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Modelling phosphorus efficiency within diverse dairy farming systems - pollutant and non-renewable resource?

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ABSTRACT

Increased demand for protein rich nutrition and a limited land capacity combine to create a food supply issue which imposes greater dependence on phosphorus, required for yield maximization in crops for humans, and for animal feeds. To determine the technical and environmental efficiency of diverse milk production systems, this work evaluates the use of phosphorus (P), within confined, conventional grazing, and innovative dairy management regimes across two genetic merits of Holstein Friesian cows, by calculating annual farm gate P budgets and applying a series of common and novel data envelopment analysis (DEA) models. Efficiency results provide an insight into P effective dairy management systems as the DEA models consider P as an environmental pollutant as well as a non-renewable resource. We observe that dairy system efficiency differs, and can depend upon, model emphasis, whether it is the potential for losses to the environment, or the finite nature of P. DEA scores generated by pollutant focused models were wider ranging and, on average, higher for genetically improved animals within housed systems, consuming imported by-product feeds and exporting all manure. However, DEA models which considered P as a non-renewable resource presented a tighter range of efficiency scores across all management regimes and did not always favour cows of improved genetics. Divergent results arising from type of model applied generate questions concerning the importance of model emphasis and offer insight into the sustainability of P use within varied dairy systems.

Key Words: Dairy system, Phosphorus, Efficiency, DEA, Non-renewable inputs, Undesirable outputs

1. Introduction

Increasing demand for food and a limited land capacity combine to create a food supply issue, which imposes increased dependence on phosphorus required for yield maximization in crops for humans and for animal feeds. Intergenerational equity regarding the consumption of finite phosphorous reserves demands efficient use of this naturally occurring element, an essential plant and animal nutrient as well as an environmental pollutant. Phosphorus (P) is a key constituent of fertilisers with over 90% of the current 220 million tons of rock phosphate mined annually being used for agricultural purposes (Jasinski, 2014). Even though estimated global P reserves have increased from 50-100 years (Steen, 1998; Smit et al, 2009) to 370 years at present extraction rates (USGS, 2011), concerns relating to resource shortages and security of supply remain. In 2014 the European Commission (EC) added phosphate rock to its critical raw materials list (EC, 2014) and because production of P is controlled by a limited number of countries this can generate geopolitical anxiety (Cordell, 2010).

The UK is akin to most European Union (EU) member states, food security is dependent on imported P fertilisers to sustain crop yields (Cooper & Carliell-Marquet, 2013), and because there is no substitute for this non-renewable resource in agriculture, food security could be improved by moving towards closed loop farming systems. This would increase resource use efficiency, reducing losses to the environment and lowering total P consumption (Childers et al., 2011; Cooper & Carliell-Marquet, 2013).

In dairy systems, P can be imported onto the farm within animal feeds, in fertilisers, bedding, animals, and manure, and is exported in milk products, animals or in crops and manure that are transferred off the farm (Nousiainen et al., 2011). Unlike nitrogen fertiliser, rock phosphate is fairly stable and moves slowly through the soil, therefore the nutrient is available to crops over a number of years and field management can be designed over a whole rotation in order to maintain P at desirable levels in the soil (Defra, 2010). Over application of P can harm beneficial soil organisms, which restricts plant growth and can lead to P losses by means of erosion, run-off, or leaching, where-by P is transferred to surface waters. The resulting anthropogenic eutrophication of lakes and waterways has been described as the worlds' most prevalent water quality issue (Schindler, 2012).

Despite recent improvements in EU surface water quality (Kristensen, 2012) largely stemming from EU legislation such as the Water Framework and Nitrates Directives (EC, 2000; EC, 1991), a lack of internationally agreed legislation to account for and manage the application of phosphate fertilisers leads to an absence of common methodologies (Amon et al., 2011) and also a plethora of national measures to regulate phosphate application adopted by individual EU member states (Amery and Schoumans, 2014).

The global dairy industry is growing at 2.2% per year, worldwide consumption of dairy products is expected to rise by 20% by 2021 (IDF, 2014) and as a response to the 2015 dairy quota removal, the UK is among several EU countries planning to increase the output of dairy products (EC, 2013). To service demand, some EU member states have raised milk production (DairyCo, 2014), to supply increasing domestic populations as well develop new markets (EC, 2013; DairyCo, 2014). Dairy industry expansion, could lead to intensification as additional animals brought onto established farms would increase herd sizes and therefore manure volumes resulting in environmental challenges.

Livestock systems have a propensity to incur positive P balances (Cuttle et al, 2007), and research has highlighted a variation in nutrient surpluses between farming systems which can be caused by differences in nutrient management techniques rather than farm structure (Brandt and Smit, 1998). Calculating farm nutrient balances and identifying differences across a variety of dairy management regimes can reveal areas of opportunity, to lower environmental impacts, by aiming to optimize nutrient recycling and minimise negative impacts to water (Cooper and Carliell-Marquet, 2013; Mihailescu et al, 2015).

Here we compare P efficiency within novel, intensive and conventional grazing dairy systems across average and improved genetic merits of Holstein Friesian cows by calculating annual farm gate P budgets and applying data envelopment analysis models to test the relative efficiency of the management systems. Nutrient budgets convey farm gate flows and efficacy of P use, whilst the DEA models incorporate further resources such as land requirement and use of nitrogen fertiliser which can characterize the diverse farming systems. We present results generated by multiple application of two types of DEA model, the first of which focuses on the potential polluting aspect of a P surplus by considering residual P as an undesirable output from the milk production system. The second DEA model type reflected the finite nature of P as a resource as well as the potential to pollute by including imported P as an additional non-renewable input variable within the function.

2. Materials and methods

2.1. Dairy system diets and genetic merit

Production data were obtained from the Langhill herds of Holstein Friesian (HF) dairy cows, based at SRUC's Crichton Royal Farm, Dumfries, Scotland. The cows were part of a long term investigation to assess genetic line × feeding system interactions (Pollott and Coffey, 2008). Production and management data were extracted from dairy feed system experiments with the herds being comprised of two distinct genetic lines. The Langhill cows are selected for either increased milk fat plus crude protein (CP) yield (Select line), or they are designated to remain close to an annually established average genetic merit for milk fat plus CP yield for Holstein–Friesians in the UK (Control line) (Pryce et al., 1999; Bell et al., 2011).

Data was drawn from four distinct feeding system trials maintained between 2007 and 2013. During the first comparison (2007 – 2010) cows were given either a low forage (LF) diet consuming an average of 3.0 tons of concentrate annually or a high forage (HF) diet containing approximately 1.2 tons of concentrate (Chagunda et al., 2009). Diets within the second comparison (2011 to 2013) either consisted solely of purchased by-products (BP), or of forage and protein crops grown exclusively on the farm, (HG). The BP and HG regimes can be considered novel as these diet types are unconventional and would not be routinely fed by farmers in the UK.

Forages fed in LF, HF and HG diets included grass silage, maize silage and whole crop wheat silage and Table 1 outlines constituents and dry matter proportions of rations with their respective P contents. The HG forages also included lucerne, red clover, spring beans and wheat grain. No forages grown on the farm were included within the BP diets, as these consisted solely of imported feedstuffs (Table 1).

Insert Table 1 here

Each diet was developed to deliver appropriate levels of metabolized energy (ME) and CP for the required maintenance plus a target yield for cows within each of the genetic line × feeding systems. Feeding systems within the groups are defined here as: Low Forage Control (LFC), Low Forage Select (LFS), By-product Control (BPC), By-product Select (BPS), High Forage Control (HFC), and High Forage Select (HFS), Homegrown Control (HGC), and Homegrown Select (HGS).

Groups were managed so that calving took place all year round and each group contained approximately 50 cows being fed a total mixed ration (TMR), approx. 750g of concentrate per cow per day was given in the milking parlour within the HF and LF experiments only. The LF and BP cows were housed all year round (i.e. non-grazing), the HF and HG cows were grazed when there was sufficient available herbage. The HG cows were managed at grass for 2 periods per day and housed for 1 period overnight (approx. 8hrs) whilst feeding on TMR throughout the grazing season. Cows were kept in the herd for at least 3 lactations unless welfare dictated that culling was necessary. In addition cows who failed to conceive after 7 inseminations were removed form the herd.

2.2. Data

The dataset compiled in this study consisted of production variables from all cows within the experiments. Variables were extracted from the database for each cow and aggregated annually at group levels. Feeding for the herds was *adlib* and individual feed intakes were recorded for lactating cows when indoors using HOKO automatic feed measurement gates (Insentec BV, Marknesse, The Netherlands). All cows were milked three times a day and samples taken weekly from each of the three milking periods were analysed to provide fat and CP concentrations of the milk.

Production data regarding milk yield, fat and protein concentrations, fertiliser application, herd inventory, land use and diet consumed were extracted directly from the systems database and feed mixer datasheet. Figures for bedding imports were obtained directly from the farm manager (H. McClymont, SRUC, Crichton Farm, Dumfries personal communication). In this analysis, for all herds, heifers were brought into the system at first calving and all calves were assumed to be sold and left the farm. Slurry was not stored separately for each management group and therefore manure volumes for lactating and dry cows were estimated for each system using herd inventory data. Milk yields were expressed in terms of energy corrected milk (ECM) by applying the following formula (Sjaunja et al., 1990) (Equation 1):

$$ECM = 0.25 * Mass\ of\ Milk + 12.2 * Fat\ (kg) + 7.7 * Protein\ (kg) \quad (1)$$

2.3. Dairy system phosphate balances

A farm gate nutrient balance can be defined as a calculation of system inputs and system outputs, where surplus is a positive difference between the total input and output of each nutrient (Table 2). Within dairy production, common inputs include feed stuffs fertiliser, purchased animals and bedding and P outputs leaving the farm are found in milk, animals and manure (Table 2). Measuring nutrient balances, such the farm gate phosphorus surpluses, is widely used to gauge the potential losses of nutrient to the environment. The phosphorous content in each feed product was taken from the database or from the products themselves and if these were not available from the Feeds Directory (Ewing, 2004) or Feedipedia (Feedipedia, 2015).

Insert Table 2 here

Quantities of P in milk were estimated using a factor of 0.0093 provided by the Dairy Council (2002). Phosphorous contained within the heifers brought onto the farm system and within animals sold was calculated using an equation based on the weight of animals (Nousiainen et al., 2011) (Equation 2):

$$Phosphorous_{animal}\,(kg) = 0.00067 * Live\ Weight\ (kg) + 0.055 \quad (2)$$

Table 2 shows descriptive statistics for variables applied to evaluate annual farm phosphate balances for each of the dairy production systems.

Manure production was calculated by determining monthly herd inventory figures for each of the dairy systems and applying liquid and solid manure factors according to milk yield (DairyCo, 2010; Nennich et al., 2005). Estimates for amounts of P contained in slurry and farm yard manure (FYM) were derived from standard values (Defra, 2010). P requirements of crops were taken from the Fertiliser Manual and used to calculate the additional P required (Defra, 2010) to sustain the soil at Index 2, a recommended index, and that which is found in Crichton Royal Farm land. All manure was assumed to be exported from the BP herds because no grazing or crop lands were required within this feeding system.

2.4. Data envelopment analysis

To represent each dairy production system at farm level, non-phosphate related variables such as land requirement and nitrogen application were included as inputs within the DEA models. Table 3 shows descriptive statistics for non P inputs and outputs common to each system and includes

ECM, tonnes of nitrogen, hectares of land and the average number of cows present in each system. Data relating to annual land use for crops and grazing as well as nitrogen fertiliser application within the systems were extracted directly from the database.

Insert Table 3 here

Data envelopment analysis (DEA) is a method used to estimate the efficiency of production systems based on the assumption of optimizing behaviour, namely it provides a way of analysing the degree to which producers fail to optimize and the extent of the deviations from technical and economic efficiency (Färe et al., 1994). Pitman (1983) extended the traditional efficiency analysis to account for undesirable outputs (*e.g*., pollutants associated with agricultural emissions from dairy farms) by estimating efficiency measures that allow for the asymmetric treatment of desirable and undesirable outputs (desirable outputs are strongly disposable as it is always possible to reduce the production of a desirable output without increasing costs; undesirable outputs are weakly disposable as it is not possible to reduce the production of an undesirable output without reducing the production of a desirable output or increasing the use of an input). Since then several DEA modelling approaches have been developed for environmental efficiency measurement (Färe et al., 1996; Piot et al., 1995; Tyteca, 1996; Kuosmanen and Kortelainen, 2005; Kortelainen, 2008). Additionally, DEA approaches have been developed for the specific treatment of those inputs which can be viewed as valuable resources (e.g. non-renewable resources such as phosphorus) whose uptake can exert a threat on the environment. Some of these modelling approaches consider both non-renewable resource inputs and undesirable outputs (Tyteca, 1996, Korhonen and Luptacik, 2004; Liu et al., 2006; Bian et al., 2010; Bi et al., 2012).

This paper estimates two DEA models, one to consider at the treatment of phosphorus as undesirable output (undesirable output-orientated model (UO)) and the other incorporating phosphorus as both undesirable output and non-renewable input (input-undesirable output-orientated model (IUO) model) (Tyteca, 1996).

The Nonparametric Undesirable Output-Orientated Model (UO) is as follows:

minimise T $(T \leq 1)$ (3)

subject to $$\sum_{k=1}^{K} z^k v_m^k \geq v_m^0 \,, \quad m = 1, ..., M$$

$$\sum_{k=1}^{K} z^k w_j^k = T w_j^0 \,, \quad j = 1, ..., J$$

$$\sum_{k=1}^{K} z^k x_n^k \leq x_n^0 \,, \quad n = 1, ..., N$$

$$z^k \geq 0 \,, \quad k = 1, ..., K$$

Where:

M, J, and N are the numbers of desirable outputs, inputs, and undesirable outputs, respectively; K is the number of observations (producers, time periods, or in our case, dairy systems by year and treatment); v_m^0, w_j^0, x_n^0 are desirable outputs, undesirable outputs and inputs, respectively. In the case of observation 0, observation $0 \in \{1, ..., K\}$ takes values from 1 to K, successively. Variable T represents the standardized indicator of environmental performance; variable Z is a vector which denotes the intensity levels at which each of the K observations are conducted, enables shrinking or expanding individually observed activities for the purpose of constructing unobserved but feasible activities, and provides weights which facilitate the construction of the linear segments of the piecewise linear boundary of the technology.

The model shows one key difference to the classical DEA formulation, namely that instead of minimizing a ratio of inputs to outputs or maximizing a ratio of outputs to inputs, it minimises a ratio of undesirable outputs to a weighted sum of desirable outputs and inputs. Thus the undesirable outputs are considered as peculiar outputs which one tries to minimise with respect to the other factors of production (inputs and desirable outputs) (Tyteca, 1996):

minimise $$h_0 = \frac{\sum_{j=1}^{J} c_j w_j^0}{\sum_{m=1}^{M} a_m v_m^0 - \sum_{n=1}^{N} b_n x_n^0} \qquad (4)$$

subject to $$\frac{\sum_{j=1}^{J} c_j w_j^k}{\sum_{m=1}^{M} a_m v_m^k - \sum_{n=1}^{N} b_n x_n^k} \geq 1, \quad k = 1, ..., K$$

$$a_m, b_n \geq 0, \; c_j \text{ free}$$

where h_0 represents the standardized indicator of environmental performance; and a_m, b_n and c_j denote intensity levels.

The model assumes constant returns to scale, *i.e.*, in pollution terms, for efficient decision making units (DMU), namely those showing a value of T equal to 1, a given increase in desirable outputs and/or inputs would result in a proportional increase in undesirable outputs (Färe, 1992).

The input—undesirable output-orientated model (IUO) is a variant of the nonparametric undesirable output-orientated model (UO) and is as follows:

minimise $$h_0 = \frac{\sum_{n=1}^{N} b_n x_n^0 + \sum_{j=1}^{J} c_j w_j^0}{\sum_{m=1}^{M} a_m v_m^0} \qquad (5)$$

subject to $$\frac{\sum_{n=1}^{N} b_n x_n^k + \sum_{j=1}^{J} c_j w_j^k}{\sum_{m=1}^{M} a_m v_m^k} \geq 1, \quad k = 1, ..., K$$

$$a_m, b_n \geq 0, \; c_j \text{ free}$$

The model minimises the ratio of a weighted sum of inputs and undesirable outputs over the desirable outputs. From an environmental performance viewpoint, this means that firms likely to operate near points where output productivity (ratio of inputs to desirable outputs) is optimal will be differentiated as regards environmental performance and the most environmentally efficient firms will show the smallest possible ratio (i.e. 1) while the less environmentally efficient firms will be prevented from reaching the frontier (Tyteca, 1996). This model is suitable for the treatment of those inputs which can be considered as valuable resources (e.g. non-renewable resources) (Tyteca, 1996, Korhonen and Luptacik, 2004; Liu et al., 2006; Bian et al., 2010; Bi et al., 2012).

A number of research papers analyse system efficiency using various DEA methods depending on the way nitrogen use or phosphorus use variables are incorporated in the models (Reinhard et al., 2000; Ondersteijn et al., 2001; Coelli et al., 2007; Barnes et al, 2009; Picazo-Tadeo, 2011; Molinos-Senante et al., 2011; Hoang and Alauddin, 2012; Toma et al., 2013) and comparing different farming systems, in some cases dairy farms (Reinhard et al., 2000; Ondersteijn et al., 2001; Barnes et al, 2009; Toma et al., 2013). To the best of our knowledge, our paper is the first to analyse phosphate efficiency of dairy systems using the models detailed above.

Ten models were estimated, namely: four undesirable output-orientated (UO) models, (where undesirable outputs were phosphate surplus), and six input-undesirable output-orientated (IUO) models, (where undesirable outputs were phosphate surplus and non-renewable resource inputs were phosphorus in feed, fertiliser, straw bedding and also that contained within the bones and tissues of animals entering the herd). Included in all models were land and nitrogen fertilisers as inputs, and phosphorus in milk, phosphorus in animals sold and phosphorus in manure exported as desirable outputs.

In building the relative environmental efficiency measure, we use the DEA endogenous weighting scheme (Farrell, 1957; Charnes et al., 1978; Tyteca, 1996). We estimated the models using the General Algebraic Modeling System (GAMS 22.8). We used DEA to account for temporal aspects, *i.e*., not only to compare the dairy systems amongst themselves, but to quantify changes in environmental efficiency over time. The models consider each of the systems as divided into a number of independent DMUs, namely four annual observations each for LFC, LFS, HFC and HFS and respectively two annual observations each for BPC, BPS, HGC and HGS. This follows a similar approach used by Färe et al., 1996; Ball et al., 1994 and Toma et al., 2013 and results in a set of 24 DMUs. Thus the best practice production frontier is composed of systems that were efficient in any of the years considered. The analysis allows us to provide a measurement of improvement (or deterioration) in environmental efficiency for each system over time.

3. Results

3.1. Dairy systems production differences

Across feed systems, mean milk sales were highest from the Select genotype within the continuously housed LF and BP groups, which produced an average of 551,852 kg /system /year and 516,105 kg / system / year respectively. The lowest milk output stemmed from the HGC system which produced 343,753 kg / system / year on average (Table 3). The need for on farm land varied between systems, with the greatest mean land area of 59.4 ha being required by the HG system. Select cows consistently yielded more than the Control line, and within systems, Select cows required slightly more food and hence land because feed intakes were higher. Land, nitrogen fertiliser and home grown feeds were a feature of all feed groups apart from the BP system (Table 3). The BP system imported an average of 641 tons / year of fresh weight purchased feeds and bedding whereas the least imports arose from the HG system which required 68.9 tons / year on average. Foodstuff imports for the HG system arose from a shortage of farm grown beans and wheat, however supplements such as minerals and magnesium chloride are required to be imported in all systems. Compared to other management regimes there was little difference between the Select and Control cow yields within the HG diets, which could be due to dietary factors such as the quality of grazed grass or forage within the ration.

3.2. Farm phosphate budgets

When evaluating absolute quantities of surplus P among all feed systems, lowest amounts of excess nutrients were generated from the HF groups because P feed input was minimal, and on average, P exports were proportionally higher. Higher fertility rates within the grazed systems resulted in fewer heifer imports and a greater number of calves leaving the system. Highest quantities of surplus nutrient arose mainly from the BP and LF feed systems because much larger amounts of P were imported within purchased feeds. Even though all manure was exported from the BP system it was insufficient to offset imports of P (Table 3). The HG systems attracted a higher P surplus in 2012 as imported feed P was greater than anticipated which highlights the prospect of variable establishment costs relating to this system due to local climates.

On average, system P Nutrient Use Efficiency (NUE) (represented by P outputs divided by inputs), was found to be greatest within the BP group (0.49) because all manure was exported from the farm (Table 2). The HF feed group averaged 0.39 NUE and this conventional grazed system was more P effective than an intensive housed LF management regime feeding large amounts of concentrates combined with farm grown forages. Within the feed systems, Control cows generally consumed marginally less feed and exported less milk than Select groups, however there was little difference between each systems' average P NUE.

When production of energy corrected milk (ECM) is considered, between all systems, per litre surpluses ranged from 0.002 to 0.005 kg P/ litre. On average a UK conventional HF feeding system generated the lowest average surplus of 0.002 kg ± 0.0003, whilst the HG feed system attracted the highest average surplus of 0.004 ±0.002 kg P per litre of ECM because of a poor establishment year. Within each feeding system, on average, cows of Select genetic merit always generated less surplus P per litre of ECM than cows of an average UK merit.

3.3. Data envelopment analysis

Two distinct types of DEA model were applied to assess any differences emphasis regarding the P resource. Efficiency scores generated by an undesirable output orientated model as well as an input undesirable output orientated model were calculated. The undesirable output model assesses the ability of each system to produce milk whilst considering environmental externalities whereas the input undesirable output model considers externalities and also reflects the non-renewable nature of the resource. Four and six runs respectively of each model type generated annual efficiency scores for each system depending on the nature of variables included in the models (Tables 4 & 5).

Insert Table 4 and Table 5 here

3.3.1. Undesirable output model – potential to pollute

Across all years and models, average efficiency scores ranged from 0.55 within HGS to 0.97 within BPS, with the highest to lowest average system scores being BPS>BPC>HFS>LFS>HFC>LFC>HGC>HGS. Factors in the BP management regime, i.e.

manure exportation, no requirement for crop land, grazing pasture or fertilisers have merged to benefit this feed system. However Select cows within a more conventional grazed HF system had the potential to be almost as efficient, because imported feed P was much lower comparatively. Select cows were generally more efficient in each feed system, apart from HG which was the lowest yielding system.

Results showed a wider range of scores within the HG feed systems which are reliant on local weather conditions for crop production. Lower scores in 2012 are attributed to poorer than expected crop yields caused by a season of higher than average rainfall which hindered the establishment of lucerne and also affected other crops. Lower end efficiency scores obtained within the LF feed systems stemmed from a proportionally higher P input from purchased feeds and lower P outputs from milk yield in 2007 (Table 3). All systems except BP 2013 were found to be less efficient using Model 4 (Table 4) which could be because the various P input and P output variables are aggregated within this model (Table 4).

3.3.2 Input undesirable output model - Pollution potential and finite resource

Efficiency scores across all years ranged from a low of 0.85 in the LFS system, to 1.0 within the BPC and HGC systems, with the next most efficient systems being the BPS and HFS management regimes (Table 5). When non-renewable properties of the P resource were considered, average efficiency scores increased across all six models which could reflect the nature of formulated rations. Overall increases in comparative efficiency scores across the board are likely to have occurred as a result of the fact that diets formulated for each of the systems are tailored to meet the energy and protein needs of the animals and thus excess inputs should be minimal.

Even though the BP system again attained the highest average efficiency score, in this case, a HG system was found to be comparatively just as efficient. This could highlight that farmers adopting housed systems importing large amounts of purchased P within feeds are not practicing feeding regimes that adopt minimal inputs of the resource with least surplus to the environment. When comparing efficiency of genetic merits between the IUO models, within the different feed systems, on average, Select cows were less efficient than Control cows. This may suggest that higher feed P intakes of Select groups has not equated directly to sufficient increases in the outputs of P in milk. Greater P intakes of the heavier Select cows do not seem to be required for animal maintenance or milk production.

4. Discussion

Comparing the efficiency of phosphorus use within novel, intensive, and conventional dairy systems across two genetic merits of Holstein Friesian dairy cows by focusing on both the potential to pollute and also the finite nature of the resource, shows that alternate management regimes can be perceived to be more efficient depending on the emphasis of the DEA model. When accounting for the potential to pollute, Figure 1 illustrates that Select genetic merit cows are generally more ecologically efficient than those of an average merit, which could be expected because of greater volumes of milk production combined with improved nutrient utilization. When potential losses of P to the environment are considered, a conventional grazing system with limited purchased feed inputs can be comparatively more efficient than a continually housed high concentrate approach, importing large amounts of purchased feeds as well as growing forages.

Insert Figure 1 here

Farms that exclusively bring in non-human edible by-products and have the added ability to export manure are found to be more P efficient than a grazing system with low imported feeds. This is because P outputs leaving the farm boundary are greater, and this would be desirable as long as the exported manure P is applied to land within a reasonable geographical distance and utilised as a replacement for imported rock phosphate. Traditionally, UK dairy farms are concentrated in westerly regions, favourable for grass growing. Whilst it is accepted that a BP system would not be collectively desirable, crop growing agricultural areas requiring high imports of purchased P within range of by-product feed sources may value a local supply of manure.

Insert Figure 2 here.

When pollution potential is included alongside an additional prominence of inputs of P into the systems, to represent the finite nature of the resource, animals within more conventional grazed regimes, supplemented with home-grown feeds or low amounts of purchased concentrates, can be, on average, as efficient, or do not differ greatly in efficiency from the confined systems. Across the Input Undesirable Output model scores averaged in Figure 2, efficiency scores derived from animals of an average UK genetic merit are comparable to improved merit Select cows. This could be because the difference in P inputs for Select animals is not reflected in the P outputs, so the extra feed P is not fully required for maintenance, lactation or gestation and hence is likely to be excreted.

High P excretion would not be unexpected as a dairy cow could be described as an inefficient consumer of P because these animals can excrete up to 70% of their P intake (Ferris et al., 2010; Nennich et al., 2005) and a direct relationship exists between P intake and P in faeces (Morse et al., 1992; Kebreab et al., 2005). A dairy cow absorbs a varying amount of P depending on her stage of lactation and gestation (NRC, 2001), and endogenous processes further inflate P excretion to faeces (Guegen et al., 1988). In the UK, calls have been made to re-evaluate outdated feeding standards for mineral requirements such as P because the objective of production has shifted to human health and the environmental effects (McDonald et al, 2011). Total mixed rations with ad lib feeding systems formulated to meet major nutrient requirements could over supply minerals to cows with higher intakes.

Whilst deficiencies of dietary phosphate can be associated with health issues such as reduced fertility, recent experiments have shown that feeding less P to dairy cows resulted in lowered faecal P output (Ferris et al., 2010). Opportunities exist to lower the amount of P consumed as a percentage of dry matter intake, lowering overall use via a reduction in dietary intake, and thus resulting in less P entering waterways as less is excreted. Farmers may tend to apply maximum rates of fertiliser to increase crop yields and may also utilise higher levels of concentrate feeds when costs are relatively low and milk prices are high. Therefore more efficient use of nutrients such as phosphorus may not generally drive management decisions.

The farm gate P balance can be described as a broad indicator of losses to aquatic systems and is equivalent to the OECDs gross balance, with the addition of bedding imports (Amon et al., 2011). A soil phosphate balance may give a more representative indication of environmental losses however the data required necessitates estimations associated with greater uncertainty than the Farm Balances applied here. Nutrient use efficiencies (NUE’s) presented here are comparable with estimates reported from similar dairy systems (Gourley et al, 2012; Defra, 2011). NUE results ranged from 0.19 to 0.55 (Table 2) and surpluses per hectare ranged from 14.9 kg P in a HGS system to 48.1 kg P in a LFS system (Table 2 and Table 3). However, lack of required crop land in the BP system renders a per hectare unit obsolete and high surpluses per hectare stemming from LF systems would be expected due to no necessity for grazing land. Intensive grazing systems, with lower than UK average yields per cow (circa 5000 litres per annum) tend to attract higher NUE's and a lower P surplus per hectare. NUE means of 0.71 and surpluses of 4.93 kg P/ha were reported from a study of nineteen dairy farms in Southern Ireland adopting grass based low input dairy systems (Mihailescu et al., 2015). A surplus median of 28 kg P/ha was found across a range of Australian dairy farming systems (Gourley et al. 2012) which compares with a median surplus of 27 kg P /ha found in this analysis.

Calculating nutrient balances and the potential for losses to the environment provides a gauge of farm system efficiency (Jarvis and Arts, 2000; Mihailescu et al, 2015, Thomassen and De Bour 2005) and can assist management decisions (Halberg, 1999). Nutrient budgets expressed in this paper provide a range of P efficiencies and surpluses per litre of ECM, depending upon the genetic merit of an animal within a particular dairy feeding system. Generic procedures could be adopted to calculate and compare nutrient losses so as to inform future strategies for nutrient regulation and mitigation. Specific coefficients could be recommended based on current research; various factors of P output within milk can be applied and manure P content may differ between intensive and grazed systems which could influence P surplus calculations. For example milk samples from the BP system were analysed and P content ranged from 850 to 1169 mg/kg (Pers. Comm., Alan Sneddon).

Differences in model results presented here outline the importance of emphasis within analytical techniques when considering non-renewable resources such as phosphorus. P budgets highlight the potential for efficiency gains, attained by manure recycling within localized protein crop growing regimes, or by exportation to other agricultural systems within an economically feasible range. These results could support efficiency approaches incorporating more cyclical nutrient management, which can reuse, and recycle P, within livestock systems (EC, 2014; Buckwell et al., 2014). The results may also assist those appealing for an increased understanding of mutually beneficial adaptation techniques that improve environmental performance in a practical, economically viable manner (Ulrich & Frossard, 2014).

Whilst the EU Nitrates and Water Framework Directives (EC, 1991; EC 2000) indirectly regulate agricultural P applications to soils, and even though national and regional legislation is implemented across member states, these are not legally binding. Countries such as Denmark, Ireland and the Netherlands have implemented restrictions on P application, depending on variables such as soil type and crop requirements, whereas farmers in England or Hungary have no additional restrictions (Amery and Schoumans, 2014). Close attention to appropriate livestock nutrient requirements alongside on farm soil P status and combined with mitigation methods such as buffer zones may bring about improvements in surface water quality (Schindler, 2012).

Ulrich and Frossard (2014), argue that persistent debate regarding resource scarcity should shift towards a comprehensive understanding of the environmental and economic consequences of prolonged utilization of P. Calls to improve unsustainable food production methods (Foresight, 2011) have furthered a discussion of the environmental benefits of high input (Ross et al., 2014) and low input dairy systems (O’Brien et al., 2012; Casey and Holden, 2005). Results expressed here show that when one pollutant is considered, model emphasis alters perceived system efficiency. Depending on the focus of sustainability, whether it be phosphorus, nitrogen, greenhouse gases, or ammonia emissions, intrinsic qualities and weaknesses seem apparent within dairy management regimes. National dairy farming regimes are likely to be a function of history, demand, culture and regional climate.

Working towards closed loop farming systems is a feature of organic (Steinshamn et al., 2004) and biodynamic dairying, and techniques to reuse P can be developed using model budgets. A combination of HG and BP systems may have the ability to generate a dual production regime in which P is recycled from a confined system feeding by-products (inedible to humans) with negligible land requirement, to a regime feeding a selection of farm grown protein crops to complement grazing. Manure P exported from a BP system could be utilized within an HF, HG or other low input system, thus reducing the need for imported fertiliser, manure exportation and employing a system that is not solely reliant on either purchased feeds or local weather.

Of all the essential dietary minerals required by dairy cows, an excess of P poses the greatest risk to the environment (NRC, 2001). Planned dairy sector development across the EU leading to increases in milk production, could propel trends towards larger herd sizes (DairyCo, 2014) as well as modifications in feeding practices. Crops grown in the UK are dependent on imported phosphorus, amounting to 138 kilo tonnes in 2009 (Cooper and Carliell-Marquet, 2013) and it's estimated that up to 80% of extracted rock P is potentially lost from mine to food to fork (Childers et al, 2011).

Understanding and improving resource use efficiency whilst minimizing undesirable outputs are crucial steps to achieving more sustainable milk production. Further research comparing the merits of alternate farming systems, taking into consideration resources such as water, and pollutants such as greenhouse gas emissions, would benefit the overall understanding of the merits of each management regime.

5. Conclusion

The purpose of this paper was to evaluate and compare phosphorus efficiency within novel, intensive and conventional dairy systems across two genetic merits of Holstein Friesian cows by application nutrient budget calculations and dual DEA model types. Undesirable output orientated models showed that, on average, cows selected for improved production within a By-product system exporting all manure attracted the highest NUE's and DEA efficiency scores. However, a low concentrate input grazing system generated the lowest per litre P surplus and efficiency scores were higher than confined feeding systems that did not export manure. Input undesirable output orientated models did not always favour the Select improved genotype and the lower input Home-grown and High Forage feed systems were most efficient. Nutrient budget estimates of dual systems highlighted possibilities to reuse and recycle P. Results presented here raise questions regarding suitable pathways to be taken by policymakers, industry stakeholders and farmers to achieve optimal use of phosphorus with minimal surplus to the environment.

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Table 1 Constituents and dry matter proportions of rations with P contents

Diet	Foodstuff	DM Diet Proportion[e]	DM Content	P Content g/kg DM	P Content (g/day)
By-product	Barley straw	0.23	0.82	1.50[a]	8.00
	Sugar beet pulp molasses	0.21	0.89	1.00[a]	4.90
	Breakfast cereal	0.13	0.91	10.2[b]	30.6
	Wheat distillers grains	0.09	0.28	1.60[c]	3.50
	Biscuit meal	0.09	0.91	3.00[c]	6.00
	Distillers dark grains	0.09	0.91	9.10[b]	18.2
	Soya bean meal	0.09	0.91	6.25[c]	12.5
	Molasses cane	0.06	0.65	1.00[d]	1.30
	Minerals/vitamins	0.01	1.00	60.0[c]	12.0
Low forage	Wheat Grain	0.16	0.88	3.60[b]	13.8
	Sugar beet pulp molasses	0.13	0.89	1.00[a]	3.10
	Soya bean meal	0.12	0.91	6.25[c]	17.6
	Wheat distillers grains	0.06	0.91	9.10[b]	12.2
	Soya hulls	0.02	0.88	1.60[b]	0.90
	Sopralin	0.01	0.85	6.50[c]	2.20
	Grass silage	0.28	0.33	2.80[b]	18.5
	Maize silage	0.09	0.27	2.76[d]	6.10
	Wheat alkalage	0.09	0.67	1.66[d]	3.70
	Minerals/vitamins	0.01	1.00	60.0[c]	15.0
High forage	Grass silage	0.45	0.33	2.80[b]	26.9

	Maize silage	0.15	0.25	2.69[d]	8.60
	Wheat alkalage	0.15	0.65	1.66[d]	5.30
	Rapeseed meal	0.07	0.88	5.60[b]	8.40
	Barley distillers grains	0.11	0.92	3.30[d]	7.60
	Wheat distillers grains	0.06	0.86	9.10[b]	10.9
	Minerals/vitamins	0.01	1.00	60.0[c]	12.0
Homegrown	Grass silage	0.43	0.26	2.80[b]	25.2
(Winter ration)	Spring beans	0.22	0.85	4.90[b]	23.03
	Wheat grain	0.16	0.85	3.60[b]	12.24
	Red clover silage	0.10	0.20	2.40[b]	4.80
	Maize silage	0.05	0.25	2.69[b]	2.69
	Lucerne silage	0.03	0.30	3.00[b]	1.80
	Minerals/vitamins	0.01	1.00	60.0[c]	12.0

[a] Ewing
[b] Feedipedia
[c] Product data
[d] SRUC database
[e]DM = dry Matter

Table 2 Descriptive statistics of farm gate phosphorus (P) balances for each milk production systems[ab] (mean and standard deviation)

	LFC		LFS		HFC		HFS		BPC		BPS		HGC		HGS	
Variable	Mean	SD[c]	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Input (kg P)																
Feed/Bedding	1466.2	67	1565.3	83	850.1	54	864.8	91	2234.7	285	2456	258	821.5	416	845.3	441
Animals	80.5	15.8	79.4	6.1	80.9	10.3	71.1	16.8	78.5	4.8	82.7	0.8	65.7	23.8	65.9	0.2
Fertilizer	252.9	48.2	300.2	50.2	541	62.7	513.9	88.2	0	0	0	0	942.7	88.5	1035.8	149.1
Total Input	1799.6	120.1	1944.9	128.1	1472.0	86.9	1449.8	179.1	2313.2	279.7	2538.7	257.1	1829.9	480.6	1947	590.3
Output (kg																
Milk	469.4	15.7	524.5	51.9	395.6	28.3	431.2	52.6	436.9	19.1	512.7	15.9	336	1.9	365.6	3.7
Animals	148.5	14.1	121.5	9.2	169.6	24.7	128.0	18	155.7	23.4	147.4	9.4	149.1	30.3	142.5	11.9
Manure	0	0	0	0	0	0	0	0	518	8.8	582.0	0.8	0	0	0	0
Total Output	617.9	22.3	646	60	565.2	43.5	559.2	67.3	1110.6	13.1	1242.1	24.3	485.1	28.35	508.1	15.5
P Surplus	1181.7	134.0	1298.9	126.6	906.8	70.9	890.6	115.3	1202.6	292.8	1296.6	232.7	1344.8	509	1438.9	605.8
P NUE[d]	0.35	0.03	0.33	0.03	0.38	0.03	0.39	0.01	0.49	0.06	0.49	0.04	0.29	0.09	0.29	0.10

[a] Genotype: C = Control, S = Select;

[b]Feed systems: HF= High forage, LF = Low forage, BP = By-product, HG = Home grown.

[c]SD=standard deviation

[d]NUE=Nutrient use efficiency

Table 3 Descriptive statistics of system[a,b] variables applied as inputs within DEA models (mean and standard deviation)

	LFC		LFS		HFC		HFS		BPC		BPS		HGC		HGS	
Variable	Mean	SD[c]	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Land (ha)	28.8	1.7	29.6	2.4	42.9	1.9	42.7	3.7	0.0	0.0	0.0	0.0	57.2	1.1	59.4	3.4
Nitrogen (tonnes)	3.17	0.12	3.22	0.14	4.68	0.26	4.62	0.12	0.0	0.0	0.0	0.0	4.67	0.08	4.86	0.10
ECM[d] Milk (tonnes)	466	9.16	551	52.9	406	26.8	461	55.5	417	21.5	516	16.6	343	0.51	395	4.79
Avg. Cows	50	0.4	47	3.7	54	1.1	52	3.1	55	2.5	48	1.0	59	0.0	54	1.0

[a] Genotype: C = Control, S = Select;

[b] Feed systems: HF= High forage, LF = Low forage, BP = By-product, HG = Home grown

[c] SD=standard deviation

[d] ECM=energy corrected milk

Table 4 Dairy system[ab] efficiency scores for undesirable output (UO) data envelopment analysis models

Year	System	UO1	UO2	UO3	UO4
2007	LFC	0.62	0.575	0.51	0.325
2008	LFC	1	1	0.787	0.484
2009	LFC	1	1	1	0.495
2010	LFC	0.794	0.811	0.703	0.453
2007	LFS	0.618	0.536	0.526	0.316
2008	LFS	0.902	0.839	0.81	0.477
2009	LFS	1	1	1	0.487
2010	LFS	1	1	1	0.592
2007	HFC	0.802	0.665	0.626	0.373
2008	HFC	1	1	0.569	0.381
2009	HFC	1	1	1	0.575
2010	HFC	1	1	0.64	0.428
2007	HFS	0.944	0.782	0.782	0.416
2008	HFS	0.823	0.741	0.741	0.425
2009	HFS	1	1	1	0.498
2010	HFS	1	1	1	0.57
2012	BPC	0.774	0.687	0.679	0.588
2013	BPC	1	1	1	1
2012	BPS	1	1	1	0.773
2013	BPS	1	1	1	1
2012	HGC	1	1	0.233	0.146
2013	HGC	1	1	0.792	0.361
2012	HGS	0.331	0.269	0.233	0.153
2013	HGS	1	1	1	0.408

[a] Genotype: C = Control, S = Select;

[b] Feed system: HF= High forage, LF = Low forage, BP = By-product, HG = Home grown.

Table 5 Dairy system[ab] efficiency scores for input undesirable output (IUO) data envelopment analysis models

Year	System	IUO1	IUO2	IUO3	IUO4	IUO5	IUO6
2007	LFC	1.00	0.98	0.95	1.00	1.00	0.69
2008	LFC	0.94	1.00	0.93	0.77	0.76	0.75
2009	LFC	1.00	1.00	1.00	0.78	0.75	0.74
2010	LFC	0.94	0.98	0.92	0.72	0.71	0.71
2007	LFS	0.91	0.91	0.91	0.69	0.67	0.63
2008	LFS	0.97	0.96	0.96	0.71	0.69	0.69
2009	LFS	1.00	1.00	1.00	0.74	0.68	0.68
2010	LFS	1.00	1.00	1.00	1.00	1.00	0.65
2007	HFC	1.00	0.96	0.94	0.97	0.90	0.91
2008	HFC	0.82	1.00	0.85	0.90	0.86	0.87
2009	HFC	1.00	1.00	1.00	1.00	0.94	0.85
2010	HFC	0.89	1.00	0.85	1.00	0.86	0.85
2007	HFS	1.00	1.00	1.00	1.00	1.00	0.95
2008	HFS	0.96	0.93	0.93	0.86	0.82	0.80
2009	HFS	1.00	1.00	1.00	1.00	0.83	0.81
2010	HFS	1.00	0.99	0.99	1.00	1.00	0.75
2012	BPC	1.00	1.00	1.00	1.00	1.00	1.00
2013	BPC	1.00	1.00	1.00	1.00	1.00	1.00
2012	BPS	0.87	0.91	0.91	1.00	0.81	0.83
2013	BPS	1.00	1.00	1.00	1.00	1.00	1.00
2012	HGC	1.00	1.00	1.00	1.00	1.00	1.00
2013	HGC	1.00	1.00	0.95	1.00	1.00	1.00
2012	HGS	0.73	0.80	0.80	0.78	0.72	0.78
2013	HGS	1.00	0.97	0.91	1.00	1.00	0.91

[a] Genotype: C = Control, S = Select;

[b] Feed system: HF= High forage, LF = Low forage, BP = By-product, HG = Home grown.