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

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11

12 **ABSTRACT**

13 Increased demand for protein rich nutrition and a limited land capacity combine to create a food
14 supply issue which imposes greater dependence on phosphorus, required for yield maximization
15 in crops for humans, and for animal feeds. To determine the technical and environmental
16 efficiency of diverse milk production systems, this work evaluates the use of phosphorus (P),
17 within confined, conventional grazing, and innovative dairy management regimes across two
18 genetic merits of Holstein Friesian cows, by calculating annual farm gate P budgets and applying
19 a series of common and novel data envelopment analysis (DEA) models. Efficiency results
20 provide an insight into P effective dairy management systems as the DEA models consider P as
21 an environmental pollutant as well as a non-renewable resource. We observe that dairy system
22 efficiency differs, and can depend upon, model emphasis, whether it is the potential for losses to
23 the environment, or the finite nature of P. DEA scores generated by pollutant focused models

24 were wider ranging and, on average, higher for genetically improved animals within housed
25 systems, consuming imported by-product feeds and exporting all manure. However, DEA
26 models which considered P as a non-renewable resource presented a tighter range of efficiency
27 scores across all management regimes and did not always favour cows of improved genetics.
28 Divergent results arising from type of model applied generate questions concerning the
29 importance of model emphasis and offer insight into the sustainability of P use within varied
30 dairy systems.

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

33

34

35

36 **1. Introduction**

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

47 materials list (EC, 2014) and because production of P is controlled by a limited number of
48 countries this can generate geopolitical anxiety (Cordell, 2010).

49 The UK is akin to most European Union (EU) member states, food security is dependent on
50 imported P fertilisers to sustain crop yields (Cooper & Carliell-Marquet, 2013), and because
51 there is no substitute for this non-renewable resource in agriculture, food security could be
52 improved by moving towards closed loop farming systems. This would increase resource use
53 efficiency, reducing losses to the environment and lowering total P consumption (Childers et al.,
54 2011; Cooper & Carliell-Marquet, 2013).

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

65 Despite recent improvements in EU surface water quality (Kristensen, 2012) largely stemming
66 from EU legislation such as the Water Framework and Nitrates Directives (EC, 2000; EC, 1991),
67 a lack of internationally agreed legislation to account for and manage the application of
68 phosphate fertilisers leads to an absence of common methodologies (Amon et al., 2011) and also

69 a plethora of national measures to regulate phosphate application adopted by individual EU
70 member states (Amery and Schoumans, 2014).

71 The global dairy industry is growing at 2.2% per year, worldwide consumption of dairy products
72 is expected to rise by 20% by 2021 (IDF, 2014) and as a response to the 2015 dairy quota
73 removal, the UK is among several EU countries planning to increase the output of dairy products
74 (EC, 2013). To service demand, some EU member states have raised milk production (DairyCo,
75 2014), to supply increasing domestic populations as well develop new markets (EC, 2013;
76 DairyCo, 2014). Dairy industry expansion, could lead to intensification as additional animals
77 brought onto established farms would increase herd sizes and therefore manure volumes
78 resulting in environmental challenges.

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

86 Here we compare P efficiency within novel, intensive and conventional grazing dairy systems
87 across average and improved genetic merits of Holstein Friesian cows by calculating annual farm
88 gate P budgets and applying data envelopment analysis models to test the relative efficiency of
89 the management systems. Nutrient budgets convey farm gate flows and efficacy of P use, whilst
90 the DEA models incorporate further resources such as land requirement and use of nitrogen
91 fertiliser which can characterize the diverse farming systems. We present results generated by

92 multiple application of two types of DEA model, the first of which focuses on the potential
93 polluting aspect of a P surplus by considering residual P as an undesirable output from the milk
94 production system. The second DEA model type reflected the finite nature of P as a resource as
95 well as the potential to pollute by including imported P as an additional non-renewable input
96 variable within the function.

97 **2. Materials and methods**

98 *2.1. Dairy system diets and genetic merit*

99 Production data were obtained from the Langhill herds of Holstein Friesian (HF) dairy cows,
100 based at SRUC's Crichton Royal Farm, Dumfries, Scotland. The cows were part of a long term
101 investigation to assess genetic line \times feeding system interactions (Pollott and Coffey, 2008).

102 Production and management data were extracted from dairy feed system experiments with the
103 herds being comprised of two distinct genetic lines. The Langhill cows are selected for either
104 increased milk fat plus crude protein (CP) yield (Select line), or they are designated to remain
105 close to an annually established average genetic merit for milk fat plus CP yield for Holstein–
106 Friesians in the UK (Control line) (Pryce et al., 1999; Bell et al., 2011).

107 Data was drawn from four distinct feeding system trials maintained between 2007 and 2013.

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

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

120 Insert Table 1 here

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

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

136 *2.2. Data*

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

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

$$153 \text{ ECM} = 0.25 * \text{Mass of Milk} + 12.2 * \text{Fat (kg)} + 7.7 * \text{Protein (kg)} \quad (1)$$

154 2.3. Dairy system phosphate balances

155 A farm gate nutrient balance can be defined as a calculation of system inputs and system outputs,
156 where surplus is a positive difference between the total input and output of each nutrient (Table
157 2). Within dairy production, common inputs include feed stuffs fertiliser, purchased animals and
158 bedding and P outputs leaving the farm are found in milk, animals and manure (Table 2).
159 Measuring nutrient balances, such the farm gate phosphorus surpluses, is widely used to gauge

160 the potential losses of nutrient to the environment. The phosphorous content in each feed product
161 was taken from the database or from the products themselves and if these were not available
162 from the Feeds Directory (Ewing, 2004) or Feedipedia (Feedipedia, 2015).

163 Insert Table 2 here

164 Quantities of P in milk were estimated using a factor of 0.0093 provided by the Dairy Council
165 (2002). Phosphorous contained within the heifers brought onto the farm system and within
166 animals sold was calculated using an equation based on the weight of animals (Nousiainen et al.,
167 2011) (Equation 2):

$$168 \text{ Phosphorous}_{\text{animal}} (\text{kg}) = 0.00067 * \text{Live Weight} (\text{kg}) + 0.055 \quad (2)$$

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

171 Manure production was calculated by determining monthly herd inventory figures for each of the
172 dairy systems and applying liquid and solid manure factors according to milk yield (DairyCo,
173 2010; Nennich et al., 2005). Estimates for amounts of P contained in slurry and farm yard
174 manure (FYM) were derived from standard values (Defra, 2010). P requirements of crops were
175 taken from the Fertiliser Manual and used to calculate the additional P required (Defra, 2010) to
176 sustain the soil at Index 2, a recommended index, and that which is found in Crichton Royal
177 Farm land. All manure was assumed to be exported from the BP herds because no grazing or
178 crop lands were required within this feeding system.

179 *2.4. Data envelopment analysis*

180 To represent each dairy production system at farm level, non-phosphate related variables such as
181 land requirement and nitrogen application were included as inputs within the DEA models. Table
182 3 shows descriptive statistics for non P inputs and outputs common to each system and includes

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

186 Insert Table 3 here

187 Data envelopment analysis (DEA) is a method used to estimate the efficiency of production
188 systems based on the assumption of optimizing behaviour, namely it provides a way of analysing
189 the degree to which producers fail to optimize and the extent of the deviations from technical and
190 economic efficiency (Färe et al., 1994). Pitman (1983) extended the traditional efficiency
191 analysis to account for undesirable outputs (*e.g.*, pollutants associated with agricultural emissions
192 from dairy farms) by estimating efficiency measures that allow for the asymmetric treatment of
193 desirable and undesirable outputs (desirable outputs are strongly disposable as it is always
194 possible to reduce the production of a desirable output without increasing costs; undesirable
195 outputs are weakly disposable as it is not possible to reduce the production of an undesirable
196 output without reducing the production of a desirable output or increasing the use of an input).
197 Since then several DEA modelling approaches have been developed for environmental efficiency
198 measurement (Färe et al., 1996; Piot et al., 1995; Tyteca, 1996; Kuosmanen and Kortelainen,
199 2005; Kortelainen, 2008). Additionally, DEA approaches have been developed for the specific
200 treatment of those inputs which can be viewed as valuable resources (*e.g.* non-renewable
201 resources such as phosphorus) whose uptake can exert a threat on the environment. Some of
202 these modelling approaches consider both non-renewable resource inputs and undesirable
203 outputs (Tyteca, 1996, Korhonen and Luptacik, 2004; Liu et al., 2006; Bian et al., 2010; Bi et al.,
204 2012).

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

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

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

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

212
$$\sum_{k=1}^K z^k w_j^k = T w_j^0, \quad j= 1, \dots, J$$

213
$$\sum_{k=1}^K z^k x_n^k \leq x_n^0, \quad n= 1, \dots, N$$

214
$$z^k \geq 0, \quad k= 1, \dots, K$$

215 Where:

216 $M, J,$ and N are the numbers of desirable outputs, inputs, and undesirable outputs, respectively; K
 217 is the number of observations (producers, time periods, or in our case, dairy systems by year and
 218 treatment); v_m^0, w_j^0, x_n^0 are desirable outputs, undesirable outputs and inputs, respectively. In the
 219 case of observation 0, observation $0 \in \{1, \dots, K\}$ takes values from 1 to K , successively. Variable
 220 T represents the standardized indicator of environmental performance; variable Z is a vector
 221 which denotes the intensity levels at which each of the K observations are conducted, enables
 222 shrinking or expanding individually observed activities for the purpose of constructing
 223 unobserved but feasible activities, and provides weights which facilitate the construction of the
 224 linear segments of the piecewise linear boundary of the technology.

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

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

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

232
$$a_m, b_n \geq 0, \quad c_j \text{ free}$$

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

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

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

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

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

242
$$a_m, b_n \geq 0, c_j \text{ free}$$

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

252 A number of research papers analyse system efficiency using various DEA methods depending
 253 on the way nitrogen use or phosphorus use variables are incorporated in the models (Reinhard et
 254 al., 2000; Ondersteijn et al., 2001; Coelli et al., 2007; Barnes et al, 2009; Picazo-Tadeo, 2011;
 255 Molinos-Senante et al., 2011; Hoang and Alauddin, 2012; Toma et al., 2013) and comparing
 256 different farming systems, in some cases dairy farms (Reinhard et al., 2000; Ondersteijn et al.,
 257 2001; Barnes et al, 2009; Toma et al., 2013). To the best of our knowledge, our paper is the first
 258 to analyse phosphate efficiency of dairy systems using the models detailed above.

259 Ten models were estimated, namely: four undesirable output-orientated (UO) models, (where
 260 undesirable outputs were phosphate surplus), and six input-undesirable output-orientated (IUO)
 261 models, (where undesirable outputs were phosphate surplus and non-renewable resource inputs
 262 were phosphorus in feed, fertiliser, straw bedding and also that contained within the bones and

263 tissues of animals entering the herd). Included in all models were land and nitrogen fertilisers as
264 inputs, and phosphorus in milk, phosphorus in animals sold and phosphorus in manure exported
265 as desirable outputs.

266 In building the relative environmental efficiency measure, we use the DEA endogenous
267 weighting scheme (Farrell, 1957; Charnes et al., 1978; Tyteca, 1996). We estimated the models
268 using the General Algebraic Modeling System (GAMS 22.8). We used DEA to account for
269 temporal aspects, *i.e.*, not only to compare the dairy systems amongst themselves, but to quantify
270 changes in environmental efficiency over time. The models consider each of the systems as
271 divided into a number of independent DMUs, namely four annual observations each for LFC,
272 LFS, HFC and HFS and respectively two annual observations each for BPC, BPS, HGC and
273 HGS. This follows a similar approach used by Färe et al., 1996; Ball et al., 1994 and Toma et al.,
274 2013 and results in a set of 24 DMUs. Thus the best practice production frontier is composed of
275 systems that were efficient in any of the years considered. The analysis allows us to provide a
276 measurement of improvement (or deterioration) in environmental efficiency for each system over
277 time.

278 **3. Results**

279 *3.1. Dairy systems production differences*

280 Across feed systems, mean milk sales were highest from the Select genotype within the
281 continuously housed LF and BP groups, which produced an average of 551,852 kg /system /year
282 and 516,105 kg / system / year respectively. The lowest milk output stemmed from the HGC
283 system which produced 343,753 kg / system / year on average (Table 3). The need for on farm
284 land varied between systems, with the greatest mean land area of 59.4 ha being required by the
285 HG system. Select cows consistently yielded more than the Control line, and within systems,

286 Select cows required slightly more food and hence land because feed intakes were higher. Land,
287 nitrogen fertiliser and home grown feeds were a feature of all feed groups apart from the BP
288 system (Table 3). The BP system imported an average of 641 tons / year of fresh weight
289 purchased feeds and bedding whereas the least imports arose from the HG system which required
290 68.9 tons / year on average. Foodstuff imports for the HG system arose from a shortage of farm
291 grown beans and wheat, however supplements such as minerals and magnesium chloride are
292 required to be imported in all systems. Compared to other management regimes there was little
293 difference between the Select and Control cow yields within the HG diets, which could be due to
294 dietary factors such as the quality of grazed grass or forage within the ration.

295 *3.2. Farm phosphate budgets*

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

305 On average, system P Nutrient Use Efficiency (NUE) (represented by P outputs divided by
306 inputs), was found to be greatest within the BP group (0.49) because all manure was exported
307 from the farm (Table 2). The HF feed group averaged 0.39 NUE and this conventional grazed
308 system was more P effective than an intensive housed LF management regime feeding large

309 amounts of concentrates combined with farm grown forages. Within the feed systems, Control
310 cows generally consumed marginally less feed and exported less milk than Select groups,
311 however there was little difference between each systems' average P NUE.
312 When production of energy corrected milk (ECM) is considered, between all systems, per litre
313 surpluses ranged from 0.002 to 0.005 kg P/ litre. On average a UK conventional HF feeding
314 system generated the lowest average surplus of 0.002 kg \pm 0.0003, whilst the HG feed system
315 attracted the highest average surplus of 0.004 \pm 0.002 kg P per litre of ECM because of a poor
316 establishment year. Within each feeding system, on average, cows of Select genetic merit always
317 generated less surplus P per litre of ECM than cows of an average UK merit.

318 *3.3. Data envelopment analysis*

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

327 Insert Table 4 and Table 5 here

328 *3.3.1. Undesirable output model – potential to pollute*

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

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

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

345 *3.3.2 Input undesirable output model - Pollution potential and finite resource*

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

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

363 **4. Discussion**

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

375 Insert Figure 1 here

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

385 Insert Figure 2 here.

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

395 High P excretion would not be unexpected as a dairy cow could be described as an inefficient
396 consumer of P because these animals can excrete up to 70% of their P intake (Ferris et al., 2010;
397 Nennich et al., 2005) and a direct relationship exists between P intake and P in faeces (Morse et
398 al., 1992; Kebreab et al., 2005). A dairy cow absorbs a varying amount of P depending on her

399 stage of lactation and gestation (NRC, 2001), and endogenous processes further inflate P
400 excretion to faeces (Guegen et al., 1988). In the UK, calls have been made to re-evaluate
401 outdated feeding standards for mineral requirements such as P because the objective of
402 production has shifted to human health and the environmental effects (McDonald et al, 2011).
403 Total mixed rations with ad lib feeding systems formulated to meet major nutrient requirements
404 could over supply minerals to cows with higher intakes.

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

413 The farm gate P balance can be described as a broad indicator of losses to aquatic systems and is
414 equivalent to the OECDs gross balance, with the addition of bedding imports (Amon et al.,
415 2011). A soil phosphate balance may give a more representative indication of environmental
416 losses however the data required necessitates estimations associated with greater uncertainty than
417 the Farm Balances applied here. Nutrient use efficiencies (NUE's) presented here are
418 comparable with estimates reported from similar dairy systems (Gourley et al, 2012; Defra,
419 2011). NUE results ranged from 0.19 to 0.55 (Table 2) and surpluses per hectare ranged from
420 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
421 required crop land in the BP system renders a per hectare unit obsolete and high surpluses per

422 hectare stemming from LF systems would be expected due to no necessity for grazing land.

423 Intensive grazing systems, with lower than UK average yields per cow (circa 5000 litres per
424 annum) tend to attract higher NUE's and a lower P surplus per hectare. NUE means of 0.71 and
425 surpluses of 4.93 kg P/ha were reported from a study of nineteen dairy farms in Southern Ireland
426 adopting grass based low input dairy systems (Mihailescu et al., 2015). A surplus median of 28
427 kg P/ha was found across a range of Australian dairy farming systems (Gourley et al. 2012)
428 which compares with a median surplus of 27 kg P /ha found in this analysis.

429 Calculating nutrient balances and the potential for losses to the environment provides a gauge of
430 farm system efficiency (Jarvis and Arts, 2000; Mihailescu et al, 2015, Thomassen and De Bour
431 2005) and can assist management decisions (Halberg, 1999). Nutrient budgets expressed in this
432 paper provide a range of P efficiencies and surpluses per litre of ECM, depending upon the
433 genetic merit of an animal within a particular dairy feeding system. Generic procedures could be
434 adopted to calculate and compare nutrient losses so as to inform future strategies for nutrient
435 regulation and mitigation. Specific coefficients could be recommended based on current
436 research; various factors of P output within milk can be applied and manure P content may differ
437 between intensive and grazed systems which could influence P surplus calculations. For example
438 milk samples from the BP system were analysed and P content ranged from 850 to 1169 mg/kg
439 (Pers. Comm., Alan Sneddon).

440 Differences in model results presented here outline the importance of emphasis within analytical
441 techniques when considering non-renewable resources such as phosphorus. P budgets highlight
442 the potential for efficiency gains, attained by manure recycling within localized protein crop
443 growing regimes, or by exportation to other agricultural systems within an economically feasible
444 range. These results could support efficiency approaches incorporating more cyclical nutrient

445 management, which can reuse, and recycle P, within livestock systems (EC, 2014; Buckwell et
446 al., 2014). The results may also assist those appealing for an increased understanding of mutually
447 beneficial adaptation techniques that improve environmental performance in a practical,
448 economically viable manner (Ulrich & Frossard, 2014).

449 Whilst the EU Nitrates and Water Framework Directives (EC, 1991; EC 2000) indirectly
450 regulate agricultural P applications to soils, and even though national and regional legislation is
451 implemented across member states, these are not legally binding. Countries such as Denmark,
452 Ireland and the Netherlands have implemented restrictions on P application, depending on
453 variables such as soil type and crop requirements, whereas farmers in England or Hungary have
454 no additional restrictions (Amery and Schoumans, 2014). Close attention to appropriate
455 livestock nutrient requirements alongside on farm soil P status and combined with mitigation
456 methods such as buffer zones may bring about improvements in surface water quality (Schindler,
457 2012).

458 Ulrich and Frossard (2014), argue that persistent debate regarding resource scarcity should shift
459 towards a comprehensive understanding of the environmental and economic consequences of
460 prolonged utilization of P. Calls to improve unsustainable food production methods (Foresight,
461 2011) have furthered a discussion of the environmental benefits of high input (Ross et al., 2014)
462 and low input dairy systems (O'Brien et al., 2012; Casey and Holden, 2005). Results expressed
463 here show that when one pollutant is considered, model emphasis alters perceived system
464 efficiency. Depending on the focus of sustainability, whether it be phosphorus, nitrogen,
465 greenhouse gases, or ammonia emissions, intrinsic qualities and weaknesses seem apparent
466 within dairy management regimes. National dairy farming regimes are likely to be a function of
467 history, demand, culture and regional climate.

468 Working towards closed loop farming systems is a feature of organic (Steinshamn et al., 2004)
469 and biodynamic dairying, and techniques to reuse P can be developed using model budgets. A
470 combination of HG and BP systems may have the ability to generate a dual production regime in
471 which P is recycled from a confined system feeding by-products (inedible to humans) with
472 negligible land requirement, to a regime feeding a selection of farm grown protein crops to
473 complement grazing. Manure P exported from a BP system could be utilized within an HF, HG
474 or other low input system, thus reducing the need for imported fertiliser, manure exportation and
475 employing a system that is not solely reliant on either purchased feeds or local weather.
476 Of all the essential dietary minerals required by dairy cows, an excess of P poses the greatest risk
477 to the environment (NRC, 2001). Planned dairy sector development across the EU leading to
478 increases in milk production, could propel trends towards larger herd sizes (DairyCo, 2014) as
479 well as modifications in feeding practices. Crops grown in the UK are dependent on imported
480 phosphorus, amounting to 138 kilo tonnes in 2009 (Cooper and Carliell-Marquet, 2013) and it's
481 estimated that up to 80% of extracted rock P is potentially lost from mine to food to fork
482 (Childers et al, 2011).
483 Understanding and improving resource use efficiency whilst minimizing undesirable outputs are
484 crucial steps to achieving more sustainable milk production. Further research comparing the
485 merits of alternate farming systems, taking into consideration resources such as water, and
486 pollutants such as greenhouse gas emissions, would benefit the overall understanding of the
487 merits of each management regime.

488 **5. Conclusion**

489 The purpose of this paper was to evaluate and compare phosphorus efficiency within novel,
490 intensive and conventional dairy systems across two genetic merits of Holstein Friesian cows by

491 application nutrient budget calculations and dual DEA model types. Undesirable output
492 orientated models showed that, on average, cows selected for improved production within a By-
493 product system exporting all manure attracted the highest NUE's and DEA efficiency scores.
494 However, a low concentrate input grazing system generated the lowest per litre P surplus and
495 efficiency scores were higher than confined feeding systems that did not export manure. Input
496 undesirable output orientated models did not always favour the Select improved genotype and
497 the lower input Home-grown and High Forage feed systems were most efficient. Nutrient budget
498 estimates of dual systems highlighted possibilities to reuse and recycle P. Results presented here
499 raise questions regarding suitable pathways to be taken by policymakers, industry stakeholders
500 and farmers to achieve optimal use of phosphorus with minimal surplus to the environment.

501

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507 [research-strategy/Themes/ThemesIntro](http://www.scotland.gov.uk/Topics/Research/About/EBAR/StrategicResearch/future-research-strategy/Themes/ThemesIntro)

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510

511 **References**

512 Amery, F., Schoumans, O.F., 2014. Agricultural phosphorus legislation in Europe. Merelbeke,
513 ILVO, pp45.

514 http://www.ilvo.vlaanderen.be/Portals/68/documents/Mediatheek/Phosphorus_legislation_Europ
515 [e.pdf](#).

516 Amon, B., Hutchings, N., Vinther, F., Nielsen, P., Poulsen, H., Kristensen, S., Pietrzak, S., 2011.
517 Analysis of methodologies for calculating greenhouse gas and ammonia emissions and nutrient
518 balances. European Commission, Brussels. [http://ec.europa.eu/eurostat/en/web/products-](http://ec.europa.eu/eurostat/en/web/products-statistical-working-papers/-/KS-RA-11-024)
519 [statistical-working-papers/-/KS-RA-11-024](http://ec.europa.eu/eurostat/en/web/products-statistical-working-papers/-/KS-RA-11-024)

520 Ball, V. E., Lovell, C. A. K., Nehring, R.F., Somwaru, A., 1994. Incorporating undesirable
521 outputs into models of production: An application to U.S. agriculture. *Cahiers D'economie et*
522 *Sociologie Rurales* 31, 59–74.

523 Barnes, A.P., Moran, D., Topp, K., 2009. The scope for regulatory incentives to encourage
524 increased efficiency of input use by farmers. *J. Environ. Manage.* 90, 808-814.

525 Bell, M.J., Wall, E., Simm, G., Russell, G., 2011. Effects of genetic line and feeding system on
526 methane emissions from dairy systems. *Anim. Feed Sci. Tech.* 94, 3662-3678.

527 Bi, G., Luo, Y., Ding, J., Liang, L., 2012. Environmental performance analysis of Chinese
528 industry from a slacks-based perspective. *Ann. Oper. Res.*

529 Bian, Y., Yang, F., Resource and environment efficiency analysis of provinces in China: A DEA
530 approach based on Shannon's entropy. *Energy Policy* 38, 1909–1917.

531 Brandt, van den H.M.P., Smit, H.P., 1998. Mineral accounting: the way to combat eutrophication
532 and to achieve the drinking water objective. *Environ. Pollut.* 102, 705-709.

533 Buckwell, A., Nordang Uhre, A., Williams, A., Polakova, J., Blum, W.E.H., Schiefer, J., Lair,
534 G., Heissenhuber, A., Schiebl, P., Kramer, C., Haber, W., 2014. The sustainable intensification
535 of European agriculture. Brussels: RISE Foundation.

536 Casey, J.W., Holden, N.M., 2005. Analysis of greenhouse gas emissions from the average Irish
537 milk production system. *Agric. Syst.* 86, 97–114.

538 Chagunda, M.G.G., Römer, D.A.M., Roberts, D.J., 2009. Effect of genotype and feeding regime
539 on enteric methane, non-milk nitrogen and performance of dairy cows during the winter feeding
540 period. *Livest. Sci.* 122, 323–332.

541 Charnes, A., Cooper, W.W., Rhodes, E., 1978. Measuring the efficiency of decision-making
542 units. *Eur. J. Oper. Res.* 2, 429–444.

543 Childers, D., Corman, J., Edwards, M., Elser, J., 2011. Sustainability challenges of phosphorus
544 and food: solutions from closing the human phosphorus cycle. *BioScience* 61, 117–124.

545 Coelli, T., Lauwers, L., Van Huylenbroeck, G., 2007. Environmental efficiency measurement
546 and the materials balance condition. *J. Prod. Anal.* 28, 3–12.

547 Cooper, J., Carliell-Marquet, C., 2013. A substance flow analysis of phosphorus in the UK food
548 production and consumption system. *Resources, Conservation and Recycling.* 74, 82-100.

549 Cordell, D., 2010. The story of phosphorus: sustainability implications of global phosphorus
550 scarcity for food security, No. 509, I, ed. Doctoral Thesis. Linköping University Press,
551 Linköping.

552 Cuttle, S.P., MacLeod, C.J.A., Chadwick, D.R., Scholefield, D., Haygarth, P.M., Newell Price,
553 J.P., Harris, D., Shepherd, M.A., Chambers, B.J., Humphrey, R., 2007. An inventory of methods
554 to control diffuse water pollution from agriculture (DWPA): user manual. Final report for Defra
555 project ES0203.

556 DairyCo, 2010. Cost effective slurry storage facilities on dairy farms. Agriculture and
557 Horticulture Development Board, Warwickshire, UK. <http://dairy.ahdb.org.uk/resources->

558 library/technical-information/health-welfare/cost-effective-slurry-storage-
559 strategies/#.VmBT0U3Fbcs

560 DairyCo, 2014. Market information: Dairy Market Update 20th March.
561 [http://dairy.ahdb.org.uk/resources-library/market-information/dairy-market-
562 update/#.V19PUU3Fbcs](http://dairy.ahdb.org.uk/resources-library/market-information/dairy-market-
562 update/#.V19PUU3Fbcs)

563 Dairy Council, 2002. The nutritional composition of dairy products, The Dairy Council, 210
564 High Holborn, London, UK.
565 <http://www.milk.co.uk/resources/resource.aspx?intResourceID=55>

566 Defra, 2010. The Fertiliser Manual RB209. Department for Environment, Food and Rural
567 Affairs, Norwich, UK.

568 Defra, 2011. An inventory of mitigation methods and guide to their effects on diffuse water
569 pollution, greenhouse gas emissions and ammonia emissions from agriculture, Defra Project
570 WQ0106. Department for Environment, Food and Rural Affairs, UK

571 EC, 1991. Directive 91/676/EEC concerning the protection of waters against pollution caused by
572 nitrates from agricultural sources. Off. J. Eur. Union L 375, 1–8.

573 EC, 2000. Directive 2000/60/EC establishing a framework for community action in the field of
574 water policy. Official Journal of the European Union L 327, 1–73.

575 EC, 2013. Report of the conference The EU dairy sector: developing beyond 2015. European
576 Commission, Brussels.
577 http://ec.europa.eu/agriculture/events/2013/milkconference/report_en.pdf

578 EC, 2014. Report on critical raw materials for the EU. European Commission, Brussels.
579 http://ec.europa.eu/enterprise/policies/rawmaterials/documents/index_en.htm

580 Ewing, W.N., 2004. The Feeds Directory, Context Publications. Leicestershire, UK.

581 Färe, R. 1992. Productivity gauging with undesirable outputs. Mimeo. Southern Illinois
582 University, Carbondale.

583 Färe, R., Grosskopf, S., Lovell., C.A.K., 1994. Production Frontiers. Cambridge University
584 Press, Cambridge, UK.

585 Färe, R., Grosskopf, S., Tyteca. D., 1996. An activity analysis model of the environmental
586 performance of firms application to fossil fuel-fired electric utilities. *Ecol. Econ.* 18, 161–175.

587 Farrell, M. J., 1957. The measurement of productive efficiency. *J. R. Stat. Soc.* 120, 253–290.

588 Feedipedia, 2015. Animal feed resources information system, INRA, CIRAD, AFZ and FAO.
589 <http://www.feedipedia.org/>

590 Ferris, C.P., McCoy, M.A., Patterson, D.C., Kilpatrick, D.J., 2010. Effect of offering dairy cows
591 diets differing in phosphorus concentration over four successive lactations: 2. Health, fertility,
592 bone phosphorus reserves and nutrient utilisation. *Animal*, 4, 560–571

593 Foresight. 2011. The future of food and farming. Final project report. The Government Office for
594 Science, London, UK. <https://www.gov.uk/.../11-546-future-of-food-and-farming-report.pdf>

595 Gourley, C.J.P., Dougherty, W., Weaver, D.M., Aarons, S.R., Awty, I.M., Gibson, D.M.,
596 Hannah, M.C., Smith, A.P., Peverill, K.I., 2012. Farm-scale nitrogen, phosphorus, potassium and
597 sulphur balances and use efficiencies on Australian dairy farms. *Anim. Prod. Sci.* 52, 929–944.

598 Gueguen, L., M. Lamand, Meschy, F., 1989. Mineral requirements. in ruminant nutrition:
599 Recommended allowances and feed tables, R. Jarrige, ed. Institut National de la Recherche
600 Agronomique. pp.49 -56.

601 Halberg, N., 1999. Indicators of resource use and environmental impact for use in a decision aid
602 for Danish livestock farmers *Agric. Ecosyst. Environ. Ethics* 8, 30-51.

603 IDF, 2014. Factsheet: The economic importance of dairying, International Dairy Federation,
604 Diamant Building, Boulevard Auguste Reyers, 80 - 1030 Brussels. [http://www.fil-](http://www.fil-idf.org/Public/LinksPage.php?ID=40415)
605 [idf.org/Public/LinksPage.php?ID=40415](http://www.fil-idf.org/Public/LinksPage.php?ID=40415)

606 Hoang, V-N., Alauddin, M., 2012. Input-orientated data envelopment analysis framework for
607 measuring and decomposing economic, environmental and ecological efficiency: an application
608 to OECD agriculture. *Environ. Resour Econ.* 51, 431–452.

609 Jarvis, S.C., Aarts., H.F.M., 2000. Nutrient management from a farming system perspective.
610 *Grassl. Sci. Eur.* 5, 363–373.

611 Jasinski S.M., 2014. Phosphate rock mineral commodity summaries. U.S. geological survey.
612 [www.http://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/mcs-2014-phosp.pdf](http://www.minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/mcs-2014-phosp.pdf)

613 Kebreab, E., Shah, M.A., Beever, D.E., Humphries, D.J., Sutton, J.D., France, J., Mueller-
614 Harvey, J., 2005. Effects of contrasting forage diets on phosphorus utilisation in lactating dairy
615 cows. *Livest. Prod. Sci.*, 93, 125–135

616 Korhonen, P.J., Luptacik, M., 2004. Eco-efficiency analysis of power plants: An extension of
617 data envelopment analysis. *European J. Oper. Res.* 154, 437–446.

618 Kortelainen, M. 2008. Dynamic environmental performance analysis: A Malmquist index
619 approach. *Ecol. Econ.* 64, 701–715.

620 Kristensen, P., 2012. European waters: Assessment of status and pressures. Luxembourg:
621 Publications Office of the European Union.

622 Kuosmanen, T., Kortelainen, M., 2005. Measuring eco-efficiency of production with data
623 envelopment analysis. *J. Ind. Ecol.* 9, 59–72.

624 Liu, W., Sharp, J., Wu, Z., 2006. Preference, production and performance in data envelopment
625 analysis. *Annals of Operations Research* 145, 105–127.

626 McDonald, P., Edwards, R.A., Greenhalgh, J.F.D., Morgan, C.A., Sinclair, L.A., Wilkinson,
627 R.G., 2011. McDonald, P., (Ed.), *Animal Nutrition* (7th ed.), Prentice Hall/Pearson, Harlow,
628 England pp. 377.

629 Mihailescu, E., Ryan, W., Murphy, P.N.C., Casey, I.A., Humphreys, J., 2015. Economic impacts
630 of nitrogen and phosphorus use efficiency on nineteen intensive grass-based dairy farms in the
631 South of Ireland. *J. Agric. Sys.* 132, 121-132.

632 Molinos-Senante, M., Hernandez-Sancho, F., Sala-Garrido, R., Garrido-Baserba, M., 2011.
633 Economic feasibility study for phosphorus recovery processes. *AMBIO* 40, 408–416.

634 Morse, D., Head, H., Wilcox, C., Horn, H. V., Hissem, C., Jr., B. H., 1992. Effects of
635 concentration of dietary phosphorus on amount and route of excretion. *J. Dairy Sci.* 75, 3039–
636 3049.

637 Nennich, T.D., Harrison, J.H., Van Wieringen, L.M., Meyer, D., Heinrichs, A.J., Weiss, W.P.,
638 St-Pierre, N.R., Kincaid, R.L.,
639 Davidson, D.L., Block, E., 2005. Prediction of manure and nutrient excretion from dairy cattle. *J.*
640 *Dairy Sci.* 88, 3721–3733.

641 Nousiainen, J., Tuori, M., Turtol, E., Huhtanen, P., 2011. Dairy farm nutrient management model
642 1. Model description and validation. *Agricultural Systems* 104, 371-382.

643 NRC (National Research Council), 2001. *Nutrient requirements of dairy cattle*, National
644 Academy Press, Constitution Avenue, Washington, D.C. 20418.

645 O'Brien, D., Shalloo, L., Patton, F., Buckley, M., Grainger, C., Wallace, M., 2012. A life cycle
646 assessment of seasonal grass-based and confinement dairy farms. *Agricultural Systems* 107, 33-
647 46.

648 Ondersteijn, C.J.M., Oude Lansink, A.G.J.M., Giesen, G.W.J., Huirne R.B.M., 2001. Improving
649 nutrient efficiency as a strategy to reduce nutrient surpluses on dairy farms. *The Scientific World*
650 1, 866–872.

651 Picazo-Tadeo, A.J., Gómez-Limón, J.A., Reig-Martínez, E., 2011. Assessing farming eco-
652 efficiency: A data envelopment analysis approach. *J. Environ. Manage.* 92, 1154-1164.

653 Pitman, R., 1983. Multilateral productivity comparisons with undesirable inputs. *Econ. J.* 93,
654 883–891.

655 Piot-Lepetit, I., D. Vermersch, and R. D. Weaver. 1995. Agriculture's environmental
656 externalities: DEA evidence for French agriculture. *Appl. Econ.* 29, 331–338.

657 Pollott, G.E., Coffey., M.P., 2008. The effect of genetic merit and production system on dairy
658 cow fertility, measured using progesterone profiles and on-farm recording. *J. Dairy Sci.* 91,
659 3649-3660.

660 Pryce J.E., Nielsen, B.L., Veerkamp, R.F., Simm, G., 1999. Genotype and feeding system effects
661 and interactions for health and fertility traits in dairy cattle. *Livest. Prod. Sci.* 57, 193-201.

662 Reinhard, S., Knox Lovell, C.A., Thijssen, G.J., 2000. Environmental efficiency with multiple
663 environmentally detrimental variables; estimated with SFA and DEA. *Eu. J. Oper. Res.* 121,
664 287-303

665 Ross, S.A., Chagunda, M.G.G., Topp, C.F.E., & Ennos, R., 2014. Effect of cattle genotype and
666 feeding regime on greenhouse gas emissions intensity in high producing dairy cows. *Livest. Sci.*
667 170, 158—171.

668 Schindler, D., 2012. The dilemma of controlling cultural eutrophication of lakes. *Proc. R. Biol.*
669 *Soc.* 279, 4322–4334.

670 Sjaunja, L.O., Baevre, L., Junkkarinene, L., Pedersen, J., Setala, J., 1990. A Nordic proposal for
671 an energy corrected milk formula. 27th Session of the International Commission for Breeding and
672 Productivity of Milk Animals, Paris, France.

673 Smit, A.L., Bindraban, P., Schroder, J.J., Conijn, J.G., Meer, H.G. van der., 2009. Phosphorus in
674 agriculture: global resources, trends and developments. Plant Res. Int. (Report 282), 36 pp.

675 Steen, I., 1998. Phosphorus availability in the 21st Century: management of a non-renewable
676 resource. Phosphorus and Potassium 217, 25–31.

677 Steinshamn, H., Thuen, E., Azzaroli M., Bleken Brenøe, U.T., Ekerholt, G., Yri, C., 2004.
678 Utilization of nitrogen (N) or phosphorus (P) in an organic dairy farming system in Norway.
679 Agric. Ecosyst. Environ. 104, 509–522.

680 Thomassen, M.A., de Boer, I.J.M., 2005. Evaluation of indicators to assess the environmental
681 impact of dairy production systems. Agric. Ecosyst. Environ. 111, 185–199.

682 Toma, L., March, M., Stott, A.W., Roberts, D., 2013. Environmental efficiency of alternative
683 dairy systems: A productive efficiency approach. J. Dairy Sci. 96, 7014–7031.

684 Tyteca, D., 1996. On the measurement of the environmental performance of firms - A literature
685 review and a productive efficiency perspective. J. Environ. Manage. 46, 281-308.

686 Ulrich A.E., Frossard, E., 2014. On the history of a reoccurring concept: phosphorus scarcity.
687 Sci. Total Environ. 490, 694–707.

688 U.S. Geological Survey, 2011, Mineral commodity summaries 2014: U.S. Geological Survey,
689 pp118. http://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/mcs-2011-phosp.pdf
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693 **Table 1** Constituents and dry matter proportions of rations with P contents

Diet	Foodstuff	DM Diet Proportion ^c	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
<hr/>					
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

694 ^a Ewing
695 ^b Feedipedia
696 ^c Product data
697 ^d SRUC database
698 ^eDM = dry Matter

699 **Table 2** Descriptive statistics of farm gate phosphorus (P) balances for each milk production systems^{ab} (mean and standard deviation)

Variable	LFC		LFS		HFC		HFS		BPC		BPS		HGC		HGS	
	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

700 ^a Genotype: C = Control, S = Select;

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

702 ^c SD=standard deviation

703 ^d NUE=Nutrient use efficiency

704 **Table 3** Descriptive statistics of system^{a,b} variables applied as inputs within DEA models (mean and standard deviation)

Variable	LFC		LFS		HFC		HFS		BPC		BPS		HGC		HGS	
	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

705 ^a Genotype: C = Control, S = Select;

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

707 ^c SD=standard deviation

708 ^d ECM=energy corrected milk

709 **Table 4** Dairy system^{ab} efficiency scores for undesirable output
 710 (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

711 ^a Genotype: C = Control, S = Select;

712 ^b Feed system: HF= High forage, LF = Low forage, BP = By-
 713 product, HG = Home grown.

714 **Table 5** Dairy system^{ab} efficiency scores for input undesirable
 715 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

716 ^a Genotype: C = Control, S = Select;

717 ^b Feed system: HF= High forage, LF = Low forage, BP = By-
 718 product, HG = Home grown.

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