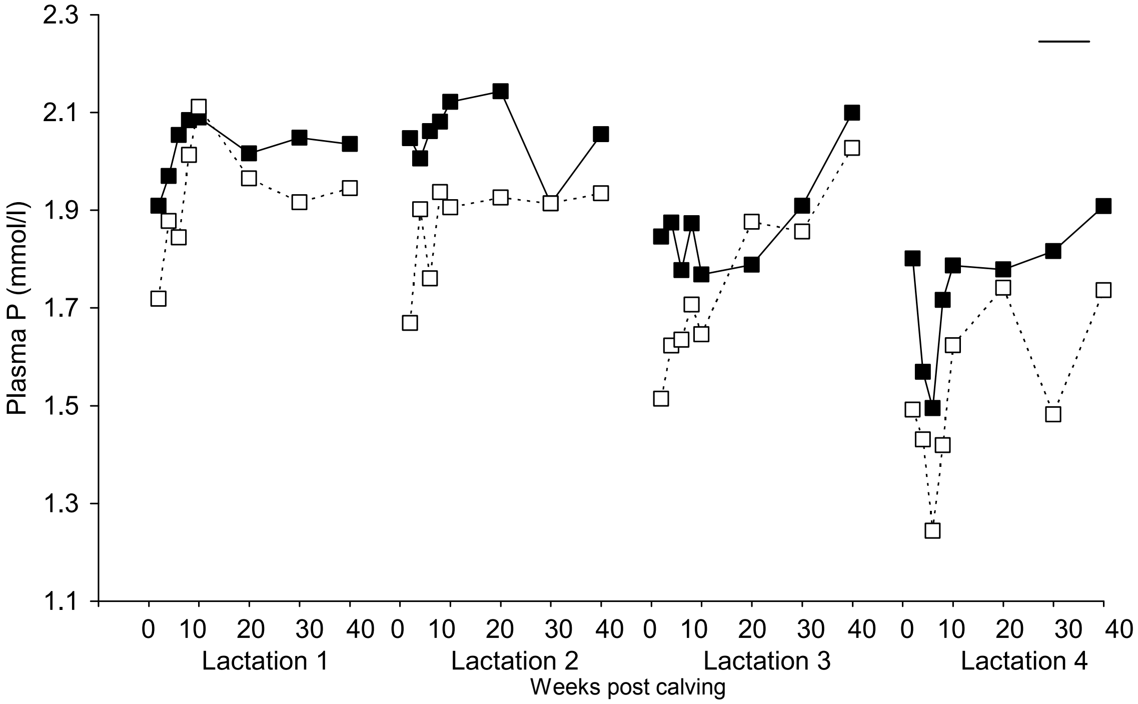

Figure 1 Effect of dietary phosphorus level (High phosphorus, —■—: Low phosphorus, --□---) on plasma phosphorus concentrations over four successive lactations (Ferris *et al*., 2010a)

A reduction in the P content of rib bones has been observed with cows offered low P diets in a number of studies (Wu *et al*., 2001; Ferris *et al.,* 2010b). However, in the former study bone strength (shear stress or fracture energy) was unaffected at a dietary P content of 3.1 g P/kg DM, despite a reduction in milk yield in late lactation. Ferris *et al*. (2010b) observed no evidence of a cumulative depletion of bone P reserves across four successive lactations, suggesting that bone P resorbed in early lactation was largely replaced later in the lactation, or during the dry period. The findings of this study provides reassurance that the dietary P levels examined (3.6 g P/kg DM) was sufficient not only for the needs of the cows in terms of performance, but also in maintaining bone P reserves long term.

Overall conclusions from dairy cow production studies

While Valk and Sĕbek (1999) suggested that a dietary P content of 2.8 g/kg DM was adequate for cows producing 9000 kg milk per lactation, they recommended a dietary P content of 3.0 g/kg DM in practice. Phosphorus requirements based on the latter study are currently being recommended within the Netherlands (Valk and Beynen, 2003), although it remains to be seen if these low P levels can actually be achieved through diet formulation in practice, and if they are in fact adequate for dairy cows long term. While it is true that no adverse cow performance effects were observed in a number of studies (including that by Valk and Sĕbek) when diets containing 3.0–3.2 g P/kg DM were offered, lower food intakes and milk outputs were observed in other studies involving similar dietary P levels, highlighting that this dietary P level will not be adequate in all situations. These inconsistent findings may reflect a carryover effect of previous P nutrition prior to the start of these studies, or possibly different P availabilities associated with the very different diets offered.

For diets with P concentrations of between 3.3 and 3.5 g/kg DM, available evidence would suggest that in most circumstances, although perhaps not in all, these levels will be adequate for lactating dairy cows. However, in the vast majority of studies no adverse performance effects were observed with cows offered diets containing at least 3.6 g P/kg DM. Thus, based on current knowledge, this would appear to be a safe lower limit for dietary P levels for cows yielding up to approximately 9000 kg milk/year. This was also the mean P level in the multi-lactation study undertaken by Ferris *et al*. (2010a), with these authors suggesting that this level of dietary P was sufficient for dairy cows with lactation yields of between 7500 and 9000 kg, when managed within a predominantly grassland-based system. With very different diets, but cows of a similar yield potential (7500-9000 kg/lactation), Wu and Satter (2000) concluded that a dietary P content of between 3.3 and 3.7 g/kg DM was adequate.

Low input grass-based systems

While a number of the studies presented in Table 1 were grassland based, none involved the low input spring calving systems that are common throughout Ireland, and that are practiced in some western parts of the UK. Within these systems cows are often turned out to grass immediately post-calving, while minimal (frequently zero) supplementary concentrates are offered during the main part of the grazing season. With total concentrate inputs normally between 200-700 kg/cow/lactation, and with the 'concentrates' offered often low cost low P by-products, such as citrus pulp (offered to sustain cows through periods of grass shortage), dietary P intakes from concentrates within these systems will be very low. That few studies have examined the impact of dietary P level within this type of system may be due to the practical difficulties of modifying dietary P intakes when concentrate supplements are not offered. In addition, oversupply of P within these systems, the key driver of the majority of recent studies, is unlikely to be a problem due to the low concentrate inputs involved. Indeed, interest in P nutrition within these systems is likely to be driven by concern about P deficiency, rather than oversupply.

One study which attempted to address this issue was conducted at Johnstown Castle Research Centre in the Republic of Ireland (Culleton *et al*., 1999). In this study three farmlets were managed to achieve soil P indexes of 1-3 ('Morgan's P index'; where 1 represents a P deficient soil, and 3 represents the target for intensively grazed systems) by applying different levels of inorganic fertiliser P (0, 14 and 28 kg P/ha) over a four-year period. However, it was not until the fourth year of this study that fertiliser management regime had a significant effect on herbage P concentrations (2.6, 3.0 and 3.3 g P/kg herbage DM, with soil P indexes 1-3, respectively). While there was no evidence of a treatment effect on milk production or milk composition in any year of the study (cows were re-randomised at the start of each year), cows on the treatment with the lowest soil P index had a significantly lower live weight (46 kg lower) at the end of year 4, compared to either of the other two treatments.

Unfortunately this study was terminated at this stage, leaving the lower live weight of the cows on the low soil index treatment unexplained. However, a dietary P content of 2.4 g/kg DM was demonstrated to be inadequate by Valk and Sĕbek (1999), while diets containing 3.0-3.2 g P/kg DM were inadequate in a number of other studies. With a mean herbage P content of 2.6 g/kg DM over the grazing season, it is possible that the cows managed on the low soil P index treatment may have come close to experiencing P deficiency.

To examine this issue further (Table 4), J.P. Murphy (unpublished data) used the Moorepark Dairy Systems Model (Shalloo *et al*., 2004) to estimated average daily milk yields, concentrate intakes, grass silage intakes and grazed grass intakes (on a monthly basis), for the average Irish dairy cow (4676 kg milk/lactation: National Farm Survey data from the Republic of Ireland: Connolly *et al*., 2005). Dairy cow P requirements (mean of 46.0 g/cow/day) were then calculated using the French P requirement system (Gueguen *et al*., 1989), while ‘actual’ P intakes were calculated for herbage with a P content of either 3.0 or 3.5 g/kg DM (P content of grass silage and concentrates assumed as 3.5 and 5.2 g/kg DM, respectively). With a herbage P content of 3.5 g/kg DM (close to national average for intensively managed farms in Ireland), mean P intake over the year was 46.1 g/day (3.8 g/kg DM), with this close to the calculated P requirement during most months. In addition, total ration P content never fell below 3.6 g/kg DM during any month. With a herbage P content of 3.0 g/kg DM, mean P intakes over the year were 42.6 g/day (3.5 g/kg DM), approximately 3.0 g/day lower than the calculated requirement. In addition, total diet P content was less than 3.6 g/kg DM throughout most of the grazing season. If this calculation had been undertaken for herbage with a lower P content, this situation would clearly be much more severe.

Nevertheless, historical evidence from farms where low input systems operate, and from research centres where cows have been managed over multi-lactations with minimal concentrate supplementation during the grazing season (C.P. Ferris, unpublished), suggest that these low input systems are sustainable in terms of P nutrition. Thus it would appear that within systems where the P status of the soil is maintained at a level optimal for herbage production, grazed grass as the sole feed can allow the P requirements of dairy cows to be met. However, with legislation increasingly forcing farmers to reduce P inputs, including inputs of inorganic fertiliser P, problems may arise in the future if the nutrient status of soils are not managed carefully.

Table 4 Calculated phosphorus requirements vs phosphorus intakes within a low input grazing system, with grass of different phosphorus contents (based on J.P. Murphy, unpublished data)

		Dry matter intake (kg/day)				P requirement (Gueguen *et al*., 1989)		P intake (herbage P, 3.0 g/kg DM)		P intake (herbage P, 3.5 g/kg DM)	
	Milk yield (kg/day)	Concentrate	Silage	Grass	Total	g/day	g/kg DM	g/day	g/kg DM	g/day	g/kg DM
January	1	0.6	11.6	0.0	12.2	33.1	2.7	43.8	3.6	43.8	3.6
February	5.1	1.7	7.0	0.9	9.6	32.6	3.4	35.9	3.8	36.4	3.8
March	11.9	3.2	4.5	3.6	11.2	42.8	3.8	43.0	3.8	44.8	4.0
April	20.0	2.9	1.7	7.9	12.5	54.9	4.4	44.7	3.6	48.7	3.9
May	20.4	1.7	0.0	11.3	12.9	55.5	4.3	42.5	3.3	48.1	3.7
June	20.0	1.7	0.0	11.8	13.4	54.9	4.1	43.8	3.3	49.7	3.7
July	18.0	1.7	0.0	11.7	13.3	52.0	3.9	43.5	3.3	49.4	3.7
August	16.8	1.7	0.0	11.5	13.2	50.2	3.8	43.2	3.3	48.9	3.7
September	15.6	1.7	0.0	11.2	12.9	48.3	3.8	42.3	3.3	47.9	3.7
October	13.2	1.7	1.4	9.8	12.8	44.7	3.5	42.7	3.3	47.6	3.7
November	9.6	1.7	7.1	3.7	12.5	46.0	3.7	44.5	3.6	46.4	3.7
December	3.5	2.0	8.8	0.0	10.8	36.9	3.4	41.2	3.8	41.2	3.8
Mean						**46.0**	**3.7**	**42.6**	**3.5**	**46.1**	**3.8**

The UK P requirement system

Phosphorus requirement systems within the UK have undergone a number of changes during the last forty years (ARC, 1965; ARC, 1980; AFRC, 1991). Within the latter (current recommendations), diet quality has a significant effect on P requirements, with endogenous P loss increasing by a factor of 1.6, and the true absorption coefficient for P being reduced from 0.70 to 0.58, when the metabolisability (q) of the diet, defined as diet metabolisable energy (ME) content/diet gross energy (GE) content, falls below 0.7. For example, according to AFRC (1991), when diet metabolisability is increased from 0.6 to 0.7, the P requirements of a 600 kg cow producing 15 kg milk/day decrease from 45 to 29 g/day (3.8 to 3.1 g P/kg DM, respectively), while for a cow producing 30 kg milk/day, P requirements decrease from 82 to 54 g/day (4.4 to 3.5 g/kg DM, respectively). While AFRC (1991) recognises that diets with $q>0.7$ will rarely be attained with forage-based ruminant diets in practice, the large increase in calculated P requirement with lower quality diets is difficult to justify, and is largely a function of the low value adopted for the true absorption coefficient of P (0.58). More recent P requirement systems have adopted higher true absorption coefficients for P, namely 0.7 (GfE, 1993; Valk and Beynen, 2003), and 0.64 and 0.70 for forages and concentrates, respectively (NRC, 2001).

Evidence reviewed earlier in this paper indicates that cows can be managed on diets with P concentrations considerably less than 4.4 g/kg DM without adverse effect, thus suggesting AFRC (1991) overestimates the P requirements of dairy cows offered lower quality diets. This was highlighted in the multi-lactation study by Ferris *et al*. (2010a and 2010b) where P intakes were proportionally 0.79 (winter period) and 0.84 (grazing/late lactation period) of AFRC (1991) P requirements (for diets with a $q<0.7$). Thus while the results of this study provide validation ‘in long term feeding trials using roughage-based diets’ of the ‘adequacy’ of AFRC (1991) requirements, they also demonstrate the real potential to reduce P intakes below those within AFRC. Indeed actual P intakes in this study were similar to those recommended within NRC (2001), while being slightly higher than those calculated using the new Dutch system proposed by Valk and Beynen (2003). Evidence available suggests a need to review the existing UK recommendations in order to prevent P being overfed, and to bring them into line with more recent recommendations in other countries.

The adoption of reduced P diets in practice

While evidence reviewed suggests that dietary P levels can be safely reduced to at least 3.6 g P/kg DM without having a negative effect on performance, accurate ration formulation requires that the P content of both the concentrate and forage components of the ration is known. Although the former may be declared, or calculated from the P content of the individual concentrate ingredients, the P content of forages can be extremely variable, and in practice will not normally be known. For example, the P concentration of 249 NI farm silages ranged from 1.4 to 5.3 g P/kg DM (mean, 3.3 g/kg DM) (R.S. Park, Unpublished data). While some feed test laboratories routinely analyse silages for P, this normally involves drying and milling the silages prior to analysis, a three step process which incurs additional cost. However, with Near Infrared Reflectance Spectroscopy (NIRS) having been widely adopted as a low cost methodology to predict both chemical and nutritional characteristics of fresh forages, the use of this technology to predict the mineral content of forages would appear to be a logical development. However, NIRS operates by measuring the Near Infrared radiation absorbed by organic bonds, and will only be able to estimate mineral levels if the minerals are chelated or bound to organic molecules.

This issue was examined by Park *et al*. (unpublished data) who, using 199 grass silage samples, developed NIRS calibrations for the P content of fresh silage on both a fresh basis and a DM basis. The actual P content of these silages was determined using an Inductively Coupled Plasma Atomic Emissions Spectrometer (ICP-AES). This calibration was then tested using an independent dataset of 50 fresh silages. While a reasonable prediction was obtained (R^2 = 0.74) for the P content of silage on a fresh basis (Figure 2), this was not sufficiently robust to allow the prediction of the

P content of fresh forages on a routine basis. In addition, the relationship was much poorer when predicted on a DM basis ($R^2 = 0.25$).

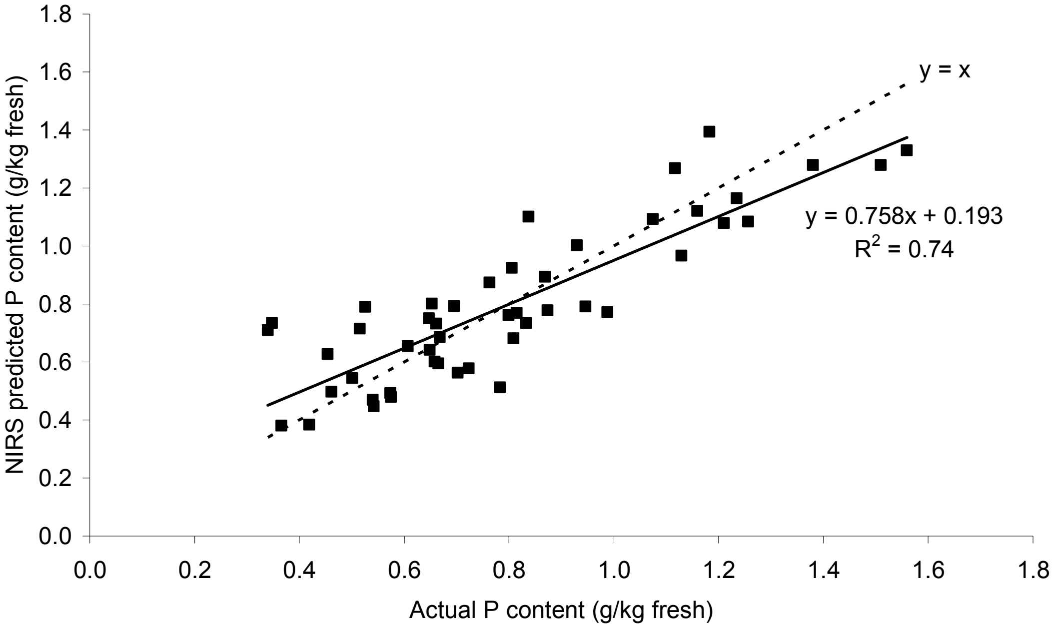

Figure 2 Regression plot showing the NIRS prediction of phosphorus in fifty fresh grass silage samples, on a fresh basis, compared to the actual P content measured using ICP-AES (R.S. Park, Unpublished data)

In addition to forage P content, level of concentrate feeding will also influence overall ration P content. Thus when advocating the adoption of reduced P concentrates, it is important that concentrate P levels adopted are adequate for silages of different P contents, over a range of concentrate feed levels. To examine this issue, the relationship between concentrate feed level (4.0, 8.0, 12.0 and 16.0 kg/day) and silage P content (2.0, 3.0 and 4.0 g/kg DM) on total ration P content, was examined for concentrates containing 4.5, 5.5 and 6.5 g P/kg DM (Table 5). Total DM intakes were modelled for a medium feed value silage from the data of Ferris *et al*. (2001). Values shaded in grey represent rations with a P concentration of less that 3.6 g P/kg DM, with these deemed to be ‘potentially inadequate’. For silages with a high P content (4.0 g/kg DM), total ration P content was adequate under all scenarios. When silage P content was reduced to 3.0 g/kg DM, a dietary P content of less than 3.6 g/kg DM only occurred when a concentrate containing 4.5 g P/kg DM was offered at a low level of supplementation (4.0 kg/day). Thus at normal concentrate feeding levels ($\geq$8.0 kg/day), and with silages with a P content close to the industry norm, rations are unlikely to be deficient in P even when concentrates containing very low P levels are offered. However, when a silage with a very low dietary P content (2.0 g P/kg DM) was supplemented with 4.0 kg concentrate/cow/day, dietary P contents were below 3.6 g/kg DM with all concentrate P contents. At a concentrate feed level of 8.0 kg/cow/day, dietary P contents were below 3.6 g/kg DM with concentrates containing both 4.5 and 5.5 g P/kg DM. Thus dietary P levels can become critical when silages containing very low P contents are supplemented with low levels of concentrates. Nevertheless, in most practical feeding scenarios involving grass silage, a concentrate P content of 5.5 g/kg DM will be adequate. However, in situations where a considerable proportion of the diet comprises maize silage or whole crop silages (which normally have lower P concentrations than grass silage), a higher concentrate P content may be necessary to ensure dietary P levels are adequate.

Table 5 Impact of silage and concentrate phosphorus content, and concentrate intake, on total ration P content (g/kg DM)*

Silage P content (g/kg DM)	Concentrate P content (g/kg DM)	Concentrate intake (kg/day)			
		4.0	8.0	12.0	16.0
2.0	4.5	2.7	3.0	3.3	3.6
	5.5	2.9	3.4	3.8	4.2
	6.5	3.2	3.8	4.3	4.8
3.0	4.5	3.4	3.6	3.8	3.9
	5.5	3.7	4.0	4.3	4.6
	6.5	3.9	4.4	4.8	5.2
4.0	4.5	4.1	4.2	4.3	4.3
	5.5	4.4	4.6	4.8	4.9
	6.5	4.7	5.0	5.3	5.6

* Shaded section represents rations with P concentrations of less than 3.6 g P/kg DM (P levels assumed as potentially inadequate)

Data in Table 5 does however confirm that there is little justification for dairy cow concentrates to contain in excess of 7.0 g P/kg DM, as was common practice in parts of the UK until relatively recently. A realisation of this fact led to a joint initiative being adopted across the feed compounding sector within NI, whereby agreement was reached that dairy cow concentrates would not contain in excess of 6.7 g P/kg DM (approximately 5.7 g/kg fresh). While this was certainly a positive move, and one which demonstrates what can be achieved with industry co-operation, nutritionally there is potential for this value to be reduced further, perhaps to 5.5-6.0 g/kg DM.

Nevertheless, a limitation to a more significant reduction in the P content of concentrates is that it can actually be more expensive to produce concentrates low in P. This is largely due to the fact that lower cost ingredients such as maize gluten, which have a low nitrogen:P ratio, must be replaced in part by more expensive ingredients such as soya-bean meal, which have a higher N:P ratio. However, the recent reduction in the availability of maize gluten within Europe, a result of difficulties associated with the slow EU approval process for products derived from genetically modified crops, is likely to have resulted in a fall in the P contents of many commercial concentrates. In addition, the high P content of forages on many farms adds to the difficulty of reducing overall ration P content. For example, in the study by Ferris *et al*. (2010a) a concentrate with a P content of 4.4 g/kg DM was necessary to allow a total dietary P content of 3.6 g P/kg DM to be achieved. This concentrate P content is much lower than would normally be adopted in practice. However, as total P inputs onto dairy farms are reduced, the P content of forages will also decline slowly, making lower P rations more achievable.

Impact of offering reduced P diets on dairy farm P balance

Using actual milk output, concentrate input and stocking rate data, Ferris and Hopps (2006) examined farm-gate P balances for 157 Benchmarked dairy herds in NI (2002–2003) under a number of different scenarios (Figure 3). Scenario 1 was based on ‘current’ industry practice and assumed a concentrate P content of 7.1 g/kg DM, and an input of P in inorganic fertiliser of 15 kg P/ha. Data points within this scenario clearly highlight the strong relationship between concentrate feed level and farm-gate P balance. Three additional scenarios were also examined, namely; offering concentrates with a P content of 5.5 g/kg DM (Scenario 2); the adoption of a ‘zero P’ fertiliser policy (Scenario 3); and Scenario 4, offering concentrates with a P content of 5.5 g/kg DM, together with a ‘zero P’ fertiliser policy.

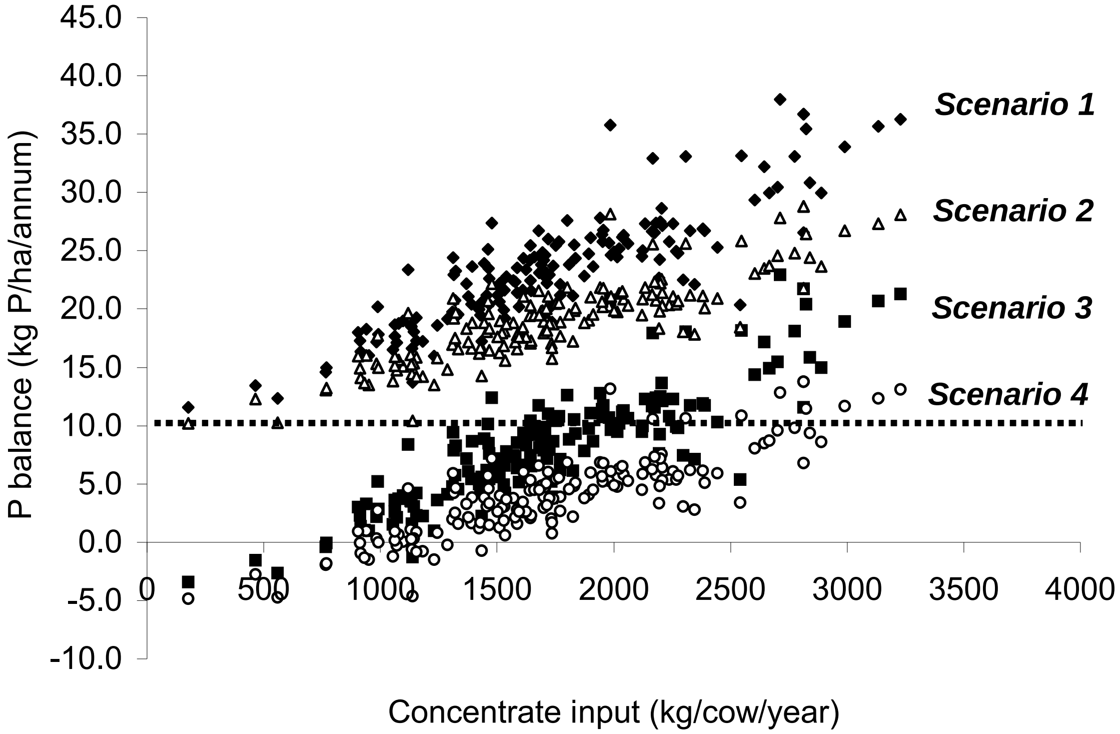

Figure 3 Impact of adopting a number of management strategies on farm P balance (Scenario 1, industry norm: Scenario 2, reduced P concentrates: Scenario 3, Zero P fertiliser policy; Scenario 4, reduced P concentrates and zero P fertiliser policy)

Under Scenario 2, the mean farm-gate P balance was reduced from 23 to 19 kg P/ha/year, the magnitude of the reduction on individual farms increasing with increasing concentrate inputs. With Scenarios 3 and 4 mean farm-gate P balances were reduced to 8.0 and 4.0 kg ha/year, respectively. In these latter two scenarios, 67% and 93% of farms had a P balance of less than 10.0 kg P/ha, respectively, while a considerable proportion of farms moved from a P surplus to a P deficit situation. Farms with a P balance >10.0 kg/ha/year tended to have concentrate inputs in excess of 2.5–3.0 t/annum.

The practical implications of this have been highlighted within UK legislation designed to fulfil the requirements of the EU Nitrates Directive, namely 'The Nitrates

Action Programme Regulations (Northern Ireland) 2006' and the 'Phosphorus (Use in Agriculture) Regulations (Northern Ireland) 2006'. For example, this legislation prohibits the application of inorganic fertiliser P unless a crop requirement can be demonstrated through the results of a soil test. With a recent survey indicating that 73% of grassland within NI (NIEA, 2009) had either high or excessive P levels (Olsen P index 3-5), the decrease in P fertiliser sales since this legislation was introduced is unsurprising. In addition, NI farmers who require a 'derogation' from the EU Nitrates Directive to allow them to operate at a stocking rate of more than 170 kg organic nitrogen/ha, are required to have an annual farm-gate P balance of <10.0 kg/ha. High concentrate feed levels are common on many of these intensively stocked farms, and in these situations, offering concentrates with lower P levels can play an important role in ensuring that farm-gate P surpluses meet the legislation. Indeed, as concentrate feed levels increase, the opportunity, and sometimes necessity, to reduced concentrate P levels becomes greater.

While the reduction in use of inorganic fertiliser P and the adoption of concentrate feeds containing lower P levels may cause few problems in the short term, the longer term implications need to be considered. For example, inorganic fertiliser P levels have a direct impact on soil P status and forage P content, as highlighted in data reviewed by Hemingway (1999). This was also demonstrated in the farmlet study by Culleton *et al*. (1999), where soil P levels in grassland receiving no inorganic fertiliser P become depleted in P over a number of years. As P levels in herbage, both grazed and conserved, decline (as highlighted in Tables 4 and 5), concentrate P content becomes increasingly important in ensuring that overall dietary P levels do not fall below critical levels. This highlights the importance of on-farm nutrient management, including regular soil testing, and the need to develop a low cost system for the rapid determination of P levels in forages.

Impact of reduced P diets on nutrient loss to the environment

In addition to reducing farm-gate P surpluses, reducing the P content of dairy cow diets will reduce P loss to the environment by reducing P excretion in manure. For example, when the P content of dairy cow diets was reduced from 5.2 to 3.7 g/kg DM, P intake was reduced from 103 to 72 g/day, while P excretion was reduced from 75 to 41 g/day (proportionally 0.45) (Ferris *et al*., 2010b). If this reduction in faecal P excretion is assumed for a 150-day winter feeding period for a farm stocked at 2.5 cows/ha, this represents a reduction in P excretion of 5.1 kg/cow, and 12.7 kg/ha.

In addition to reducing the quantity of P excreted in manure, reducing the P content of the ration will also reduce the solubility of the P fractions excreted. For example, Dou *et al*. (2002) observed an increased proportion of water soluble P in the faeces of cows offered high P diets. In addition, Ebeling *et al*. (2002) observed that reducing P in the diet of cows by 40% resulted in a 90% reduction in P losses from manures, when applied to arable ground. This can be attributed to the reduction in the soluble orthophosphate fraction in manures from animals offered reduced P diets. More recently, slurry produced by cows offered grass silage-based diets supplemented with concentrates containing different dietary P concentrations, was applied to grassland during the spring, summer and winter (O'Rourke *et al*., 2007). The P contents of the slurries applied were 13, 10, 9 and 5 g/kg DM. While the results from this experiment were not as dramatic as those observed by Ebeling *et al*. (2002), the overall trends were similar, with total P measured in run-off generated after a simulated rainfall event decreasing as the P content of the slurry decreased (Figure 4).

In addition, P loss to the environment can also be reduced by matching nutrient supply from manures to crop requirements, the adoption of 'closed periods' for spreading; limiting spreading to periods when soil and weather conditions are suitable, and the adoption of improved spreading techniques. With regards the latter, research is currently under way to examine the impact of different slurry spreading techniques (splash-plate, trailing shoe and shallow injection) on P loss in overland flows.

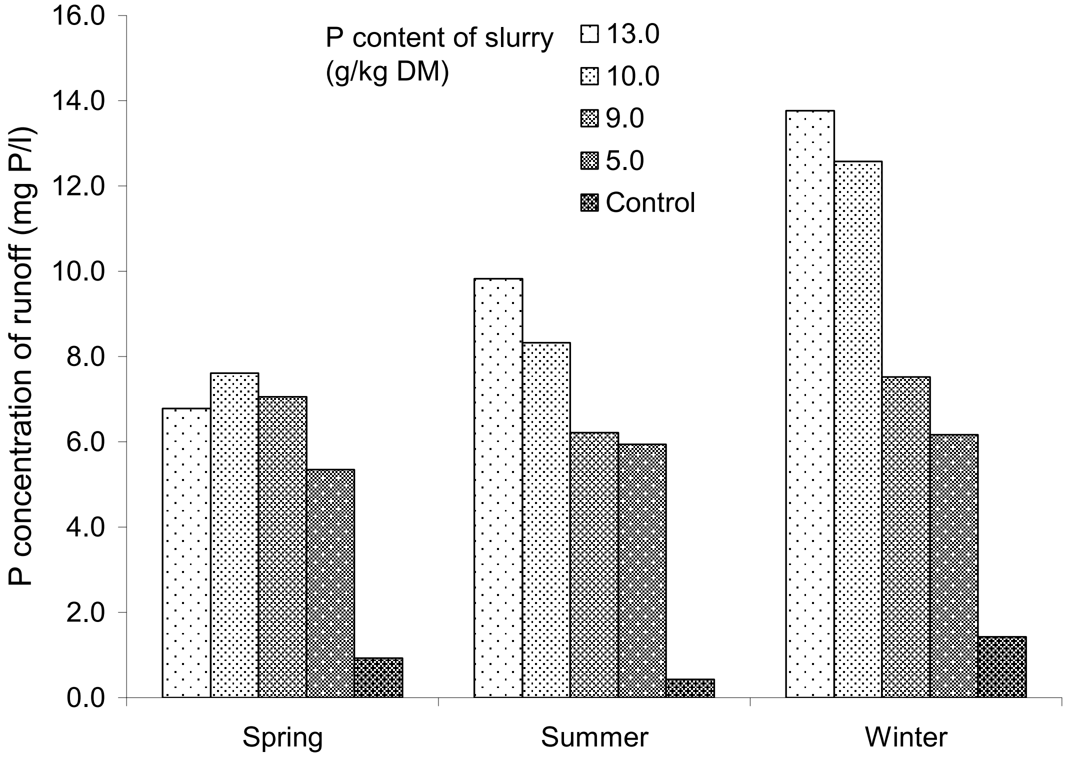

Figure 4 Flow weighted mean concentrations of total phosphorus measured in runoff generated two days after manure application during the Spring, Summer and Winter

Conclusions

Phosphorus induced eutrophication continues to reduce water quality in many areas of the world, with agriculture, including dairy farming, contributing to this problem. Reducing the P content of dairy cow diets will both reduce farm-gate P surpluses, and reduce P excretion in manures. There is now a considerable body of evidence to demonstrate that the P content of dairy cow diets can be reduced without having a detrimental effect on cow performance, health or fertility. In virtually all studies undertaken to date, a dietary P content of 3.6 g P/kg DM was adequate, and it is suggested that this dietary P content will be adequate in most situations. Nevertheless, improving the accuracy with which P is rationed to dairy cows requires the P content of the forage component of the diet to be known. However, to date the use of NIRS does not appear to be sufficiently robust to allow the P content of fresh silage to be predicted with sufficient accuracy. In addition, formulating low P diets can be difficult if the forages offered contain high concentrations of P, while low P diets can also be more expensive to produce. For lower quality diets, the P recommendations within AFRC (1991) result in dairy cows being over-fed P. The UK P recommendations need to be revised, especially in relation to ‘maintenance’ P requirements, and the true absorption coefficients of P of different feedstuffs.

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Key steps in reducing lameness in dairy cows

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Introduction

Recent research suggests that the average cost of a case of dairy cow lameness in the UK is £178 (Esslemont, 2005). This includes direct costs associated with treatment, and also indirect costs associated with reduced production performance. Evidence suggests that on average lame cows produce 360 kg less milk per lactation (Green *et al*., 2002), and have a 9-day longer calving to conception interval (Esslemont, 2005). As a result of these issues, lameness is generally recognised as one of the top three reasons for culling dairy cows.

In addition to reduced production performance, the animal welfare implications of lameness are also becoming more apparent. It is recognised that lameness is associated with pain in cows (Whay *et al*., 1997), and this is causing increasing public concern. This is reflected in the fact that at least one major UK retailer has implemented a locomotion or 'mobility' scoring scheme with their suppliers. It seems reasonable to assume that other retailers will follow suit, and that, in addition to lameness monitoring, greater emphasis will be placed on control measures in the future.

It is clear that lameness is an issue that needs to be addressed urgently on farms. A logical approach from a research perspective is to firstly identify levels of the problem, against which future progress can be benchmarked. This paper presents findings from recent AgriSearch/DARD-funded research at AFBI Hillsborough which measured levels of lameness on Northern Ireland (NI) farms. In addition, key lameness risk factors, and a number of control strategies for digital dermatitis were also investigated.

(1) Lameness levels on NI farms and key risk factors

Fifty-seven dairy farms in NI were visited once during the winter housing periods of 2005/6 or 2006/7. Farms were visited in all 6 counties of NI, and were selected without any prior knowledge of lameness levels. The average herd size on these farms was 138 cows, while the average milk yield per lactation (based on the farmers own estimate) was 8284 litres. Most farms had predominantly purebred Holstein-Friesian cattle. Total confinement was practised on five farms, while the remainder allowed cows to graze during the summer months. Most farms had either slatted concrete floors, or a combination of slats and solid concrete floors.

During the visit, all cows were locomotion scored once by one of three trained observers using the Flower and Weary (2006) locomotion scoring system. Cows were assigned a score of between 1 (sound cow (with smooth, fluid movements)) and 5 (severely lame cow (reluctant to move)). Any animal which scored 3 or higher was considered clinically lame (score 3 = slight limp detected). If a cow did not meet all requirements to fit in a score, a half score was given. Most cows were locomotion scored as they left the milking parlour.

Levels of lameness on the farms surveyed

In total, 6,292 cows were locomotion scored, an average of 110 cows per farm (minimum 37, maximum 271). Table 1 presents the average prevalence of the different locomotion scores and lame cows per farm. On average 32.6% of cows had a locomotion score of 3 or higher (with a range of 1.5 to 74.7 %).

These results show that lameness levels in NI are similar to levels in other areas of the European Union. For example, a recent survey of dairy farms in England and Wales showed a lameness prevalence of 37% (range = 0-79.2%) (Barker *et al*., 2010), and research in Austria and Germany showed a prevalence of 34% (range = 0-81%) (Dippel *et al*., 2009).

Table 1 Mean prevalence of the different locomotion scores and lame cows (score ≥ 3) in the 57 herds analysed

	Mean	Minimum	Maximum
% Score 1-1.5	2.7	0	25.8
% Score 2-2.5	64.7	25.3	83.0
% Score 3-3.5	28.6	1.5	64.9
% Score 4-4.5	3.9	0	22.2
% Score 5	0.00	0	0.00
% Lame (i.e. locomotion score ≥ 3)	32.6	1.5	74.7

Key lameness risk factors

Farmers were asked to estimate the percentage of lame cows in their milking herd, and the average response was 6%. This suggests that regular locomotion scoring would help farmers detect and treat lameness at an early stage, and reduce overall lameness levels. Guidelines on the best approach to locomotion scoring are provided on the CAFRE website at: http://www.ruralni.gov.uk/challenge_note_2e_locomotion_scoring_dpdb.pdf

A number of housing, management and attitudinal factors were recorded during the survey and their effect on levels of lameness assessed. Lameness knowledge levels were also measured by showing farmers pictures of eight common lameness-causing conditions and asking them to identify (1) the condition, (2) key causal factors and (3) appropriate treatment. The percentage of correct answers (out of a possible of 24) was calculated for each farmer.

Factors that showed a relationship with lameness are included in Table 2. These can be divided into production system, housing and individual farmer factors. Surprisingly, farms with ‘excellent’ floor maintenance had higher lameness levels than those with poorer floor maintenance. However, there were only 9 farms in the ‘excellent’ category, and of these, two-thirds had large herds and high milk yields. In addition, three of the five farms that used total confinement systems were included in this category. This suggests that this somewhat anomalous result may not in fact be due to differences in floor maintenance, but rather that some of the most intensive farms had excellent floor maintenance.

Table 2 Key factors associated with lameness on 57 Northern Ireland dairy farms

Parameter	**Category**	**Number of farms**	% of herd lame	P value
Production system factors				
Herd size (cows)*	<135	31	25.7	<0.001
	≥135	26	54.1	
Lactation milk yield (litres)*	≥8000 l	33	46.6	<0.01
	<8000 l	24	27.7	
Concentrates/cow/lactation (tonnes)	>2.2	25	50.6	<0.01
	≤2.2	30	29.8	
Housing factors				
Overstock	Yes	20	48.2	<0.05
	No	37	33.5	
Floor maintenance	Excellent	9	57.4	<0.05
	Good	31	30.9	
	Average	16	44.4	
Cubicle comfort	Excellent	8	27.6	<0.08
	Good	31	35.3	
	Average/poor	17	51.5	
Passage cleanliness*	Excellent	11	21.4	<0.09
	Good	28	42.3	
	Average/poor	17	44.3	
'Farmer' factors				
Degree to which lameness is associated with reduced welfare*	High	25	34.4	<0.2
	Low	32	42.0	
Knowledge level	Low (<90%)	31	44.4	<0.06
	High (≥90%)	26	31.9	

* Factors which were highlighted in multivariate analysis

Further (multivariate) analysis demonstrated that four key factors were most important in determining lameness levels: herd size, milk yield, cleanliness of passageways, and the degree to which the farmer felt that lameness was an animal welfare problem. It is worth noting that only two of the eleven farms with ‘excellent’ passage cleanliness also had large herd sizes (i.e. ≥135 cows). However a reduction in passage cleanliness led to an increase in lameness in farms with both large and small herd sizes.

These findings provide further evidence that the causes of lameness are mutlifactorial. It is clear that intensity of production is a key risk factor for lameness. It is likely that this is due to a combination of increased metabolic pressure predisposing cows to more lameness problems, combined with a lack of adequate time and facilities on farms with bigger herds. In addition, it is clear that maintaining clean, comfortable housing, understanding the effect of lameness on animal welfare, and knowledge of how to identify and treat different conditions are also key factors.

Key lameness causing conditions were not recorded on the farms, however 79% of farmers said that they had digital dermatitis on their farms. It is likely that this condition contributes significantly to lameness levels on dairy farms in NI and across the EU. To begin to address this issue, a series of trials was conducted at AFBI Hillsborough to assess the efficacy of a number of footbathing regimes to control digital dermatitis.

(2) Dealing with digital dermatitis

Digital dermatitis is a world-wide problem in dairy herds that accounts for approximately 20-25% of all cases of lameness (Laven, 2003). It commonly appears as lesions to the skin of the foot, particularly just above the heel, and it is thought to be caused by bacterial infection. Often the most practical solution for controlling dermatitis in dairy cows is to use a footbath. However, in order for this to be successful, an effective antibacterial product must be used. Antibiotic and formalin solutions are effective in controlling dermatitis, however neither can be recommended for use in footbaths. Antibiotics are expensive and are not currently licensed within the European Union for use as a dairy cow footbath treatment. Formalin is toxic and carcinogenic to animals and humans. Therefore alternative effective footbath solutions are required. A series of studies is described below in which the effectiveness of different footbath regimes in dealing with digital dermatitis was examined.

Experimental protocol

In all studies, the cows were footbathed after four consecutive milkings. Before walking through the treatment footbath, the cows walked through a pre-rinse footbath filled with water. The footbaths used were 207 cm long by 79 cm wide and 22 cm high, and filled to a volume of 270 litres. There was a distance of approximately 125 cm between the pre-rinse and treatment footbath. Footbath solutions were changed after no more than 200 cows passed through the footbath, or within 24 hours (if less than 200 cows walked through).

Digital dermatitis lesions were examined in the milking parlour immediately after milking on a weekly basis in all studies. The hind feet were washed and the presence or absence of active lesions on each hoof was recorded. An active lesion was defined as one which was not covered by a scab.

Are ‘parlour washings’ an effective footbath solution?

A cheap alternative footbathing solution could involve filling the footbath with circulation cleaner from the milking parlour wash cycle. Hypochlorite, commonly known as bleach, is often used in the final rinse of the parlour wash cycle. To date, however, there is little reliable information on the efficacy of hypochlorite as a footbath solution.

In this study 118 cows from the AFBI Hillsborough herd were allocated to one of three treatments over a 5-week period:

1) Footbath solution containing 5% copper sulphate
2) Footbath solution containing 2% hypochlorite
3) No footbath (control)

The number of cows with active digital dermatitis lesions on at least one hoof in the different footbathing treatments is depicted in Figure 1. The number of cows with active lesions in both the hypochlorite and control groups increased steadily over the study period, whereas the number of cows with active dermatitis lesions decreased in the 5% copper sulphate treatment.

These results show that a 2% hypochloride solution is not effective in controlling digital dermatitis, and suggest that farmers should be cautious about the use of parlour washings as a footbath solution. Boosman and Nemeth (1987) concluded that hypochlorite footbaths were ineffective in treating digital dermatitis because the chemical loses its effectiveness in a dirty environment (i.e. in the presence of organic matter like slurry). It is possible, therefore, that the solution would be more effective if replaced more frequently than in the current study. However, this may not be practically possible on many farms.

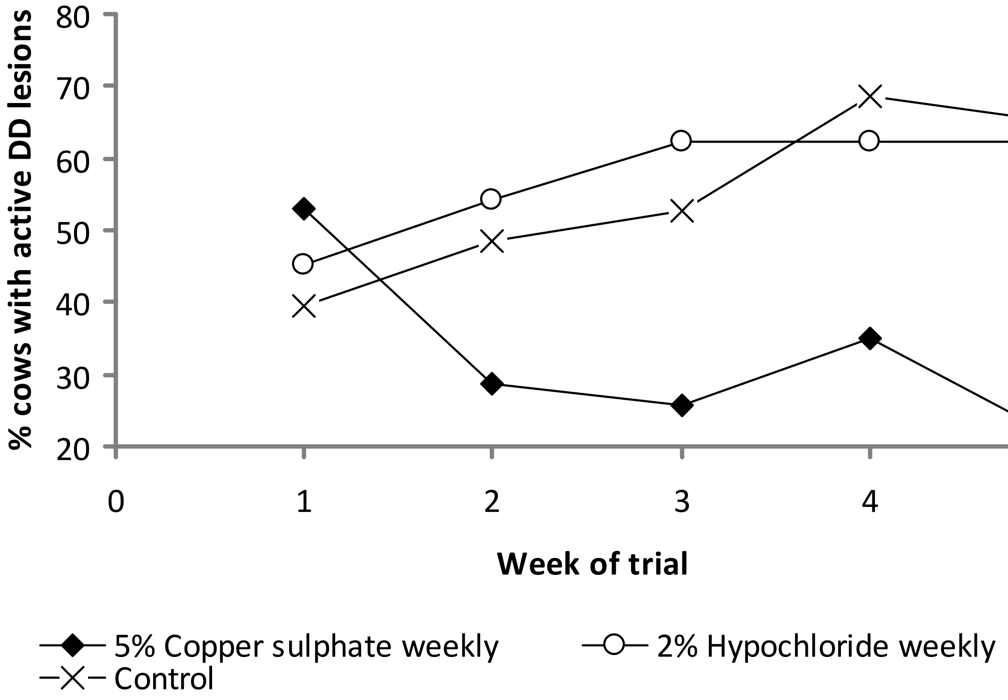

Figure 1 Effect of three different footbathing regimes on the percentage of cows with active digital dermatitis lesions in at least one hind foot (control = no footbathing)

Can copper sulphate concentrations in footbaths be reduced from 5% to 2%?

Copper sulphate is commonly used as a non-antibiotic footbath solution for dairy cows due to its wide availability and ease of use. The commercially recommended concentration of copper sulphate is 2.5-10%, used weekly or fortnightly (Bishop, 2005; Klaas *et al*., 2008). However, since it is considered an environmental hazard (Holzhauer *et al*., 2008; Salam and El-Fadel, 2008) and is quite expensive (approximately 20 pence/cow/day when used at 5% concentration four times per week), the effect of lowering the concentration of copper sulphate on levels of digital dermatitis was investigated. In particular, the following study investigated the effectiveness of 2% copper sulphate solutions in reducing dermatitis levels in herds with a high prevalence, and in maintaining low dermatitis levels in herds with a low prevalence.

In this study 117 dairy cows were allocated to one of four treatments for a period of eight weeks. Animals with a high prevalence of digital dermatitis (78 animals in total; dermatitis prevalence >60%) were assigned to one of the following treatments:

1) Weekly footbathing with 2% copper sulphate solution
2) Weekly footbathing with 5% copper sulphate solution

Animals with a low prevalence of dermatitis (39 animals in total; dermatitis prevalence ≤25%) were assigned to one of the following treatments:

1) Fortnightly footbathing with a 2% copper sulphate solution
2) Fortnightly footbathing with a 5% copper sulphate solution

The number of cows in the weekly footbathing regime with active lesions decreased over the study period for both treatments, but it decreased faster in the 5% copper sulphate treatment (Figure 2a). In the fortnightly footbathing regime, the prevalence of digital dermatitis was similar between treatments at the start and at the end of the study. However during the intervening period (Weeks 3-5) prevalence was lower in the 5% fortnightly copper sulphate treatment (Figure 2b). In addition, further analysis showed that at the end of the study there were significantly more cows with no dermatitis lesions (active or healed) in the 5% compared with the 2% fortnightly copper sulphate treatments.

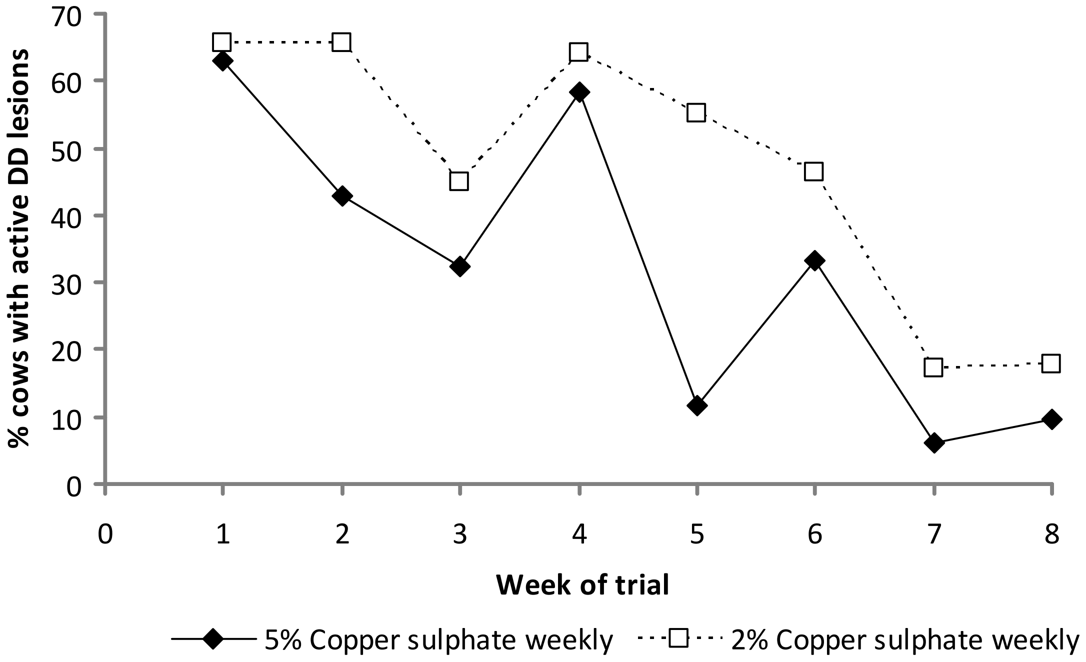

Figure 2a Effect of different copper sulphate concentrations within a weekly footbath regime on the percentage of cows with active digital dermatitis (DD) lesions in at least one hind foot

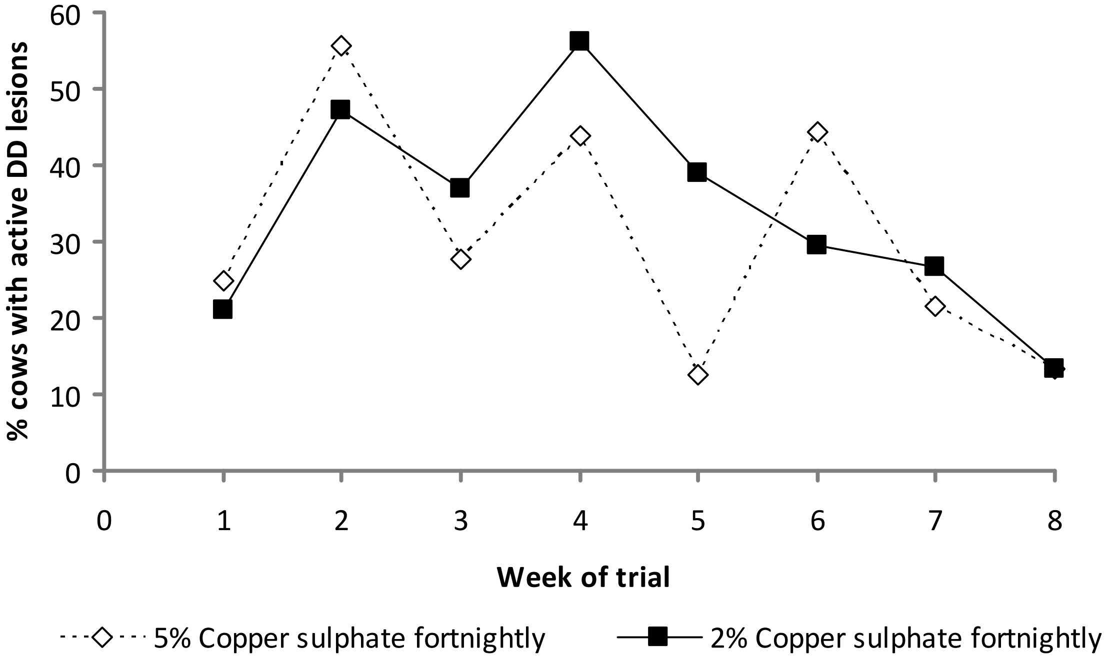

Figure 2b Effect of different copper sulphate concentrations within a fortnightly footbath regime on the percentage of cows with active digital dermatitis (DD) lesions in at least one hind foot

These results suggest that a 5% copper sulphate solution is more effective than a 2% solution in curing and controlling digital dermatitis in herds either with a high or low prevalence. However, it should be noted that the 2% copper sulphate solution still reduced the proportion of animals with active dermatitis lesions in both studies, therefore both concentrations can be considered to be effective, although to differing degrees. In low prevalence herds, fortnightly footbathing with 2% copper sulphate solution appears to offer reasonably effective control.

Are salt solutions effective in footbaths?

Some researchers suggested that salt water, when used as a topical spray, could provide a cost-effective alternative to antibiotic use on farms as a preventative measure against DD (Ishmael *et al.*, 2005). Salt is a common household antiseptic treatment which kills bacteria by dehydration. However, the efficacy of salt water as a footbath solution to help prevent and/or cure digital dermatitis appears to be untested to date.

In this study 95 lactating cows were assigned to one of three treatments over a nine week period:

1) Weekly footbathing alternating between 5% copper sulphate and 10% salt water (NaCl) every other week
2) Weekly footbathing alternating between 5% copper sulphate and tap water every other week
3) Fortnightly footbathing with 5% copper sulphate (n = 31; Control)

The percentage of cows with active dermatitis lesions over the experimental period for each of the different footbathing treatments is depicted in Figure 3. All the footbathing treatments displayed a ‘saw tooth’ pattern to some extent, with the lowest prevalence occurring during the weeks after the copper sulphate treatment was applied.

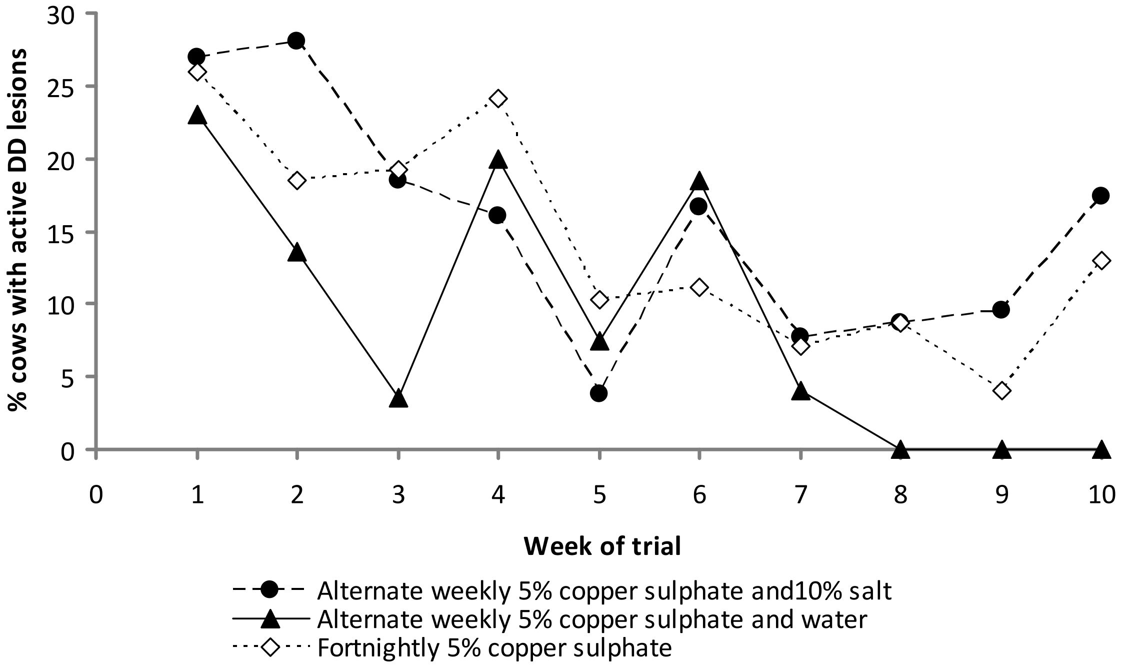

Figure 3 Effect of different footbathing regimes on the percentage of cows with active digital dermatitis lesions in at least one hind foot

The results of this study demonstrate that there was no significant advantage of using salt during alternating weeks when using a footbathing regime of 5% copper sulphate fortnightly. However, it should be noted that this study was carried out under conditions of low dermatitis prevalence. Future research will investigate if salt solutions are beneficial in herds with high levels of digital dermatitis.

Overall conclusions

This paper highlights the fact that lameness is likely to reduce the profitability of dairy farming. More importantly, lameness is increasingly recognised as an animal welfare issue, and therefore needs to be addressed.

Adopting a more proactive lameness monitoring scheme on farms will reduce prevalence levels through facilitating the identification and treatment of animals at early stages of lameness.

This research highlighted the fact that intensity of production is a key risk factor for lameness, and that managers of larger, more productive herds should prioritise lameness management. Priority should be given to ensuring that housing is comfortable and clean. In addition, farmers should seek to develop their knowledge of lameness causing conditions and treatment options.

Digital dermatitis is a significant contributory factor to lameness on Northern Ireland dairy farms. Without regular footbathing the incidence of digital dermatitis increases by 5% per week during winter housing. Research to date indicates that regular footbathing with a 2 to 5% copper sulphate footbathing solution is effective in controlling and treating digital dermatitis (although the latter concentration should be used in high prevalence herds). However, parlour washings and common salt solution cannot be recommended for controlling and treating digital dermatitis.

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Recent developments in supplementation and management strategies for grazing dairy cows

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Introduction

During the last two decades milk production per cow in Northern Ireland has increased dramatically, from approximately 4,600 litres/year in 1986 to 6,800 litres/year in 2006 (DARD, 2009). This significant increase in milk yield/cow, coupled with the fact that dairy cows in Northern Ireland now calve all year round (Carson *et al.,* 2010), means that many cows are producing high daily milk yields during the summer months, the period when grazed grass was traditionally able to sustain the milk production potential of dairy cows. As a consequence, increasing levels of concentrates are now being offered during the grazing period to make up the deficit between what grazed grass can sustain, and the milk yield potential of the modern dairy cow. However, grazed grass remains the lowest cost feedstuff on most Northern Ireland dairy farms, with recent CAFRE estimates for the full economic costs of grazed grass being £99/t DM consumed, compared to £122/t DM for grass silage and £106/t DM for maize silage. In contrast, quality dairy cow concentrates currently cost between £200 and £240/t (£224 – £270/t DM). Thus it is critical that the correct balance is achieved between optimising the use of supplementary concentrates by grazing dairy cows to achieve high levels of animal performance, and optimising the use of grazed grass, the lowest cost feed. In addition, this must be achieved within the context of high levels of dairy cow welfare and high environment standards.

This paper seeks to review recent findings from a number of experiments, most of which were undertaken at AFBI Hillsborough, which have sought to identify optimum supplementation and management strategies for grazing dairy cows.

Milk production potential of grazed grass

One of the first steps in identifying optimum supplementation strategies for grazing dairy cows is to identify the milk production potential of grazed grass as the sole feed. The theoretical potential of high quality grazed grass has been calculated by Mayne *et al.* (1991), for a cow with a yield potential of 7,500 litres/lactation (Figure 1). In addition, actual milk achieved from 'grazed grass' in two separate Hillsborough experiments (Ferris, Unpublished; Vance *et al.,* Unpublished) involving concentrate supplementation levels of 1.0 kg/cow/day have also been included within Figure 1. These data highlight that even with well managed grazing systems it can be difficult to achieve the full milk production potential of grazed grass. There are a number of reasons why this is so, including the difficulties of achieving consistency in both quantity and quality with grazed grass-based diets, both between seasons and within a season.

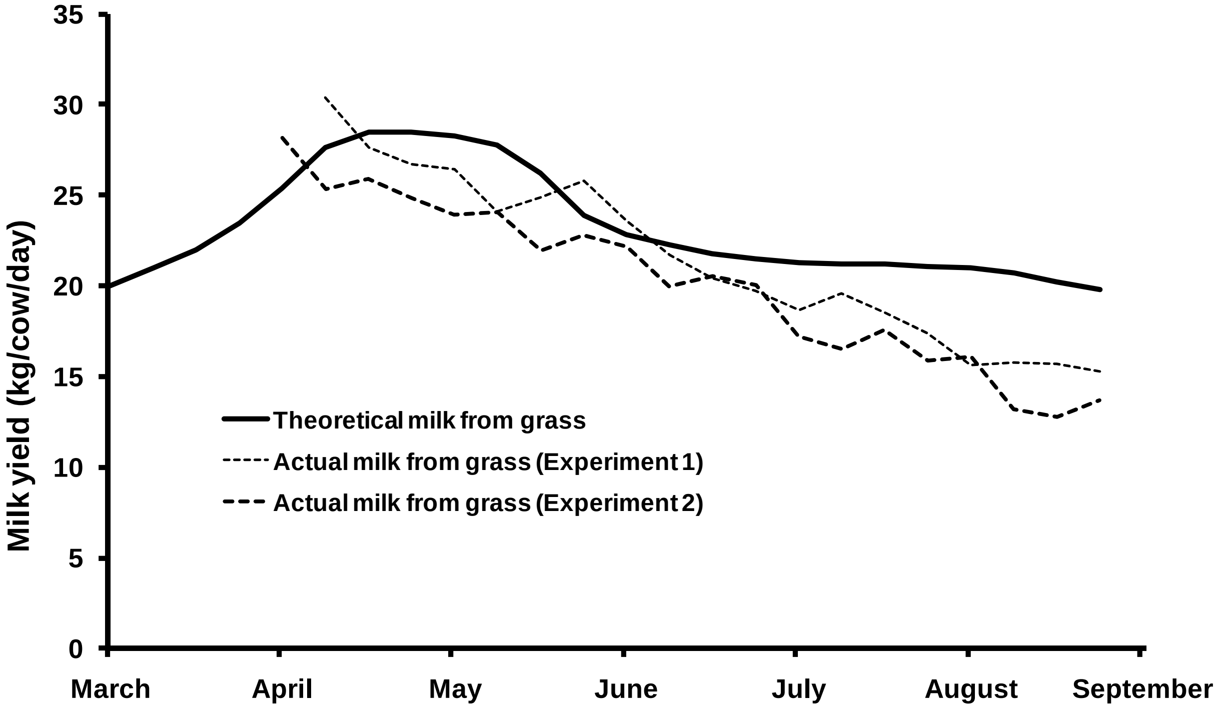

Figure 1 '**Milk from grass' achieved by Holstein cows offered minimal levels of concentrate supplementation in two separate experiments, versus the theoretical milk production potential of grazed grass (after Mayne *et al.,* 1991)

The variation in grass growth within Northern Ireland has been monitored throughout the past 10 years within the 'GrassCheck' project, with Figure 2 highlighting average daily growth from locations across Northern Ireland in 2006, 2009 and 2010. These data highlight the huge variations in grass growth that exists both between seasons and within a single season. For example, across these three years grass growth in early/mid May varied from 113 to 66 kg DM/ha/day. In addition, within a typical grazing season daily grass growth increases from an average of 15 kg DM/ha in April, to a peak of 90 kg DM/ha or higher in May, before declining in a rather inconsistent manner to approximately 35 kg DM/ha in September. Grass quality can also vary considerably between years, with the metabolisable energy (ME) content of grass samples taken in May during the past four years within GrassCheck ranging from 10.5 to 11.9 MJ/kg DM, while the crude protein content varied from 153 to 206 g/kg DM.

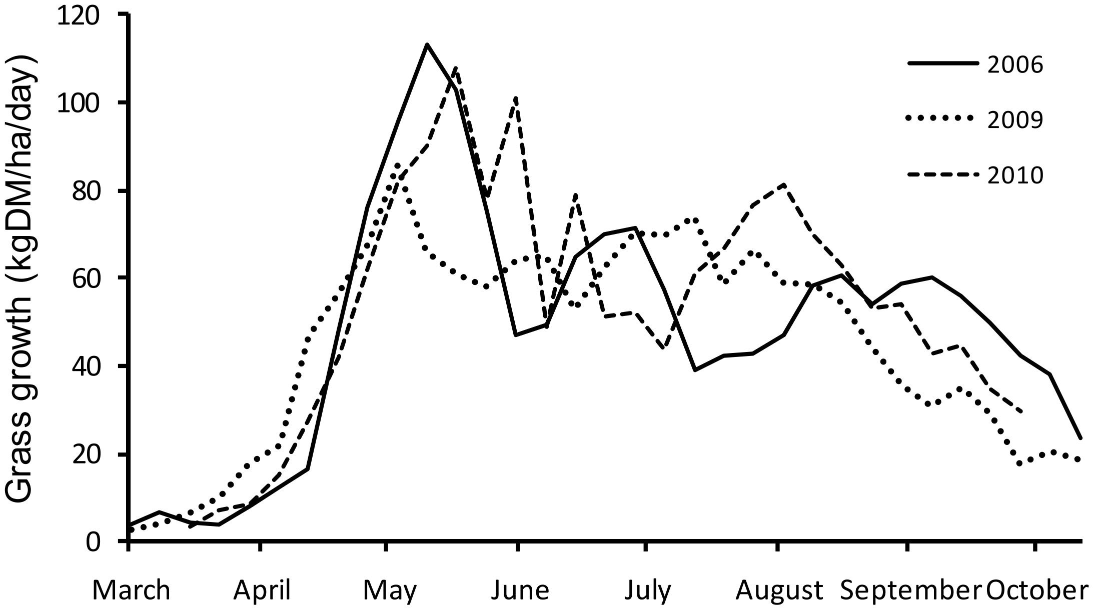

Figure 2 Within season and between season variation in grass growth within the GrassCheck project during 2006, 2009 and 2010

This variability in grass growth and quality has been recorded in grass swards which have been cut to a consistent residual height at regular three-week intervals in the absence of the grazing animal. The impact of the grazing animal on the sward (selective grazing, poaching, fouling), combined with the impact of highly variable weather conditions on grazing behaviour, will all impact on sward growth and quality. In addition, management issues such as failing to react to potential surpluses or deficits in grass supply can exaggerate the problems. A grass sward which reaches a herbage mass above the ideal grazing target is more likely to be poorly grazed, and this will have a detrimental effect on the quality of the subsequent regrowth. Although this applies throughout the grazing season, there is evidence that this is particularly important in early season, with the detrimental effects of under utilisation of grass at this stage of the season affecting milk yields and grass intakes over the whole season (Stakelum and Dillon, 1990). Therefore, although the milk production potential of grazed grass is high, many factors influence the quality and quantity of grass available for grazing dairy cattle, and these will ultimately influence the actual milk production achieved from grazed grass.

The need to supplement

High yielding dairy cows will frequently be turned out to grass producing substantially more milk than can be supported by even the best managed swards early in the grazing season (Figure 3). For example, a cow with a milk yield at turnout of 40 litres/day, and a decline in milk production of 2% per week throughout a 22-week grazing season (mid April – end September), would on average produce 7.2 litres more milk/day (1204 litres for the season) compared to that which grazed grass could theoretically sustain.

If adequate levels of feeding are not supplied, most high genetic merit cows will continue to produce high levels of milk production in the short term, but will do this at the expense of body tissue reserves. However, it is well known that high levels of body tissue mobilisation will have a detrimental effect on subsequent reproductive performance. In order to avoid this, supplementation is a vital component of grazing systems involving high yielding dairy cows.

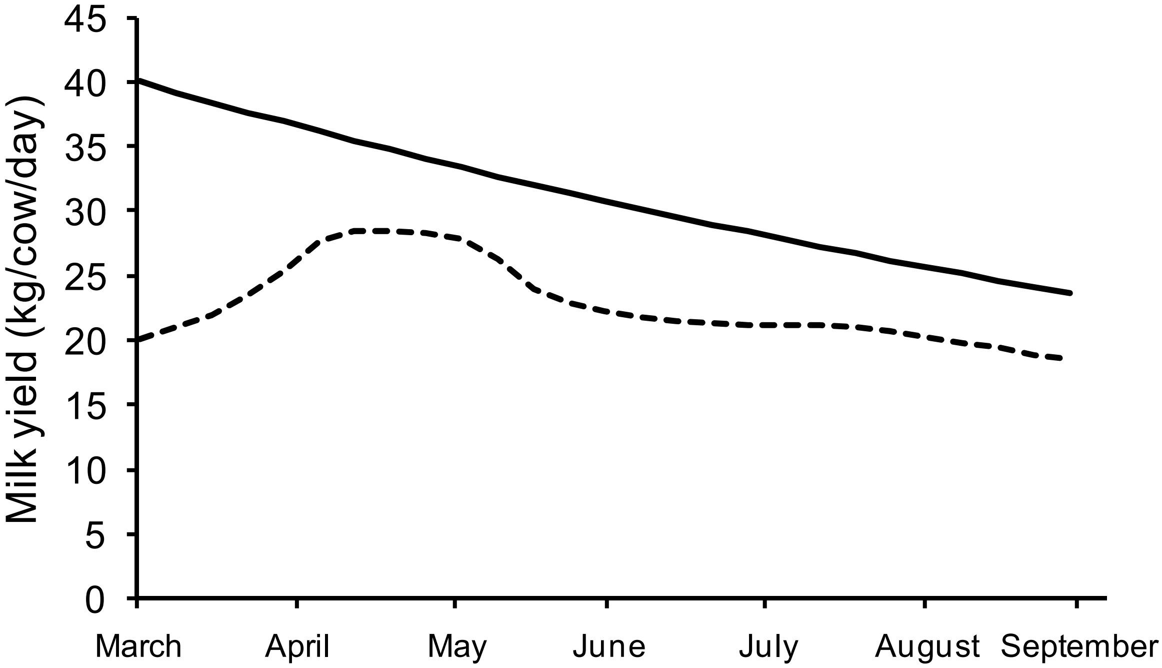

Figure 3 Identifying the gap between the theoretical milk production potential of grazed grass (----) and the actual milk yield potential of a cow producing 40 litres milk/day at turnout (—)

Response of grazing cows to concentrate supplementation

While 1.0 kg of concentrate contains approximately 11.5 MJ ME, which should in theory support the production of 2.2 litres of milk, the actual response achieved can be considerably less than this. This is due in part to the ‘substitution effect,’ whereby feeding concentrates will result in a reduction in grass intake by the grazing animal. Substitution rates are influenced by a number of factors, including the level of concentrate offered, the milk yield potential of the cows and the availability of grass. With regards the latter, substitution rates increase as the availability of grass increases, with a recent review of a number of grazing studies highlighting that at low herbage allowances (<25 kg DM/cow/day) the average substitution rate was 0.2 kg grass DM/kg concentrate DM, whereas at high herbage allowances (>25 kg DM/cow/day) it was 0.6 kg grass DM/kg concentrate DM (Bargo *et al.,* 2003). In a further review of nine grazing studies (Dillon, 2006), the average substitution rate was quantified as 0.40 kg grass DM/kg concentrate DM, which was also the ‘typical’ substitution rate cited by Mayne *et al.* (1991). Similarly, Hillsborough data (Sayers *et* *al.,* 2003) identified a mean substitution rate during the grazing season of 0.48 kg grass DM/kg concentrate DM.

An understanding of substitution rates is important as it is known that as substitution rates increased, the milk yield response to increasing concentrate feeding decreases (Bargo *et al.,* 2003). The milk response to concentrate feeding is also influenced by the cows genetic merit and stage of lactation, with a higher response achieved in cows with higher genetic merit for milk production (Dillon, 2006) and higher yielding cows (Stockdale *et al.,* 1987; Hoden *et al.,* 1991). In a study at Hillsborough an average milk yield response of 0.6 kg/kg concentrate DM offered was reported as concentrate supplementation increased from 5 to 10 kg DM/cow/day (Sayers *et al.,* 2003). In an earlier study at Hillsborough, the milk response achieved was 0.72 kg/kg concentrate DM (Ferris *et al.,* 2002). Dillon (2006) summarised the milk response from nine grazing studies and identified a milk response of 0.92 kg milk/kg concentrate DM.

The concepts of substitution rate and milk yield response are important to consider when supplementing the grazing dairy cow, as these factors could impact on the profitability of concentrate supplementation. Feeding concentrates whenever substitution rates are high will reduce the milk yield response achieved, and this is typical of the situation where high concentrate levels are fed to medium yielding cows whenever grass supply is adequate. However, if feeding concentrates to high yielding cows, or during periods of grass deficit, substitution rates will normally be low, and a high milk yield response will be achieved.

Supplement type for grazing dairy cows

There has been considerable debate over the years on whether the energy source of concentrate supplements for grazing cows should be ‘starch’ based or ‘fibre’ based. Indeed this issue was examined in a study at Hillsborough a number of years ago which involved comparing starch (barley, wheat and maize) and fibre (sugar beet pulp and citrus pulp) based grazing concentrates. This study involved high yielding Holstein cows, and the concentrates were fed at either 5.0 or 10.0 kg DM/cow/day (Sayers *et al.,* 2003). Although supplement energy source had no significant effect on herbage intake, milk yield or milk fat content (Table 1), milk protein content was increased with the starch-based concentrates. However, there was also a clear trend for milk fat content to fall when the starch-based concentrate was offered at the high concentrate feed level.

It has been previously highlighted that the effect of concentrate energy source on the performance of grazing dairy cows is inconsistent across the literature (Mayne *et al.,* 1991; Bargo *et al.,* 2003). While there is no clear animal performance advantage of using either a concentrate based on a starch or fibre energy source, it appears to be more important at high feed levels. In practise the relative costs of the raw materials could ultimately result in one concentrate type being favoured over the other.

Table 1 Performance of grazing dairy cows offered either 5.0 or 10.0 kg DM per day of a starch or fibre-based concentrate (after Sayers *et al.,* 2003)

	Supplement level and energy source				Significance of energy source
	5.0 kg DM/day		10.0 kg DM/day		
	Fibre	Starch	Fibre	Starch	
Herbage intake (kg DM/day)	12.4	11.7	9.6	9.7	NS
Milk yield (kg/cow/day)	34.0	33.3	36.0	37.3	NS
Milk fat (g/kg)	38.1	37.5	35.8	30.8	NS
Milk protein (g/kg)	31.9	33.5	32.5	34.4	*
Live weight change (kg/day)	-0.99	-1.29	-0.83	-0.68	NS

Increasing environmental pressures and the desire to reduce concentrate costs have prompted interest in reducing the crude protein content of grazing concentrates. In a recent Hillsborough study, concentrates containing either 90, 135 or 180 g crude protein/kg fresh were offered to spring calving cows at 3.0 kg (heifers) or 4.0 kg (cows) per day throughout the grazing season (Dale *et al.,* 2006). There were no adverse effects of concentrate crude protein content on milk yield or milk composition, although milk fat + protein yield was reduced with the lowest concentrate crude protein content (Table 2). Similarly, Burke *et al.* (2008) replaced a high protein concentrate with citrus pulp with no detrimental effects on milk yield and composition. While these studies demonstrate that there is potential to reduce supplement crude protein content without adverse effects on cow performance (at low to moderate feed rates: <4 kg/day), there is evidence that this may not be possible at higher concentrate feed levels. For example, Ferris *et al.* (2002) examined three concentrate crude protein levels (110, 170 and 230 g/kg fresh) offered at either a low (3.6 kg/cow/day) or high (7.2 kg/cow/day) level of supplementation to grazing cows. No effect on milk yield was observed when concentrate crude protein was reduced from 230 to 110 g/kg at the low level of supplementation, however at the high level of supplementation milk yield was reduced when concentrate crude protein was reduced from 170 to 110 g/kg. This is likely due to overall dietary crude protein content being inadequate, as high protein grass will have been substituted for low protein concentrates at the higher concentrate feed level.

Table 2 Effect of concentrate crude protein content (90, 135 or 180 g per kg fresh) on the performance of grazing dairy cows (Dale *et al.,* 2006)

	Concentrate crude protein content (g/kg)			Significance
	90	135	180	
Total milk output (178 days) (kg/cow/day)	3355	3424	3492	NS
Milk yield (kg/cow/day)	18.8	19.2	19.6	NS
Milk fat (g/kg)	39.4	39.6	39.7	NS
Milk protein (g/kg)	34.0	34.0	34.0	NS
Milk fat + protein yield (kg/cow/day)	1.38	1.41	1.45	*

These data highlight that there is an opportunity to reduce the crude protein content of concentrates offered to grazing dairy cows when feeding at moderate levels (<4.0 kg/cow/day), although caution is necessary when offering low protein concentrates at higher concentrate levels. The data also suggest that there is no need for a grazing concentrate to contain a crude protein content in excess of 170 – 180 g/kg fresh.

Concentrate allocation strategies for grazing dairy cows

This paper has highlighted that concentrate feeding is a necessary part of systems in which high yielding cows are managed within grazing systems. However, there is still a debate as to the optimum concentrate allocation strategy for dairy cows. This is a particular problem in herds with a spread calving pattern, which is now the norm within Northern Ireland. The allocation of concentrates in these situations can prove a challenge as setting levels to suit the high yielders will ultimately result in overfeeding of lower yielding animals. Conversely, moderate feeding levels that may suit the low/medium yielding animals will be insufficient for the higher yielding animals. Common approaches include a 'flat rate' approach where the feeding level is fixed for all cows, or a 'feed to yield' approach, where feeding is targeted to an individual cows requirements. While the former system is easily managed on farm, the latter includes a degree of precision management.

A recent Hillsborough study examined the effect of feeding concentrates via these two methods to a group of 56 dairy cows during the main grazing season (Dale and Ferris, Unpublished). Concentrates were offered at 0.6 kg for each litre of milk produced above that supported by grass alone, with the milk production potential of grass reviewed monthly (May-September), and feeding levels adjusted accordingly. Total concentrate inputs over the entire grazing season were equal across treatments, with the cows and heifers receiving a total of 451 and 508 kg concentrate, respectively, during the study. The cows and heifers on the flat rate treatment were offered 5.5 and 4.9 kg/day of concentrates, respectively, at the start of the study. Cows on the feed to yield treatment were offered between 1.0 and 10.0 kg/day of concentrates at the start of the study, while heifers on this treatment were offered between 2.5 and 8.0 kg/day.

Animal performance was not affected by concentrate feeding strategy in this study, with both average milk yields and milk quality being similar for both treatment groups (Table 3). Concentrate supplementation strategy had no effect on the average body condition scores or live weights of cows in each treatment group at the end of the study, with the change in live weight over the duration of the study also unaffected.

Table 3 Effect of allocating concentrates to grazing cows via either a flat rate feeding system or a feed to yield system (Dale and Ferris, Unpublished)

	Supplementation strategy		Significance
	Flat rate	Feed to yield	
Total milk output (123 days) (kg/cow)	2711	2798	NS
Milk yield (kg/cow/day)	22.4	23.0	NS
Milk fat (g/kg)	39.6	40.1	NS
Milk protein (g/kg)	33.2	33.5	NS
Milk fat + protein yield (kg/cow/day)	1.62	1.67	NS
Final body condition score	2.3	2.2	NS
Final live weight	560	559	NS
Liveweight change during the study (kg)	-12	-15	NS

Although concentrate supplementation strategy had little effect on overall performance of the cows within each treatment, there were clear differences in how individual animals within each treatment group responded (Figure 4). The lower yielding cows within the flat rate treatment produced an average of 4.2 kg/cow/day more milk than those on the feed to yield treatment. However this trend was reversed within the higher yielding cows, with those on the feed to yield treatment producing 5.5 kg/cow/day more milk than those on the flat rate system. Despite this milk yield difference, final live weight and body condition score between these animals was similar.

These data suggest there is little benefit in using a ‘feed to yield’ system of concentrate feeding compared to a ‘flat rate’ approach when feeding medium yielding cows (20-25 kg/cow/day). However, the advantages of individual cow management are likely to be more distinct if cows are higher yielding, or if the herd includes cows with a wider spread of milk yields.

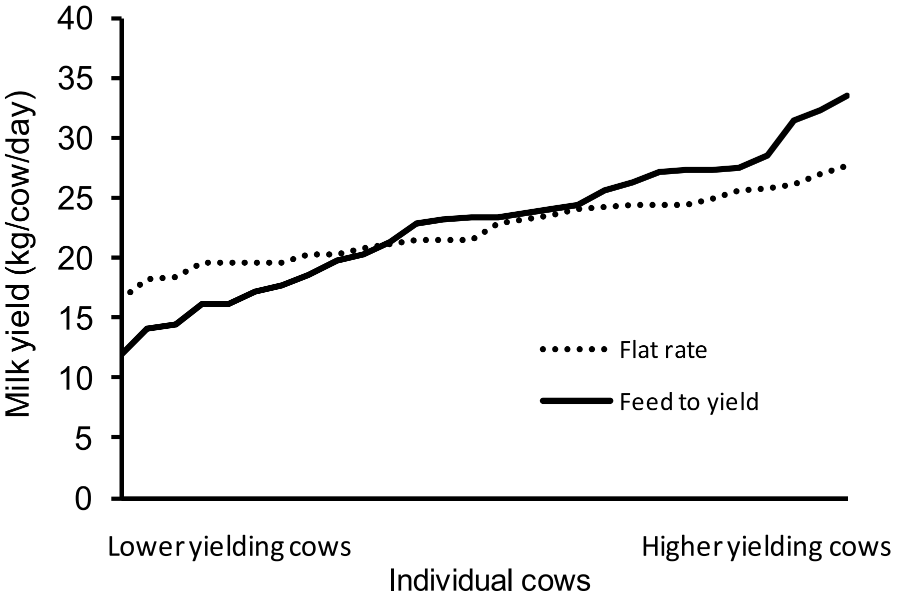

Figure 4 Effect of allocating concentrates to grazing cows via either a flat rate feeding system or a feed to yield system on average daily milk yield

How critical is herbage allowance for high yielding cows?

Achieving high herbage intakes remains one of the most significant challenges within grazing systems. While a number of sward factors are known to influence herbage intake, herbage allowance is perhaps the most critical. There is already a considerable body of evidence to demonstrate that herbage intakes can be increased by offering cows higher herbage allowances (Peyraud *et al.,* 1996; Stakelum, 1996; Mayne *et al.,* 2000). Indeed this concept was further developed by Mayne and Laidlaw (1999), who suggested that herbage intakes can be maximised by offering cows access to tall, dense, leafy swards. However, offering this type of sward inevitably results in poor grass utilisation, with a subsequent adverse effect on herbage growth and quality. Poor utilisation of grazed grass will also have a detrimental effect on costs of production, with the economic advantage of grazing over ensiled forages being eroded if utilised yields fall below 8 tonnes DM/ha.

More recently, the focus on high herbage allowances has been challenged by the New Zealand concept of 'golf ball' grazing, where pre- and post-grazing herbage masses are much lower than previous targets. The success of this technique, which appears to be suited to low input - low output grazing systems, relies on consistently achieving low post-grazing sward heights, and an associated improvement in grass quality. In achieving these low residual sward heights it is likely that herbage intake per cow is reduced. Therefore, given that high yielding cows are already under pressure to achieve adequate intakes at grass, the suitability of this approach for these cows is unclear. However, the question still remains as to the optimum grazing management strategy for high yielding cows, especially those offered high levels of supplementary concentrate. To address this issue the effect of increasing the grazing intensity (reducing post-grazing sward height) was examined in a recent study at Hillsborough (Dale and Ferris, Unpublished). The study involved sixty-three dairy cows, with these allocated to one of three treatments, 'tight', 'normal' and 'lax' grazing. Treatments were established in different sized paddocks (different stocking rate) thus achieving different post-grazing sward heights. All paddocks across all treatments were topped once during the grazing season. Preliminary data from the study are presented in Table 4. All multiparous cows were offered 9.0 kg concentrate/day throughout this study, while the primiparous cows were offered 6.0 kg/day.

Although milk yield/cow decreased as grazing intensity increased, maximum milk output/ha was achieved with the tight grazing system. Average milk yield for the cows on the tight, normal and lax grazing treatments were 33.3, 35.8 and 36.4 kg/day, with the heifers yielding 25.0, 25.8 and 26.4 kg/day, respectively. Grass utilisation (>1,600 kg DM/ha) was also highest within the tight grazing treatment, with 81% of grass utilised by the cows, compared to 69% and 62% with the normal and lax grazing treatments, respectively.

Although milk output/cow remains an important performance indicator, with land a limiting factor on many Northern Ireland dairy farms, milk output per hectare is perhaps the most critical value in terms of overall farm profitability. The results of this study highlight, that despite reduced performance on an individual cow basis, the higher stocking rate within the tight grazing treatment resulted in the highest output of milk and milk solids/ha. These data also highlight that high daily milk yields can be achieved by grazing cows, and that high yielding cows can achieve greater than 80% grass utilisation under grazing.

Table 4 Sward parameters and cow performance associated with three different levels of grazing intensity (Dale and Ferris, Unpublished)

	Grazing intensity		
	Tight	Normal	Lax
Sward parameters			
Grazing stocking rate (cows/ha)	7.8	6.7	5.6
Pre-grazing sward cover (kg DM/ha)	3,517	3,850	3,945
Post-grazing sward cover (kg DM/ha)	1,980	2,267	2,491
Pre-grazing grass quality			
ME (MJ/kg DM)	11.9	11.8	11.7
Crude protein (g/kg DM)	202	202	198
Animal performance			
Total milk output (141 days) (kg/cow)	4,327	4,579	4,663
Milk yield (kg/cow/day)	30.7	32.5	33.1
Milk fat (g/kg)	33.6	34.4	34.8
Milk protein (g/kg)	32.5	32.3	33.1
Milk fat + protein yield (kg/cow/day)	2.02	2.13	2.23
Live weight at end of study (kg)	543	553	565
Body condition score at end of study	2.4	2.4	2.3
Milk output/ha (kg)	33,751	30,679	26,113
Milk fat + protein yield (kg/ha)	2,222	2,012	1,761
Grass utilisation (>1,600 kg DM/ha) (%)	81	69	62

Is there a role for buffer feeding within grazing systems?

The concept of buffer feeding is not new. However, while in the past buffer feeding tended to be adopted during the ‘shoulders’ of the grazing season, or during periods of grass shortage, many dairy herds in Northern Ireland now offer a forage buffer as standard management practise during the grazing season. This ‘buffer feed’ is normally accessible for 2 - 3 hours/day, normally when cows are in the farm yard for milking. Grass silage, maize silage and whole crop cereal are all used as buffers for grazing dairy cows. But how effective is buffer feeding as a strategy to be adopted throughout the grazing season when grazed grass is not in short supply? To address this issue Morrison and Patterson (2007) allowed cows to have access to either grass silage, maize silage or whole crop wheat silage. These three forages were compared with a grazed grass only treatment within this Hillsborough study. Cows had access to the forages for two hours after the morning milking, while the control group of cows only had access to grass. Cows grazed as a single group, and so were offered the same quality and quantity of grazed grass during the remainder of the day. No additional concentrates were offered.

Intakes of the maize silage supplement were considerably higher than intakes of either the grass silage or whole crop silage supplement (Table 5). Although total dry matter intakes were increased with all supplement treatments, offering grass silage and whole crop wheat silage as a buffer to grazed grass had no effect on milk yield compared to grazed grass as the sole feed. However, milk yield within the maize silage buffer treatment was higher than with the grazed grass only treatment. Feeding supplements had no effect on milk fat or milk protein content compared to grazed grass alone although milk protein content was significantly reduced when grass silage was offered as a buffer, compared to when maize silage was offered as a buffer.

In general, whenever grass supply is not restricted, the literature suggests that there is little benefit in feeding forage supplements (Phillips, 1988; Bargo *et al.,* 2003), with some studies observing a reduction in milk yield and milk protein yield from their inclusion. Offering forages as a buffer to grazed grass normally results in a high substitution rate, and as forage supplements (especially grass silage) are generally of poorer quality than grazed grass, feeding them can reduce animal performance compared to grazed grass alone. Thus the primary use of forage supplements should be to overcome periods of grass shortage, or to improve intakes during difficult weather conditions, rather than being used as a method to improve total nutrient intakes during normal grazing conditions. This relates specifically to dairy cows with moderate daily yields, however the role of buffer feeding for the high yielding cow (>40.0 kg/cow/day) has not been examined.

Table 5 Effect of offering maize silage, grass silage or whole crop wheat silage as a buffer to grazed grass on forage intake and milk production of grazing dairy cows (Morrison and Patterson, 2007)

		Supplement type			
	Grazed grass only	Maize silage	Grass silage	Whole crop wheat silage	Significance
Grass intake (kg DM/cow/day)	12.9	8.9	11.2	11.0	***
Supplement intake (kg DM/cow/day)	-	6.3	3.0	3.6	***
Total DM intake (kg/cow/day)	12.9	15.3	14.2	14.7	***
Milk yield (kg/cow/day)	17.1	19.8	18.4	18.0	***
Milk fat (g/kg)	39.8	41.5	39.9	40.2	NS
Milk protein (g/kg)	32.1	32.8	31.4	31.7	**
Milk fat + protein yield (kg/cow/day)	1.21	1.46	1.29	1.27	***

Potential of partial confinement systems

Partial confinement systems, whereby cows normally graze by day, while being housed at night and offered a conserved forage-based diet, have become increasingly common in Northern Ireland. These systems are frequently being adopted by producers struggling to maintain animal performance within full-time grazing systems, or where the grazing platform is insufficient to support increasing herd sizes. To examine the effect of partial confinement systems on cow performance, two studies were conducted at Hillsborough. Within these studies cows either grazed full-time, or were housed at night and offered grass silage together with grazed grass during the day (Ferris *et al.,* 2008). Concentrate feed levels within these two studies were between 3.0 and 4.0 kg/cow/day. Cow performance, stocking rates and average weekly labour requirements within these two studies are presented in Table 6.

Table 6 The impact of either a full-time grazing system or a partial confinement system on cow performance, stocking rates and weekly labour requirements in two separate studies (Ferris *et al.,* 2008)

	Full-time grazing	Grazing by day, housed plus silage at night	Significance
Study 1			
Milk yield (kg/cow/day)	17.2	18.6	*
Milk fat (g/kg)	42.2	41.0	NS
Milk protein (g/kg)	35.4	33.5	***
Grazing stocking rate (cows/ha)	4.4	7.0	
Overall stocking rate (cows/ha)	4.4	4.3	
Study 2			
Milk yield (kg/cow/day)	20.0	18.4	**
Milk fat (g/kg)	42.4	41.0	NS
Milk protein (g/kg)	35.8	33.4	***
Grazing stocking rate (cows/ha)	5.2	8.6	
Overall stocking rate (cows/ha)	5.2	5.3	
Weekly time requirement (per 100 cows)	7 hours 10 minutes	6 hours, 53 minutes	

A higher milk yield was achieved with cows on the partial confinement system in Study 1, while this was reversed in Study 2. Although milk fat content was not affected by treatment, increased milk protein contents were observed in both studies with cows grazing full-time. This highlights the potential of diets containing high levels of grazed grass to increase milk protein content. The differences in animal performance between years can be explained by difficult grazing conditions and good quality silage in Study 1, compared to excellent grazing conditions and medium quality silage in Study 2. While grazing stocking rates were very different between treatments, the overall stocking rate, which takes account of the land required to provide the conserved forage, was similar between treatments. Although housing cows overnight reduces the time spent with droving and pasture management, it requires time being spent feeding silage, cleaning cubicles and sheds, and spreading slurry. The result was that the average weekly labour input was similar with the full-time grazing system and the partial confinement system. These labour calculations do not take account of the labour involved in making the additional silage required for cows housed at night. While specific circumstances may force some farmers to adopt night time housing, replacing grazed grass with silage fed during overnight housing is unlikely to improve profitability in most situations.

Do total confinement systems have a role?

While partial confinement systems are now common place on many dairy farms in Northern Ireland, a small but an increasing number of producers have now moved to total confinement systems. These are frequently larger units with higher producing cows. While confinement systems are common in many other intensive dairy regions of the world, for example the US, their use within the UK is much less common. Worldwide there is relatively little information available on how cows perform within these confinement systems, compared to conventional grazing systems.

While a research programme to examine the role of confinement systems is not currently in place within Northern Ireland, a number of recent studies have provided some preliminary data on cow performance within these systems. For example, in a study designed to compare the performance of two different cow genotypes, twenty Holstein cows were managed on either a total confinement system or a low input grazing system. Within the confinement system cows were offered a mixture of grass silage and concentrates in the form of a total mixed ration throughout the full lactation. Cows within the low input grazing group were offered a total mixed ration from calving until turnout, and then 1.0 - 2.0 kg concentrate/day for the duration of the grazing season. Total lactation concentrate inputs were approximately 3,500 kg/cow for the confinement system and 870 kg/cow for the grazing system (Table 7).

Table 7 Effect of managing cows on a high input total confinement system or a low input grazing system for a full lactation, on cow performance (Vance *et al.,* Unpublished)

	Total confinement	Low input grazing	Significance
Days in milk	325	291	**
Total concentrate input (kg/cow)	3491	868	***
Milk yield (kg/cow)	9473	5974	***
Milk fat (g/kg)	43.5	43.4	NS
Milk protein (g/kg)	34.0	33.5	NS
Milk fat + protein yield (kg/cow)	731	459	***
Live weight at drying off (kg)	606	590	NS
Body condition score at drying off	2.5	2.3	NS
Days to 1st service	79	76	NS
Conception to 1st and 2nd service (%)	58	67	NS
Pregnancy rate after 12 weeks (%)	74	72	NS

Cows within the total confinement system produced an additional 3,500 kg milk during the course of the lactation compared to those on the low input grazing system, while neither milk fat nor milk protein content was influenced by management system. As a result, fat plus protein yield was 270 kg higher for cows on the total confinement system. Cows on the total confinement system lost significantly less live weight from calving to nadir than those on the low input grazing system (55 vs 96 kg), although live weight at drying off was similar for cows on both systems. Despite this difference in liveweight change between the systems, fertility performance was unaffected by system. In addition, overall stocking rates within each of the two systems were similar, namely 2.8 and 2.6 cows/ha (confinement and grazing, respectively). The latter reflects the tight grazing regime adopted within the low input grazing system.

A separate set of Hillsborough data provides information on how cows within a total confinement system perform, compared with grazing cows managed within a moderate concentrate input system. Fifty autumn calving Holstein cows were managed on a high concentrate diet within a total confinement system from calving until 25 April. At this point the group was divided, with half of the cows remaining indoors on a confinement system, while the other half moved to a full-time grazing system. Cows on the indoor system were offered a grass silage-based diet and 11.9 kg concentrate/cow/day (on average) until the end of August. During the same period the grazing cows were offered an average of 7.9 kg concentrates/cow/day, and were given access to fresh grass after every afternoon milking. Trends in average weekly milk yields for the two groups are presented in Figure 5. The average total milk output of cows on the indoor and grazing treatments during the study were 3,755 kg/cow and 3,422 kg/cow, respectively. Final live weight (655 and 651 kg) and body condition score (2.6 and 2.6) were similar for both treatments. The majority of the cows had already been confirmed in-calf at the commencement of the study.

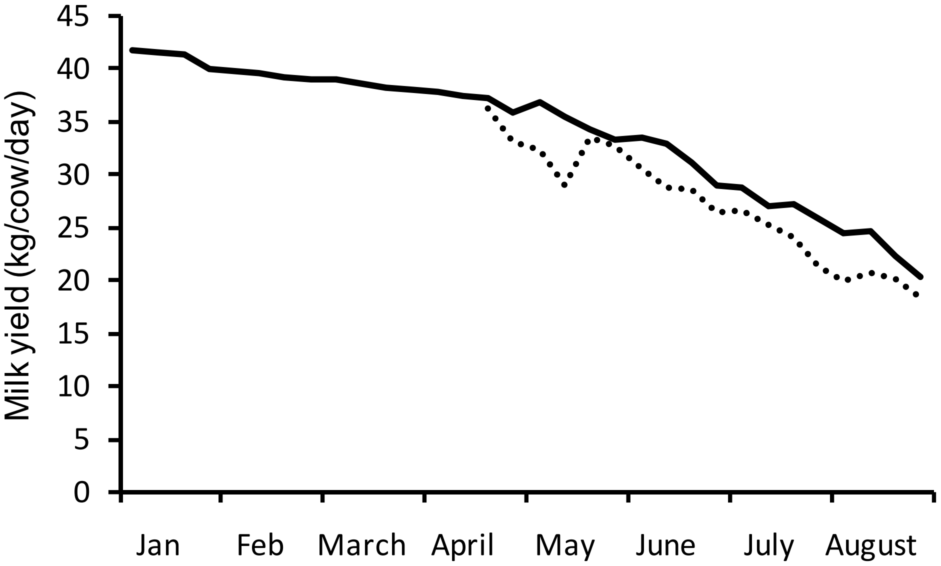

Figure 5 Average daily milk yield of mid-late lactation cows managed on either a total confinement system (—) or a full-time grazing system (·····) (Law *et al.,* Unpublished)

The results of this experiment highlight that when high quality pasture is offered, high levels of cow performance can be achieved within a grazing system, provided adequate levels of concentrate supplementation are provided. While higher levels of cow performance were achieved within the total confinement system, total concentrate inputs were considerably higher with this system (1578 vs 1003). In addition, the conserved forage offered had a higher cost than the grazed grass.

These two studies have provided some preliminary information on cow performance associated with total confinement and grazing systems. However, the environmental impact, cow welfare and health implications of adopting total confinement systems need to be examined within a long term structured research programme.

Conclusions

- Well managed grazed grass has the potential to support significant levels of animal performance. However, for a variety of reasons the full potential of grazed grass is rarely achieved.
- The modern high yielding dairy cow is unable to meet its nutrient requirements from grazed grass alone.
- The effects of feeding ‘starch’ versus ‘fibre’ based concentrates on animal performance are inconsistent. However there is evidence that the crude protein content of grazing concentrates can be reduced (<130 g/kg) without impacting on animal performance when offered at moderate levels (<4.0 kg/cow/day).
- Feeding concentrates ‘to yield’, as opposed to ‘flat rate’, had no effect on the average performance of medium yielding Holstein cows (20.0 – 25.0 kg/day). Nevertheless, this strategy had an impact on the spread of milk yields within the two concentrate allocation groups.
- Individual cow performance was compromised when high yielding cows were managed on a ‘tight’ grazing system. However grass utilisation efficiency and milk output per hectare were maximised with the tight grazing system.
- Offering forage buffers will reduce intakes of grazed grass, except during periods of forage shortages. Animal performance benefits were achieved when maize silage was offered as a buffer to grass, but not when grass silage was offered. The use of forage buffers has not been tested with high yielding dairy cows.

- The milk yield response when grass silage was offered to cows housed overnight was dictated by the quality of the silage offered and the grazing conditions encountered. This practise had little effect on labour requirements.
- In two preliminary studies, higher levels of animal performance were achieved with total confinement systems, compared to grazing systems. However, a structured research programme is required to quantify the effects of total confinement systems on cow welfare, health, fertility, longevity and economic performance.

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Calculating the greenhouse gas footprint of dairy systems: a preliminary analysis of emissions from milk production systems in Northern Ireland, and some practical mitigation strategies

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1. Introduction

The main atmospheric gases associated with the ‘greenhouse effect’ are carbon dioxide (CO_2), chlorofluorocarbons (CFC’s), methane (CH_4) and nitrous oxide (N_2O). Each of these gases has an associated 100-year global warming potential (GWP) which is expressed in the form of CO_2 equivalents (CO_2e). Methane and N_2O have a GWP of 25 and 298 respectively, being 25 and 298 times more potent as a greenhouse gas (GHG) respectively, relative to carbon dioxide (IPCC AR4, 2007). The main GHG’s that arise from Agriculture are CO_2, mainly from fossil fuels, CH_4 from enteric fermentation in ruminant animals and manure storage and N_2O from agricultural soils and fertiliser use.

1.1 UK GHG inventory

Sources of GHG emissions in the UK from 1990-2008 are given in Table 1, with energy supply being the predominant source of emissions. During this period, total emissions from most sectors, including Agriculture, have decreased. Key sources of CH_4 and N_2O emissions within the UK between 1990 and 2008 are presented in Tables 2 and 3, respectively. In 2008, the main sources of CH_4 were landfill sites

(41% of the total) and agriculture (38%), although emissions from these two sources have declined by 59% and 18%, respectively, since 1990 (Department of Energy and Climate Change (DECC), 2010). Agriculture remains the main source of N_2O emissions, accounting for 83% of emissions in 2008, with these being predominantly from agricultural soils (Table 3).

Table 1 Sources of GHG emissions in the UK from 1990-2008 (Mt CO_2e) (DECC, 2010*)

	1990	1995	2000	2005	2006	2007	2008
Energy supply	274.0	235.6	219.5	228.7	231.0	226.2	219.7
Business	111.0	106.9	110.0	101.9	99.6	98.3	95.7
Transport	124.7	124.7	129.0	133.8	135.5	136.0	131.9
Public	13.6	13.2	11.7	11.0	10.5	9.6	10.2
Residential	81.5	82.6	90.1	88.2	85.1	81.8	84.4
Agriculture	61.3	59.1	55.5	51.8	49.9	48.9	48.4
Industrial process	54.3	44.7	24.4	17.8	16.5	18.0	16.7
LULUCF**	2.9	1.2	-0.4	-2.0	-1.9	-1.9	-2.0
Waste Management	52.9	46.9	34.1	22.9	22.8	22.8	22.7
Total	776.1	714.9	673.9	654.1	649.2	639.6	627.6

**LULUCF=Land use, land use change and forestry

Table 2 Sources of CH_4 emissions in the UK from 1990-2008 (Mt) (DECC, 2010*)

	1990	1995	2000	2005	2006	2007	2008
Landfill	2.4	2.1	1.5	1.0	1.0	1.0	1.0
Agriculture	1.1	1.0	1.0	0.9	0.9	0.9	0.9
Gas leakage	0.4	0.4	0.3	0.2	0.2	0.2	0.2
Coal mines	0.9	0.6	0.3	0.2	0.2	0.1	0.1
Other	0.3	0.2	0.2	0.1	0.1	0.2	0.1
Total	5.1	4.3	3.3	2.5	2.4	2.3	2.3

*All figures are for the UK and Crown Dependencies only, and exclude Overseas Territories

Table 3 Sources of N_2O emissions in the UK from 1990-2008 (Kt) (DECC, 2010*)

	1990	1995	2000	2005	2006	2007	2008
Agriculture	109	104	98	90	86	84	83
Industrial process	80	48	18	9	8	9	8
Road transport	4	5	5	4	4	4	3
Other	18	16	15	16	16	15	15
Total	210	173	136	119	114	112	109

*All figures are for the UK and Crown Dependencies only, and exclude Overseas Territories

Agriculture's contribution to total UK GHG emissions in 2008, and to emissions within England, Scotland, Wales and Northern Ireland are presented in Table 4. Within Northern Ireland agriculture contributes 23% of total GHG emissions, higher than within any other devolved administration within the UK. However, this is less than the figure of 26% quoted for the Republic of Ireland in 2007 (Ireland Environmental Protection Agency (EPA), 2009), where pastoral dairy farming was estimated to be the source of 38% of agricultural emissions (Lovett *et al*., 2008).

The reduction of 10% in Northern Ireland's GHG emissions relative to the base year of 1990 is the lowest of any UK region. The contribution of dairy cow CH_4 emissions (from enteric fermentation and manure management) to total GHG emissions in the UK in 2008 is shown in Table 5. Within Northern Ireland, 16% of total agriculture GHG emissions are due to CH_4 from dairy cows.

Table 4 Contribution of agriculture to total GHG emissions in the UK in 2008, and the % reduction in agriculture emissions relative to 1990 (Thistlethwaite and MacCarthy, 2010)

	Total GHG emissions (kt CO_2e)	GHG emissions from agriculture (kt CO_2e)	Agriculture as a % of total GHG emissions	% Reduction in agriculture emissions in 2008, relative to 1990
UK	626041	48254	8	21
England	484505	30309	6	22
Scotland	53707	7632	14	22
Wales	49526	5220	11	23
Northern Ireland	22186	5093	23	10

Table 5 Contribution of dairy cow CH_4 emissions (from enteric fermentation and manure management) to total GHG emissions in the UK in 2008 (Thistlethwaite and MacCarthy, 2010)

	Total GHG emissions (kt CO_2e)	GHG emissions from agriculture (kt CO_2e)	CH_4 from enteric fermentation and manure management (kt CO_2e)	Dairy cow CH_4 emissions as a % of total GHG emissions	Dairy cow CH_4 emissions as a % of total agriculture emissions
UK	626041	48254	5440	1	11
England	484505	30309	3416	1	11
Scotland	53707	7632	548	1	7
Wales	49526	5220	651	1	12
Northern Ireland	22186	5093	824	4	16

1.2 GHG emissions in Northern Ireland

Emissions of GHG within Northern Ireland are dominated by CO_2 from power stations, road transport and residential combustion, with these accounting for 60% of total net emissions (AEA, 2010) (Table 6). However, agricultural soils and CH_4 from enteric fermentation in cattle are also significant sources of GHG emissions in Northern Ireland. For example, in 2008, emissions from enteric fermentation in cattle and agricultural soils contributed 8.4% and 8.5% of total emissions, respectively (AEA, 2010). From 1990 (base year) until 2008, CO_2, CH_4 and N_2O emissions within Northern Ireland have reduced by 6.7%, 23.8% and 26.8% respectively (AEA, 2010).

Table 6 Summary of main sources of GHG emissions (% kt CO_2e) for Northern Ireland in 2007 (AEA, 2010)

GHG emission source	GHG emissions (% kt CO_2e)
Power stations	22
Road transport	20.7
Residential combustion	17.5
Agricultural soils	8.5
Enteric fermentation-cattle	8.4
Other industrial combustion	6.7
Land converted to cropland	5.1
Landfill	3.6
Land converted to settlements	2.6
Cement-decarbonising	1.7

1.2.1 Methane

Methane emissions from the agriculture sector in Northern Ireland are due to enteric fermentation in livestock (85%) and the management of animal wastes (15%) (AEA, 2010). Methane from enteric fermentation in cattle is the largest single source of CH_4 emissions in Northern Ireland, accounting for 56% of total CH_4 emissions and 76% of total GHG emissions from the agricultural sector (AEA, 2010). Figure 1 shows changes in CH_4 emissions from dairy cows in Northern Ireland (via enteric fermentation and manure management) from 1990 to 2008, with emissions from enteric fermentation having risen by 21% during this period (520.8 kt CO_2e (1990) to 661.7 kt CO_2e (2008)). This is in part due to an increase in size of the national dairy herd, from 277,628 cows in 1990 to 289,247 cows in 2008 (DARD statistics, (http://www.dardni.gov.uk/cattle_2009.pdf)) and the increase in milk yield per cow during this time, with an associated increase in feed intake.

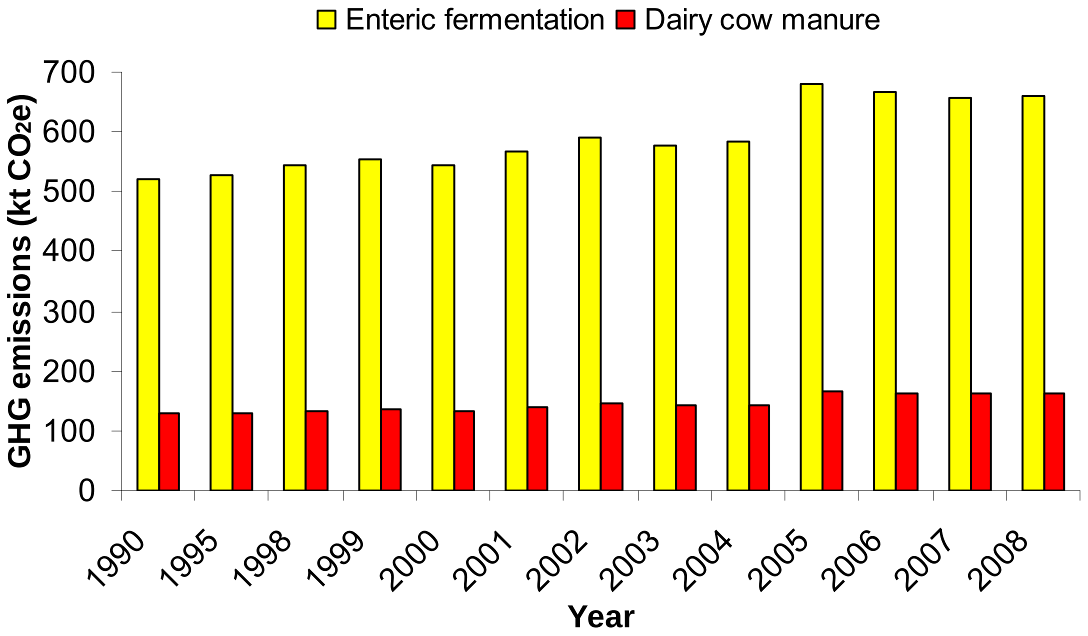

Figure 1 Methane emissions from dairy cows in Northern Ireland via enteric fermentation and manure management (1990-2008) (Thistlethwaite and MacCarthy, 2010)

1.2.2 Nitrous oxide

Agriculture represents the largest source of N_2O emissions in Northern Ireland, with emissions from agricultural soils accounting for 79% of Northern Ireland's N_2O emissions in 2008. However, N_2O emissions from Northern Ireland agriculture have fallen by 18.3% between 1990 and 2008, representing 8.5% of UK agricultural N_2O emissions in 2008 (AEA, 2010). A further breakdown of the agricultural soils sector emission in Northern Ireland is given in Table 7, with over 50% of losses being attributed to leaching of fertiliser nitrogen and nitrogen in animal manures to ground and surface water, plus emissions from wastes produced by grazing animals. The N_2O emissions from manure management systems are shown in Table 8, with solid manure storage and dry lot systems being the predominant sources of emissions.

Table 7 Breakdown of agricultural soils sector emissions in Northern Ireland (AEA, 2010)

Source of N_2O emissions	% Contribution
Leaching of fertiliser N and animal manures to ground/surface water	29.2
Wastes from grazing animals	27
Synthetic fertiliser application	16
Manure used as fertiliser	17
Atomspheric deposition of ammonia and NO_x	8.2
Ploughing in crop residues	1.3
Improved grass	1

Table 8 Nitrous oxide emissions from livestock* manure management systems

In Northern Ireland (2008) (kt CO_2e) (Thistlethwaite and MacCarthy, 2010)

N_2O source	kt CO_2e
Manure liquid systems	8
Manure solid storage and dry lot	204
Manure other	60

*Includes all livestock categories in Northern Ireland

2. Background to paper

2.1 Political context

The UK has a number of targets, both international and domestic, for reducing GHG emissions. The Climate Change Act (2008) made the UK the first country in the world to have legally binding long-term targets to cut GHG emissions, with these being a reduction in GHG emissions by at least 34% by 2020 and by at least 80% by 2050 (both relative to 1990 levels). It also establishes a system of binding five-year carbon budgets to set the trajectory towards these targets (DECC, 2010). At a local level, the Northern Ireland Programme For Government (2008) includes a target to reduce total GHG emissions by 25% by 2025, relative to 1990 levels, although there are not yet specific targets for the agriculture sector. The UK's performance in relation to emission reduction targets are provided by DECC (2010). When all GHGs are considered, 777 million tonne CO_2e was emitted in 1990, with 626 million tonne CO_2e emitted in 2008, representing a reduction of 19.5% in total emissions.

2.2 Producer targets and retail pressure

Dairy farms in the UK produce between 13 and 14 billion litres of raw milk each year, of which, approximately 6 billion litres are processed into liquid milk (Dairy Supply Chain Forum, 2008). In Western Europe, 78-83 of emissions from the dairy sector occur at the farm gate (Food and Agriculture Organisation of the United Nations (FAO), 2010). In 2008, the Milk Roadmap was established by key stakeholders in the dairy industry to further reduce the environmental impact of producing, processing and consuming liquid milk (Dairy Supply Chain Forum, 2008). Within this roadmap producer targets were established to reduce GHG emissions by 20-30% by 2020.

In view of the significant contribution that dairy farming makes to total GHG emissions, and the importance of dairy farming to the Northern Ireland economy, it is essential that emissions from this sector are quantified and mitigation strategies identified, in order to allow legislative requirements to be met. The future sustainability of dairy farming will not only depend on profitable milk production, but also on the ability of farms to meet reduction targets for GHG emissions.

2.3 GHG emissions from milk production

The main GHG emissions from milk production systems include those associated with enteric fermentation, energy use, fertiliser, straights for concentrate feed production, transport of material to farms and manure management systems (Cederberg and Mattsson, 2000). In an analysis of GHG emissions from the average Irish milk production system, Casey and Holden (2005) reported that 49% of emissions were due to enteric fermentation, with 21%, 13%, 11% and 5% attributed to fertiliser, concentrate feed, manure management and electricity plus diesel use, respectively. Within the UK, Foster *et al*. (2007) reported a GHG footprint of 1.14 kg CO_2e/kg milk from the production, processing, distribution and consumption of liquid milk. To date, the GHG footprint per litre of milk from Northern Ireland has not been established and this is a key requirement in order to deliver practical mitigation strategies for the industry.

3. Objectives of paper

3.1 The objectives of this paper were to:

a. provide an outline of how lifetime GHG emissions from milk production systems are calculated

b. calculate lifetime GHG emissions from the average Northern Ireland dairy system

c. calculate lifetime GHG emissions from a number of experimental milk production systems in Northern Ireland

d. examine sustainable GHG mitigation strategies for the Northern Ireland dairy sector

4. Calculating the GHG footprint of a dairy system (assumptions and emission factors (EF))

4.1 System boundary

For the purpose of calculating the GHG footprint of Northern Ireland milk production systems within this paper, the system boundary was the farm gate. Emissions associated with fertiliser manufacture and the production of concentrate feeds prior to the farm gate were also considered within this definition.

4.2 Emission sources

The following emissions sources/sinks were considered in the GHG footprint calculations:

a. enteric fermentation
b. manure management
c. fertiliser application and manufacture
d. concentrate manufacture
e. carbon sequestration from grassland

Emissions from fuel and energy used on the farm were not included in GHG footprint calculations within this paper, although values presented by Casey and Holden (2005) suggest that these are relatively small (approximately 5% of total emissions). Heifer emissions were included within the lifetime GHG footprint calculations in this paper, but heifers were treated as beef animals in terms of EF used in calculations. Emissions from calves during the first three months of life were not included in calculations as these animals would only consume approximately 25 kg milk replacer and 90 kg meal during this period (Morrison *et al.,* 2010). Furthermore, emissions from calves would be minimal as they are largely non-ruminants for the first 2 months of life. Although both male calves and cull cows represent inputs into 'beef production systems', no account was taken of this within the current paper.

4.3 Description of Emission factors used in this paper

In order to calculate the GHG footprint of milk production in Northern Ireland, appropriate EF data were required. The Intergovernmental Panel on Climate Change (IPCC) (2006) divide EF into three categories, namely Tier 1 EF, Tier 2 EF and Tier 3 EF.

(i) Tier 1 Emission Factors

The Tier 1 approach involves the application of generic EF to a representative activity parameter. These default EF provided by the IPCC (2006) do not account for variation between, for example, dairy cows of different breeds/production potential, or differences in diet.

(ii) Tier 2 Emission Factors

A Tier 2 approach involves the application of specific EF for each country. As such, a Tier 2 EF is more accurate than a Tier 1 EF and accounts for some variation in production parameters between various animal types within the “dairy” category.

(iii) Tier 3 Emission Factors

Tier 3 are tailored to address national circumstances. Data detailing Tier 3 EF are limited as they represent actual measured emissions from dairy animals, and therefore account for variation in animal production parameters.

Within this paper, a combination of both Tier 1 and Tier 3 EF were adopted.

4.3.1 Emission factors for methane produced by enteric fermentation

(i) Tier 1 emission factor

The two main sources of CH_4 associated with dairy production systems are rumen enteric fermentation and manure management. The two main categories for cattle within the IPCC (2006) classifications are “dairy” and “non-dairy”. For dairy cattle in Western Europe with a mean milk yield of 6000 kg/head/year, the IPCC (2006) CH_4 EF is 117 kg CH_4/head/year. It is important to note that this EF is used for all dairy animals, regardless of the diet offered, parity, milk yield or stage of lactation and represents a Tier 1 EF. This value compares with 57 kg methane/head/year for the “non-dairy” category within the IPCC and includes bulls, calves and growing steers/heifers.

(ii) Tier 3 emission factor

In terms of measuring CH_4 emissions from animals, respiration chambers are regarded as the gold standard method. Previous research at AFBI Hillsborough involved the measurement of CH_4 emissions from 299 lactating Holstein-Friesian dairy cows and 16 Holstein-Friesian dry cows in indirect calorimeter chambers between 1993 and 1999 (Table 9). The cows were of various genetic merit (low to high), lactation number (1 to 9), stage of lactation (early to late) and live weight (light to heavy). Milk yield ranged from 3.2 to 49.1 kg/day (mean 22.9 kg/day). All cows received a mixed diet of grass silage and concentrate, except for 43 which were offered silage as the sole diet. Within this data set, the mean total CH_4 output was 518 litre/animal/day, equivalent to 135 kg CH_4/head/year (with a range from 45-197 kg/head/year). Although this mean value is greater than the IPCC (2006) value of 117 kg/head/year, the range in CH_4 emissions within the data set (45-197 kg/head/year) was extremely variable and dependent on the type of system being examined. This is something which is not reflected in standard IPCC EF. This dataset was used to develop Tier 3 EF's for enteric fermentation in dairy cows, which were representative of cows housed indoors and offered a range of grass silage and concentrate-based diets.

Table 9 Summary of dairy cow characteristics (*n*=299) and dietary regimes adopted when measuring actual CH_4 emissions at AFBI Hillsborough (Yan *et al.,* 2006)

	Mean	Minimum	Maximum
Dairy cow data			
Live weight (kg)	568	385	747
Milk yield (kg/day)	21.7	0	49.1
Dry matter intake (kg/day)	16.2	4.6	24.5
Feeding level*	3.5	0.9	6.9
Grass silage proportion in diet (DM basis)	0.56	0.18	1.0
Diet crude protein (g/kg DM)	180	116	250
Methane produced (litre/head/day)	518	173	757

* Feeding level = Total ME intake divided by ME requirement for maintenance

4.3.1.1 Prediction equations to calculate CH_4 emissions

Using the data summarised in Table 9, Yan *et al.* (2006) developed a series of equations to predict CH_4 emissions from enteric fermentation in dairy cows (Table 10). The most accurate equation (Equation 4, R^2=0.79) uses silage DM intake, total DM intake, dietary crude protein concentration and cow live weight to predict CH_4 output. Where possible, this equation was used in subsequent calculations.

Methane emissions from enteric fermentation were calculated for the Northern Ireland dairy cow systems examined in this paper. However, as grazed grass is normally a component of dairy cow and heifer diets, when calculating CH_4 emissions using Equation 4, forage (grazed grass plus silage) dry matter (DM) intake was used in these calculations, rather than silage DM intake.

Table 10 Prediction equations for CH_4 production for dairy cows (all relationships are significant ($P < 0.001$)). (s.e. in brackets) (Yan *et al.*, 2006)

Equation number	Prediction equation: CH_4 (litre/day) =	R^2
1	$47.82_{(6.98)}\ \mathrm{DMI} – 0.762_{(0.212)}\ \mathrm{DMI}^2 – 41_{(60)}$	0.75
2	$0.336_{(0.057)}\ \mathrm{LW} + 19.72_{(1.43)}\ \mathrm{DMI} + 12_{(39)}$	0.77
3	$0.324_{(0.056)}\ \mathrm{LW} + [16.55_{(1.71)} + 0.006_{(0.002)}\ \mathrm{S/T}]\ \mathrm{DMI} + 14_{(39)}$	0.78
4	$0.296_{(0.056)}\ \mathrm{LW} + [23.89_{(2.96)} + 0.006_{(0.002)}\ \mathrm{S/T} – 0.033_{(0.011)}\ \mathrm{CPc}]\ \mathrm{DMI} + 15_{(38)}$	0.79
5	$9.07_{(2.36)}\ \mathrm{MY} – 0.111_{(0.046)}\ \mathrm{MY}^2 + 382_{(44)}$	0.53
6	$0.642_{(0.063)}\ \mathrm{LW} + 9.01_{(2.04)}\ \mathrm{MY} – 0.123_{(0.040)}\ \mathrm{MY}^2 + 24_{(53)}$	0.65

CPc = dietary CP concentration; S/T = silage DM intake as a proportion of total DM intake. Units for CH_4, CPc, DMI, LW, MY and S/T are litre/day, g/kg DM, kg/day, kg, kg/day and g/kg DM respectively

4.3.2 Emission factors for methane produced from manure management

(i) Tier 1 emission factor

Methane emissions from manure are categorised according to the livestock species and the mean annual temperature in a particular country, being classified as 'cool' (≤10 to 14°C), 'temperate' (15 to 25°C) and 'warm' (26 to ≥28°C) (IPCC, 2006). Under Northern Ireland conditions (mean temperature of 10°C), the EF for CH_4 production from dairy cow manure is assumed to be 21 kg CH_4/head/year (IPCC, 2006). This compares with a value of 6 kg CH_4/head/year for "non-dairy" animals. Further details are given in Table 11.

Table 11 Manure management methane EF for "dairy" and "non-dairy" cattle according to temperature (kg CH_4/head/year) (IPCC, 2006)

Regional characteristics	Livestock species	Cool			Temperate					Warm	
		≤10	12	14	16	18	20	22	24	26	28
Western Europe	Dairy cows	21	25	29	37	43	51	59	70	83	92
	Other cattle	6	7	8	11	13	15	17	20	24	26

4.3.3 Emission factors for nitrous oxide

In relation to dairy production in Northern Ireland, the main N_2O emission sources arise from organic and inorganic fertiliser applications to agricultural fields, and land use change. Unlike CH_4, IPCC (2006) does not provide a single value for N_2O emissions as these depend on a range of factors including fertiliser application rates, nitrogen excretion rates, and volatilisation and leaching losses after nitrogen is applied to soil. Direct N_2O emissions occur as a result of nitrification and denitrification of nitrogen in manure. Emissions of N_2O from manure during storage and treatment will vary with the nitrogen and carbon content of the manure, the duration of storage and type of treatment. Indirect N_2O emissions arise from volatile nitrogen losses which occur mainly in the form of NO_x and NH_3.

(a) Direct N_2O emissions from manure management

(i) Tier 1 emission factor

The Tier 1 method involves multiplying the amount of nitrogen excreted from dairy cows in each type of manure management system by an EF for that particular manure management system. The IPCC (2006) generic nitrogen excretion rate for dairy cattle in Western Europe is 0.48 kg N/1000 kg animal/day, which compares with a value of 0.33 kg N/1000 kg animal/day for "non-dairy". However, these estimates have an uncertainty of ±50% associated with them (IPCC, 2006).

The N_2O emissions from slurry stored in a pit below a slatted shed is 0.002 kg N_2O-N/kg N excreted (IPCC, 2006). Default EF for direct N_2O emissions from various manure management systems are given in Table 12.

Table 12 Default EF for direct N_2O emissions from manure management (IPCC, 2006)

Manure management system	N_2O emission factor (kg N_2O-N/kg N excreted)	Uncertainty range
Daily spread	0	N/A
Manure/solid storage	0.005	Factor of 2
Liquid/slurry		
- With natural crust cover	0.005	Factor of 2
- Without natural crust cover	0	N/A
Uncovered anaerobic lagoon	0	N/A
Pit storage below slatted shed	0.002	Factor of 2
Anaerobic digester	0	N/A

(b) Indirect N_2O emissions from manure management

(i) Tier 1 emission factor

Indirect N_2O emissions from manure management are caused by N volatilisation in the form of NH_3 and NO_x, leaching or runoff. Emissions are calculated by multiplying the amount of nitrogen excreted and managed in each manure management system by the fraction of volatilised nitrogen. The IPCC (2006) stated that the fraction of manure nitrogen that leaches from manure management systems is uncertain and needs to be developed as a country specific Tier 2 value. All nitrogen losses across each manure management system are then summed together. For example, 28% of nitrogen is lost from dairy cow manure that is stored in a pit (range 10-40%), in the form of NH_3 and NO_x. Default IPCC (2006) values for nitrogen losses from volatilisation of NH_3 and NO_x from manure management are given in Appendix 1.

(c) N_2O emissions from managed soils

(i) Tier 1 emission factor

Nitrous oxide emissions from managed soils (all soils on land, including forest land, which are managed) arise from a variety of sources. Nitrous oxide is produced naturally in soils via the processes of nitrification (aerobic microbial oxidation of ammonium to nitrate) and denitrification (anaerobic microbial reduction of nitrate to nitrogen gas (N_2)). Nitrous oxide is a gaseous intermediate produced during denitrification and a by-product of nitrification. It leaks from microbial cells into the soil and finally into the atmosphere. One of the main controlling factors in this reaction is the availability of inorganic N in the soil. It is therefore important to take account of N_2O emissions from nitrogen additions to soils (e.g. via synthetic or organic fertilisers, manure, crop residues, sewage sludge), or from mineralisation of nitrogen in soil organic matter after drainage/management of organic soils, or cultivation/land-use change on mineral soils. Nitrous oxide emissions from anthropogenic sources or from nitrogen mineralisation occur through direct and indirect pathways. Direct pathways involve the direct emission of N_2O-N from soils to which nitrogen is added. IPCC (2006) direct N_2O EF for the application of inorganic fertilisers or organic manures is 0.01 kg N_2O-N/kg N applied, while for dung and urine deposited by grazing animals the EF is 0.02 kg N_2O-N/kg N deposited (Table 13). Indirect pathways of N_2O emissions from managed soils involve either volatilisation or leaching and runoff of nitrogen from managed soils, where N that was added to the soil is converted to nitrate before being converted to N_2O-N. Emission factors for each of these processes are provided by IPCC (2006) and are presented in Table 14.

Table 13 Sources and default values for direct N_2O emissions from managed soils (IPCC, 2006)

Source	Default EF kg N_2O-N/kg N	Uncertainty range
Synthetic N fertiliser	0.01	0.003-0.03
Organic N applied as fertiliser (e.g. animal manure)	0.01	0.003-0.03
Urine and dung N deposited on pasture, range and paddock by grazing animals	0.02	0.007-0.06
N in crop residues	0.01	0.003-0.03
N mineralisation	0.01	0.003-0.03
Drainage/management of temperate organic crop and grassland soils	8	2-24

4.3.4 Emission factor for fertiliser manufacture

The EF used to calculate GHG emissions from fertiliser manufacture was 6.28 kg CO_2e/kg N applied (Edwards-Jones *at al*., 2009).

4.3.5 Emission factor for concentrate manufacture

Lovett *et al*. (2006) provided an EF for concentrate manufacture of 0.232 kg CO_2e/kg fed, and this was used in calculations within this paper.

4.3.6 Emission factor for carbon sequestration from grassland

Carbon sequestration is the process by which carbon is removed from the atmosphere (via plants and soil microbes) and subsequently stored in the soil. The Natural England Carbon Baseline Survey (Natural England, 2008) provides a value for average carbon sequestration of 1.16 tonne CO_2e/ha/year, and this value was adopted in calculations in this paper for silage and grazing areas.

Table 14 Default EF, volatilisation and leaching factors for N_2O emissions from managed soils (IPCC, 2006)

	Unit	EF	Uncertainty range
Volatilisation from organic N fertilisers and dung and urine deposited by grazing animals	kg NH_3-N + NO_X-N/kg N applied or deposited	0.20	0.05-0.5
Emission factor for N volatilisation and re-deposition	kg N-N_2O (kg NH_3-N + NO_X-N volatilised)$^{-1}$	0.010	0.002-0.05
Volatilisation from synthetic fertiliser	kg NH_3-N + NO_X-N/kg N applied	0.10	0.03-0.3
N losses by leaching/runoff	kg N/kg N additions or deposition by grazing animals	0.30	0.1-0.8
Leaching/runoff	kg N_2O-N/kg N leaching/runoff	0.0075	0.0005-0.025

5. GHG footprint of the average Northern Ireland milk production system

The second objective of this paper was to calculate the GHG footprint of the average Northern Ireland dairy system. However it is important to note that this value will differ from the GHG footprint of the average litre of milk produced within Northern Ireland, as the latter will be weighted towards production systems on larger farms where an increasing proportion of milk is produced. Unfortunately, there is no single data source which provides all the information necessary to calculate either of these GHG footprints. To overcome this difficulty data were obtained from a number of sources, the two main sources being:

a. Northern Ireland Farm Performance Indicators 2008/09 (DARD, 2009), with data used based on average gross margin performance.

b. Farm Business Data (2010) for herds with an average calving pattern (58% summer milk)

When the appropriate information was not available from either of these two sources, data were obtained from a variety of other sources, including scientific reports/papers, technical articles and personal communications.

5.1 Physical performance data used in calculations

When calculating the lifetime GHG emissions associated with each litre of milk produced during the lifetime of a dairy cow, emissions associated with both the heifer rearing period and the lactation/dry periods of the cow must be included. A summary of data used to calculate the GHG footprint of the average Northern Ireland dairy system is presented in Table 15.

Table 15 Summary of key physical performance data used to calculate GHG emissions for the average Northern Ireland dairy system

	Performance data used in GHG footprint calculations	
Lactation		
Annual milk yield (litre)[a]	5,894	
Annual concentrate intake (tonne, fresh)[ab]	1.83	
Annual silage intake (tonne, fresh)	9.5	
Annual land requirement - grazing (ha/cow)	0.262	
Annual fertiliser input (kg N/ha)[a]	139	
Annual grass yield (tonne DM/ha/year)[c]	11.0	
Grass utilisation (%)[c]	80	
Mean cow live weight (kg)*	600	
CP concentration of total diet (g/kg DM)*	180	
Annual herd replacement rate (%)	25	
Length of grazing period (days)[f]	197	
Length of housing period (days)[f]	168	
Productive life (years)	3.5	
Heifer rearing period	**Spring born**	**Autumn born**
Period covered (months)	4-27	4-30
Average live weight (kg)[g]	390	411
Silage intake (tonne)[†]	9	11.7
Concentrate intake (kg)[†]	550	490
Stocking rate (grazing + silage) (ce/ha)[†]	2	2
Annual grass yield (tonne DM/ha)*	7	7
Grass utilisation (%)*	70	70
Annual fertiliser input (kg N/ha)[a]	139	139

[a] DARD (2009); [b] 0.31 kg concentrate/litre milk; [c] Dale *et al*. (2005); [d] Carson *et al*. (2009); [e] Carson *et al*. (2010); [f] Average turnout date is 1st April and the cows are re-housed on 15th October;

* Estimated values; [†] Relates to full rearing period

5.2 GHG emissions associated with the heifer rearing period

Data used to calculate GHG emissions during the heifer rearing period were primarily obtained from the Farm Business Data handbook (2010). For autumn and spring born heifers, calculated emissions relate to months 4-30 of life and 4-27 of life, respectively. During this period spring born heifers were assumed to have a mean live weight of 390 kg and autumn born heifers a mean live weight of 411 kg (calculated from Morrison *et al*. (2010) and Carson *et al*. (2002)). Methane emissions were calculated using the equations of Yan *et al*. (2006), based on total quantities of feed consumed during the rearing period. Total GHG emissions associated with spring born and autumn born heifer rearing systems are presented in Table 16.

Table 16 GHG footprint associated with rearing a spring born heifer (months 4-27) and an autumn born heifer (months 4-30) (Farm Business Data, 2010)

	GHG emissions (kgCO_2e)	
Source	Spring born	Autumn born
Enteric Fermentation	3156	3680
Manure Management	154	157
Direct and indirect N_2O	1288	1472
Concentrate manufacture	128	114
Fertiliser manufacture*	436	436
Carbon sequestration	-580	-580
TOTAL	4582	5280

Total GHG emissions were higher for autumn born heifers than for spring born heifers. This can be attributed, in part, to the higher mean live weight of autumn born heifers (411 kg vs 390 kg), and the fact that autumn born heifers were in the system for 3 months longer than spring born heifers, resulting in a greater overall food intake. As dairy cows in Northern Ireland now calve all year round, the average

GHG emissions for these two heifer rearing systems (4931 kg CO_2e over the rearing period) was adopted in subsequent calculations of GHG emissions for an average Northern Ireland dairy system.

5.3 Calculation of the GHG footprint of the average Northern Ireland dairy system (per litre of milk produced)

Data presented in Table 15, together with the EF discussed earlier in this paper, were used to calculate the lifetime GHG footprint for each litre of milk produced within the average Northern Ireland dairy system. Emissions were calculated as the sum of emissions produced during the heifer rearing period (4931 kg CO_2e), plus emissions produced during the productive lifetime of the cow (3.5 years), divided by the total lifetime milk production of the cow (3.5 x 5894 = 20629 litres). The steps involved in this calculation (ass expressed as kg CO_2e/litre milk) are presented in Table 17.

Table 17 GHG footprint (kg CO_2e/litre milk) of the average Northern Ireland milk production system (calculated as emissions from the heifer rearing period plus the productive lifetime of the cow, divided by lifetime milk production)

	GHG footprint (kg CO_2e/litre milk)	% Total GHG emissions
Greenhouse gas footprint		
Methane (kg CO_2e/litre milk)		
Enteric fermentation[a]	0.720	64
Manure storage[b]	0.049	4
Nitrous oxide (kg CO_2e/litre milk)		
Manure storage	0.01	1
Direct emissions		
Dung and urine deposited by grazing cattle	0.114	10
Slurry spreading	0.05	4
Inorganic fertiliser spreading for grass plus silage making[c] (EF=0.01 kg N_2O-N/kg N)	0.071	6
Indirect emissions		
Volatilisation from inorganic fertiliser spreading, slurry spreading and dung and urine deposited by grazing animals	0.021	2
Leaching losses from slurry spreading + dung and urine deposited by grazing animals	0.024	2
Leaching losses from inorganic fertiliser for silage making and grass growth	0.016	1
Concentrate manufacture (kg CO_2e/litre milk)[d]	0.08	7
Carbon sequestration (kg CO_2e/litre milk)[e]	-0.13	-11
Fertiliser N manufacture (kg CO_2e/litre milk)[f]	0.10	8
TOTAL CO_2e (kg/litre milk)	1.13	100

[a] Predicted from Yan *et al*. (2006); [b] Cows housed for 197 days in total (EF=21 kg CH_4/cow/year (IPCC, 2006)); [c] Negligible volatilisation losses from CAN applied; [d] Lovett *et al*. (2006) 0.232 kg CO_2e/kg concentrate fed; [e] Mean carbon sequestration rate of 1.16 tonne CO_2e/ha/year (Natural England, 2008); [f] Edwards-Jones *et al*. (2009) 6.28 kg CO_2e/kg N applied. N for silage making and grazing included in calculations and fertiliser applied in dry weather conditions.

The results of this calculation indicate that emissions from the average Northern Ireland dairy system were 1.13 kg CO_2e/litre milk produced. When emissions during the heifer rearing period were excluded from this calculation, a GHG footprint of 0.87 kg CO_2e/litre milk was obtained. This highlights how the 'non-productive' heifer rearing period adds to the per litre GHG footprint.

5.4 Potential mitigation strategies to reduce GHG emissions from the average Northern Ireland dairy system

If GHG emissions from Northern Ireland dairy systems are to be reduced, appropriate mitigation strategies must be developed. Some mitigation strategies are examined in this paper, although these represent only a few of many potential strategies.

5.4.1. Avoid sowing inorganic fertiliser nitrogen in wet weather

The baseline GHG footprint for the average Northern Ireland milk production system (Table 17) assumes that fertiliser nitrogen was applied in dry weather. However researchers at AFBI have compared the effect of sowing different forms of inorganic fertiliser N (calcium ammonium nitrate (CAN), urea, urea amended with a urease inhibitor Agrotain and urea ammonium sulphate (UAS)) applied to grassland on N_2O emissions (Watson and Laughlin, 2010). When these fertilisers were applied during wet conditions in May, N_2O-N emissions were up to three times greater from CAN compared with the ammonium-based forms of N fertiliser. This indicated that the timing and form of nitrogen applied had an impact on GHG emissions in this particular year. Based on this local data, an emission factor of 0.03 kg N_2O-N/kg N was assumed when CAN was applied in wet conditions, compared to the standard IPCC default value of 0.01 kg N_2O-N/kg N. This new EF was then applied to the average Northern Ireland dairy system.

Applying fertiliser in wet weather increased the GHG footprint of the average Northern Ireland dairy system from 1.13 kg CO_2e/litre milk to 1.24 kg CO_2e/litre milk

(Table 18), a 9.7 % increase in emissions. It will of course not always be possible to apply fertiliser N during dry conditions, however this data does highlight that there is scope to reduce emissions by applying fertiliser during dry conditions, whenever this is practically possible. It is also important to note that some moisture is required to allow nitrogen uptake.

5.4.2 Increase cow productive life from 3.5 to 4.25 years

Data in Table 18 demonstrates the effect of increasing cow longevity from 3 lactations (3.5 productive years) to 3.6 lactations (4.25 productive years), (a 20% increase in longevity), on the lifetime GHG footprint of the average Northern Ireland dairy system. This increase in cow longevity reduced the GHG footprint from 1.13 to 1.08 kg CO_2e/litre milk, a 4.4% reduction.

Table 18 Effect of spreading inorganic fertiliser nitrogen in wet weather (as opposed to dry), and of increasing cow longevity from 3.5 to 4.25 productive years, on the GHG footprint of the average Northern Ireland dairy system

Strategy	Lifetime production GHG footprint (kg CO_2e/litre milk)
Baseline GHG footprint (Table 17)	1.13
CAN fertiliser applied in wet weather	1.24
Cow longevity increased from 3.5 to 4.25 productive years	1.08

6. GHG emissions associated with four experimental milk production systems

Four contrasting grassland-based systems of milk production were examined during a recent full lactation study at AFBI Hillsborough (Ferris *et al*., 2003). Cows involved in each of these systems were winter calving and of high genetic merit. Key details of the management regimes adopted within each of these systems are summarised in Table 19, while data used to calculate the GHG footprint of each of the four milk production systems is given in Table 20. The letters ‘F’ and ‘C’ describe a ‘forage’ or ‘concentrate’ based component of a system, while the first and second letters of the pair refer to the winter and grazing regimes respectively. In moving from system F-F to system C-C, total concentrate input increased from approximately 908 to 2226 kg/lactation.

Table 19 Summary of the four experimental systems examined by Ferris *et al*. (2003)

System	Winter period	Transitional grazing/main grazing period
F-F	Silage of high feeding value, supplemented with 6.0 kg/cow/day of a high protein concentrate (pelleted), via an out-of-parlour feeding system	Early spring turnout. Main grazing period involved high allowances (23 kg herbage DM/cow/day, above a height of 4 cm) of high quality pasture within a flexible grazing system, supplemented with 0.5 kg/cow/day of a high magnesium concentrate
F-C	Same as F-F	Conventional spring turnout date. Main grazing period involved lower pasture allowances within a rigid paddock grazing system, supplemented with a grazing concentrate offered on a ‘feed to yield’ basis
C-F	Silage of medium feeding value, supplemented with 14.0 (multiparous) or 10.5 (primiparous) kg/cow/day of a medium protein concentrate in the form of a complete diet	Same as F-F
C-C	Same as C-F	Same as F-C

When calculating GHG emissions from each of these four systems, emissions associated with the heifer rearing period were included, with the value used being the emissions from an autumn born heifer rearing system (described in Table 16).

Methane emissions during the lactating and dry periods were calculated using Equations 4 and 3 respectively, as described earlier (Table 10). Methane and N_2O emissions from manure storage were calculated using standard IPCC (2006) EF’s. Cow longevity was assumed to be 3.6 years, while a 28% replacement rate was adopted (Mayne *et al*., 2002). As such, all GHG emissions from dry cows were multiplied by 0.72 to reflect the fact that a certain proportion of dry cows were culled each year without a dry period. The calculated GHG footprint of each of the four systems is shown in Table 21.

Table 20 Performance data (lactation basis, unless otherwise stated) used to calculate GHG emissions from the four systems described by Ferris *et al*. (2003)

	System			
	F-F	F-C	C-F	C-C
Mean live weight (lactating period) (kg)	566	565	582	564
Mean live weight (dry period) (kg)	612	610	630	622
Milk yield (kg/day)	22.6	24.4	23.8	24.2
Lactation milk yield (kg)	7541	7527	7458	7825
Lifetime milk yield (kg)	27148	27097	26849	28170
Milk fat (g/kg)	42.1	41.2	41.9	41.1
Milk protein (g/kg)	32.8	32.8	33.2	33.5
Milk lactose (g/kg)	48.7	48.6	48.9	49
‘Silage’ stocking rate (cow/ha)	5.2	5.0	7.6	7.1
‘Grazing’ stocking rate (cow/ha)	3.9	5.0	3.9	5.0
Fertiliser application (silage; kg N/ha)	347	347	243	243
Fertiliser application (grazing; kg N/ha)	385	424	385	424
Replacement rate (%)	28	28	28	28
Cow productive life (years)	3.6	3.6	3.6	3.6
Duration of grazing period (days)	193	173	191	186
Duration of housing period (days)	196	193	178	194
Total concentrate intake (kg DM/cow)	908	1296	1788	2226
Total forage intake (kg DM/cow)	5581	4863	4597	4117
Lactation feed intake (kg DM/cow)	6489	6159	6385	6343

Table 21 Total GHG footprint of each of the four grassland based milk production systems described by Ferris *et al*. (2003), and lifetime emissions/litre milk produced (kg CO_2e/litre milk)

	System			
	F-F	F-C	C-F	C-C
Methane (kg CO_2e/cow)				
- Enteric fermentation	15155	14464	15119	15067
- Manure storage	1106	1087	1024	1111
Nitrous oxide (kg CO_2e/cow)				
- Manure storage	218	215	208	219
Direct emissions				
- Dung and urine from grazing cattle	2348	2159	2381	2281
- Slurry spreading	1092	1074	1041	1096
- Inorganic fertiliser spreading[a]	3115	2925	2529	2332
Indirect emissions				
- Volatilisation from inorganic fertiliser spreading, slurry spreading, dung + urine from grazing animals[b]	453	431	446	447
- Leaching losses from slurry spreading plus dung and urine deposited by grazing animals	510	484	502	503
- Leaching losses from inorganic fertiliser	701	658	569	525
Concentrate input (kg CO_2e/cow)	983	1358	1853	2273
Carbon sequestration (kg CO_2e/cow)	-2478	-2250	-2186	-2020
Fertiliser N manufacture (kg CO_2e/cow)	4177	3923	3391	3127
TOTAL CO_2e (kg/cow)	27379	26527	26878	26962
TOTAL CO_2e (kg/litre milk)	1.01	0.98	1.00	0.96

[a] EF = 0.01 kg N_2O-N/kg N; [b] Negligible volatilisation losses from CAN applied

Despite the very different management regimes adopted within each of the four systems (differences in concentrate, fertiliser and silage inputs), the calculated GHG footprint was remarkably similar for all systems. This is likely to reflect the fact that total milk outputs associated with each of the four systems were similar, and that a similar culling rate was assumed for each system. While there was a trend for emissions to decrease from system F-F (1.01 kg CO_2e/kg milk) through to system C-C (0.96 kg CO_2e/kg milk), this may simply reflect the higher milk yield associated with the latter system. It is of course also possible that the EFs used were not able to pick up some of the subtle differences which existed between systems, and which may have impacted on emissions, such as silage quality and herbage allowances.

6.1 An examination of potential GHG mitigation strategies within the four experimental milk production systems

(1) Reduce fertiliser nitrogen application

Research at AFBI has shown that total denitrification losses from soil (kg N/ha/year) are positively correlated with nitrogen application rate (Garrett *et al.,* 1992). For example, at fertiliser application rates of 100, 200, 300 and 500 kgN/ha/year, denitrification losses were 9, 22, 55, 80 and 107 kg N/ha/year. As 25% to 33% of total N losses from denitrification are believed to be in the form of N_2O-N, it is reasonable to assume that a reduction in inorganic fertiliser nitrogen input will lead to a concomitant reduction in N_2O emissions.

To address this issue, data from the four systems described by Ferris *et al*. (2003) were used to examine the impact of reducing inorganic fertiliser nitrogen inputs by 50%. However, it should be noted that actual fertiliser nitrogen inputs within these systems were considerably higher than those which would be commonly used today, this experiment having been undertaken before the Nitrates Directive Action Programme was implemented within Northern Ireland. In addition, within these calculations, fertiliser nitrogen application rates during the heifer rearing period were not reduced as inputs during this period were already relatively low (139 kg N/ha; DARD, 2009).

The adoption of this mitigation strategy has a number of impacts, namely a reduction in emissions from fertiliser manufacture of 50%, a reduction in N_2O emissions associated with fertiliser spreading, and a reduction in herbage yield and hence stocking rates. The reduction in herbage yield was estimated using the data of Dillon *et al*. (2007), which describes the relationship between grass DM production and fertiliser N application (obtained from a range of grass cutting experiments in Teagasc over a large number of years). The relationship developed from these data indicated a reduction in the yield of herbage produced of 12.0 kg DM/ha for every 1.0 kg reduction in fertiliser nitrogen input (for fertiliser nitrogen application rates between 250 and 350 kg N/ha). Reducing fertiliser use by 50% was calculated to increase the areas required for silage production and grazing, such that ‘silage stocking rates’ were reduced to 4.25, 4.14, 7.22 and 6.76 cows/ha, and grazing stocking rates were reduced to 3.34, 4.14, 3.30 and 4.14.cows/ha, for systems F-F, F-C, C-F and C-C, respectively. With a greater area of land now included within the system, the total quantities of carbon sequestered were increased.

When inorganic fertiliser N applications within each of the four systems were reduced by 50%, GHG emissions from all systems were reduced by between 9.4 and 11.9% (Table 22). The greatest reduction was for system F-F, where the diet was predominantly forage, while the smallest reduction was for system C-C, where the diet had a high level of concentrate offered.

Table 22 Effect of reducing inorganic fertiliser N application by half during the lactating and dry periods on GHG emissions (kg CO_2e/litre milk) from the four milk production systems described by Ferris *et al*. (2003)

	System			
Lifetime GHG footprint (kg CO_2e/litre milk)	F-F	F-C	C-F	C-C
Baseline GHG footprint (Table 21)	1.01	0.98	1.00	0.96
50% reduction in fertiliser N	0.89	0.87	0.90	0.87
% Reduction in GHG footprint	11.9	11.2	10.0	9.4

(2) Effect of sowing inorganic fertiliser nitrogen in dry weather vs. wet weather

As already discussed, when fertiliser nitrogen is sown in wet weather, N_2O emissions increase up to three fold for nitrate-based fertilisers, from 0.01 to 0.03 kg N_2O-N/kg N applied. Data from the four systems were again used to examine the impact on emissions of sowing fertiliser under either wet or dry conditions, with the calculation including fertiliser sown during the heifer rearing period. When fertiliser N was sown under wet, rather than dry conditions, emissions per litre of milk produced were increased by 22.8, 21.4, 19.0 and 16.7% for systems F-F, F-C, C-F and C-C, respectively (Table 23). These data again demonstrate the potential for achieving lower GHG emissions from dairy systems by ensuring that fertiliser N is sown under optimal climatic conditions.

Table 23 Effect of applying inorganic fertiliser nitrogen in wet weather during the lactating and dry periods and the heifer rearing period on the GHG footprint of the four milk production systems (kg CO_2e/litre milk) examined by Ferris *et al*. (2003)

Lifetime GHG footprint (kg CO_2e/litre milk)	System			
	F-F	F-C	C-F	C-C
Baseline GHG footprint (dry weather; Table 21)	1.01	0.98	1.00	0.96
Wet weather	1.24	1.19	1.19	1.12
% Increase in GHG footprint	22.8	21.4	19.0	16.7

(3) Reduce culling rate in dairy herd

Because of the duration of the study, and the relatively small numbers of animals involved, robust data on culling rates were not available. Nevertheless, there was no evidence that dairy cow fertility was affected by management system, and for this reason, a common culling rate (28%; Mayne *et al*., 2002) was assumed across all four systems in the baseline calculation (Table 21). As it is known that GHG emissions can be reduced by reducing culling rates, the impact of reducing the culling rate within each of the four milk production systems from 28% to 20%, on the GHG footprint, was examined. The impact of this on animal numbers was two fold, namely, a reduction in heifer numbers and an 8% increase in the number of dry cows on the farm at the end of each lactation. When the impact of these factors was examined, the reduction in GHG emissions associated with each of the milk production systems was relatively constant across each of the four systems, and averaged 6% (Table 24). This overall reduction of 6% calculated is in line with the findings of Garnsworthy (2004), who reported that total herd emissions of CH_4 could be reduced by 4-5% if fertility was restored from 2000/2002 levels (78 days to first insemination) to 1995 levels (72 days to first insemination) (without milk quotas). Garnsworthy (2004) also reported that the proportion of total CH_4 emissions produced by herd replacements ranged from 27% (fertility at 2000/2002 levels) in a high yielding herd, to 12% under ideal management conditions (70 days to first insemination). In the study described by Ferris *et al*. (2003), CH_4 from heifer replacements accounted for 23.6% of lifetime CH_4 emissions, with a 28% culling rate, while this was reduced to 18% with a 20% culling rate.

Table 24 Effect of reducing the culling rate from 28% to 20% on the GHG footprint of the four milk production systems (kg CO_2e/litre milk) described by Ferris *et al*. (2003)

	System			
Lifetime GHG footprint (kg CO_2e/litre milk)	F-F	F-C	C-F	C-C
Baseline GHG footprint (28% culling rate, Table 21)	1.01	0.98	1.00	0.96
20% Culling rate	0.95	0.92	0.94	0.90
% Reduction in GHG footprint	5.9	6.1	6.0	6.2

(4) Effect of reducing culling rates and fertiliser levels simultaneously

The combined impact of reducing culling rates (from 28% to 20%) and reducing fertiliser application rates (by 50%) were examined under a scenario when fertiliser was applied under dry conditions (Table 25). In this scenario, the overall impact (mean across all systems) was a reduction in GHG emissions of 17.45%.

Table 25 Effect of reducing culling rate from 28% to 20% and of reducing inorganic fertiliser N application by 50%, on GHG (kg CO_2e/litre milk) from the four milk production systems described by Ferris *et al*. (2003)

	System			
Lifetime GHG footprint (kg CO_2e/litre milk)	F-F	F-C	C-F	C-C
Baseline GHG footprint (Table 21)	1.01	0.98	1.00	0.96
20% culling + fertiliser nitrogen reduced by 50%	0.82	0.80	0.83	0.81
% Reduction in GHG footprint	18.8	18.4	17.0	15.6

6.1.1 Overview of some GHG mitigation strategies that could be adopted on Northern Ireland dairy farms

To abate on-farm GHG emissions, a number of strategies could be employed immediately. These strategies are based on some of the mitigation strategies examined in this paper and reflect more efficient management practices, and as such, may improve profitability. Details of some practical GHG mitigation strategies are summarised in Table 26.

Table 26 Practical mitigation strategies for Northern Ireland dairy farms

Mitigation strategy	Reason(s)	How to achieve
Apply inorganic fertiliser to meet crop requirements	Match nitrogen supply to crop demand. Excess inorganic nitrogen supplied is subject to high GHG emissions	Awareness of crop nitrogen requirements. Make more effective use of organic manure
Select appropriate type of fertiliser	Higher emissions from nitrate based fertilisers than ammonium based fertilisers in wet weather	Use ammonium-based fertilisers in wet conditions. Check weather forecast!
Reduce culling rates	Reduced GHG emissions through improved lifetime performance and fewer replacement heifers	Improve fertility, health and longevity through improved nutritional and management strategies
Apply slurry under optimum weather conditions	Slurry applied in wet weather is subject to leaching losses, resulting in increased N_2O emissions	Don't apply slurry when the soil is water logged, or heavy rain is forecast
	Nitrogen applied in excess of crop requirements is subject to high losses	Don't spread slurry when the crop is not growing, or in excess of crop requirements
	Nitrogen applied using low trajectory techniques, such as trailing shoe, is utilised more efficiently and subject to lower GHG emissions	Apply slurry using low trajectory systems rather than a splash plate slurry tanker

6.2 Comparison of the GHG footprint of experimental milk production systems in Northern Ireland and the Republic of Ireland

Lovett *et al*. (2006) modelled GHG fluxes from a study involving nine experimental milk production systems, comprising 3 concentrate feed levels (338 (LC), 736 (MC) and 1403 kg/cow/year (HC)) and 3 cow genotypes (low pedigree milk production index (PMPI) of ≤ 100 kg (LP), medium PMPI of 100-200 kg (MP) and high PMPI of 300-300 kg respectively (HP)). In addition to taking account of the emissions presented within this paper, these authors also took account of emissions associated with diesel and electricity use using standard EF. Within this modelling exercise, the lowest emissions were from the medium pedigree index cows (MP) offered a high concentrate diet (HC), being 1.03 kg CO_2e/kg milk, while the highest emissions were from HP LC cows (1.2 kg CO_2e/kg milk). As cow genotype increased, there was a concomitant reduction in herd fertility and overall increase in replacement rate, with replacement rates being 16%, 22% and 28% for genotypes LP, MP and HP, respectively. This high replacement rate was the primary reason for the high emission rates with the high pedigree index cows.

In general, emissions presented by Lovett *et al*. (2006) for these nine production systems were relatively similar to those presented within this paper for the four systems described by Ferris *et al*. (2003). This is further highlighted when we consider two of these systems which involved relatively similar concentrate inputs and milk outputs, namely systems F-C (Ferris *et al*., 2003) and MP HC (Lovett *et al*., 2006). Full lactation concentrate inputs and milk yields were 1296 kg and 7527 kg, respectively (Ferris *et al*., 2003) and 1403 kg and 8065 kg, respectively (Lovett *et al*., 2006). Emissions associated with these systems were calculated to be 1.033 kg CO_2e/kg milk (Lovett *et al*., 2006) and 0.98 kg CO_2e/kg milk (Ferris *et al*., 2003). However, it is worth noting that although these calculated emissions were similar, there were a number of differences in the components included within each of the calculations, as highlighted in Table 27.

While the above differences will clearly impact on the proportions of emissions attributed to various biological and physical processes, in both systems approximately half of the emissions arose from enteric fermentation, 14% from fertiliser manufacture, 7-11% from fertiliser application and 5-6% from slurry storage (Table 28).

Table 27 Summary of some of the main areas of commonality and difference in the calculation of GHG emissions from the studies of Ferris *et al*. (2003) and Lovett *et al*. (2006)

	Ferris *et al*. (2003)	Lovett *et al*. (2006)
System	F-C	MP HC
Lactation milk yield (kg)	7541	8065
Concentrate input (kg/cow/year)	1296*	1403
Fertiliser application - silage (kg N/ha/year)	347	330**
Fertiliser application - grazing (kg N/ha/year)	424	
Manure storage (days)	193	120
Replacement rate (%)	28	22
Electricity emissions included	No	Yes
Diesel emissions included	No	Yes
Emissions from silage effluent included	No	Yes
GHG emissions from calves included	No	Yes
GHG emissions from heifers included	Yes	Yes
GHG emissions from lime included	No	Yes
Carbon sequestration included	Yes	Yes
Global warming potential of CH_4	25	23
Global warming potential of N_2O	298	296

* Concentrate input per lactation; **Total fertiliser input

Table 28 Contribution (%) of the different components within each of systems F-C (Ferris *et al*., 2003) and MP HC (Lovett *et al*., 2006) to the total GHG emissions associated with each litre of milk produced

System	Lovett *et al*. (2006) MP HC	Ferris *et al*. (2003) F-C
On-farm components of system		
Enteric fermentation	44.49	54.52
Silage effluent	4.58	
Slurry storage	6.27	4.91
Slurry spreading	1.10	4.05
Farm yard manure storage	0.34	
Farm yard manure spreading	0.01	
Excreta at pasture	2.52	8.14
Fertiliser application	7.53	11.03
Diesel use	2.26	
Lime breakdown	0.13	
Off-farm components of system		
N leaching	6.77	4.30
NH_3	1.19	1.62
Electricity	3.99	
Fertiliser manufacture	13.56	14.79
Concentrate feeds	4.45	5.12
Diesel	0.80	
Lime production	0.01	
Carbon sequestration	*	-8.48
Total (%)	100	100

* Assumed that the soil carbon fluxes were in balance and soil sinks were included in calculations

6.3 *Published GHG footprints/litre milk from other countries*

Table 29 summarises the GHG footprint/litre milk as calculated in a number of other countries. These data demonstrate that it is often difficult to compare the GHG footprint of milk between countries due to differences in the methodologies used. For example, some countries adopt a full life cycle analysis in calculations, whereas others do not. In addition, some footprints allocate a proportion of emissions to 'beef' as well as milk, whereas others allocate 100% of emissions to milk.

Table 29 Published values for GHG footprint/litre milk in different countries

Country	GHG footprint (kg CO_2e/kg milk)	Reference	Comment(s)
Northern Ireland	1.13	Woods *et al*. (2010)	Average milk production system (5894 litre milk/year) to farm gate. No CO_2 from fossil fuels. 100% allocation milk
Ireland	1.5 (ECM)	Casey and Holden (2005)	Average dairy unit (4822 litre milk/290 day lactation). Cradle to farm gate. 100% allocation milk
Ireland	1.03	Lovett *et al*. (2006)	Cradle to farm gate. Medium pedigree index. 1403kg concentrate/head/year
UK	1.14	Foster *et al*. (2007)	LCA , 100% allocation milk
New Zealand	0.74 (ECM)	Barber (2010)	Partial LCA to farm gate. Conventional system. Allocation=86% milk, 14% meat
Sweden	1.02 (ECM)	Cederberg *et al*. (2009)	LCA to farm gate in 2005. Allocation=85% milk, 15% meat

ECM=Energy corrected milk; LCA=Life cycle analysis

7. Summary and conclusions

(1) The UK established legally binding targets to reduce GHG emissions by 80% by 2050. Approximately 23% of Northern Ireland's GHG emissions come from agriculture, being considerably higher than any other part of the UK.

(2) There is increasing pressure from retailers to demonstrate that their products have a low GHG footprint. Consumer awareness of issues relating to the GHG footprint of purchases is also growing.

(3) The current UK Agriculture inventory uses IPCC Tier 1 methods to calculate GHG emissions from agriculture. In calculating the GHG emissions associated with dairy farming in Northern Ireland, many generic EF were employed. There is an urgent need to develop Tier 2 and Tier 3 EF for Northern Ireland dairy farming, through research across a wide range of areas, to allow a more precise calculation of GHG emissions, and a smarter UK Agriculture inventory that recognises mitigation strategies that could be adopted on farm.

(4) A preliminary analysis shows that GHG emissions associated with the average Northern Ireland dairy system was 1.13 kg CO_2e/kg milk. However, a further refinement of this value will take place as this project develops.

(5) The impact of a number of GHG mitigation strategies were modelled within this paper. When cow longevity was increased from 3.5 to 4.25 productive years, the GHG footprint per litre of milk was reduced by 4.4%. When fertiliser nitrogen was sown in wet rather than dry conditions, emissions were increased by 9.7%.

(6) Greenhouse gas emissions were calculated for four experimental milk production systems. These involved concentrate inputs of between 908 and 2226 tonne/cow/lactation and milk yields of between 7458 and 7825 litre/lactation. Emissions ranged from 1.01 to 0.96 kg CO_2e/kg milk. The

similar GHG footprint associated with each of the four systems highlights that milk yield is a key driver of GHG emissions.

(7) A number of mitigation options were modelled using the data from these four systems. Reducing fertiliser nitrogen input by 50% reduced the lifetime GHG footprint per litre of milk by 10.6%, while reducing culling rates from 28% to 20% reduced GHG emissions by 6.0%. A combination of these two mitigation strategies reduced the overall GHG footprint per litre of milk by 17.4%.

(8) It is important to further develop the evidence base to identify and implement practical and cost effective GHG mitigation strategies for the dairy industry.

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Appendices

Appendix 1 Default values for nitrogen loss due to volatilisation of NH_3 and NO_x from manure management (IPCC, 2006)

Animal type	Manure management system	N loss from manure management system due to volatilisation of N-NH_3 and N-NO_x (%)
Dairy cow	Anaerobic lagoon	35 (20-80)
	Liquid/slurry	40 (15-45)
	Pit storage	28 (10-40)
	Dry lot	20 (10-35)
	Solid storage	30 (10-40)
	Daily spread	7 (5-60)
Other cattle	Dry lot	30 (20-50)
	Solid storage	45 (10-65)
	Deep bedding	30 (20-40)

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