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Title: Assessment of phosphorus use efficiency on Great Britain dairy farms to identify barriers to, and facilitators for, reducing phosphorus losses in diverse dairy farming systems

Reducing phosphorus loss from diverse dairy farming systems

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CONTENTS

1. Industry Summary

Improving phosphorus (P) management on dairy farms provides financial savings for farmers, whilst also mitigating their environmental impact and is therefore important in improving the sustainability of dairy farming. However, improving P management in Great Britain (GB) dairy farming requires system-specific information on P management because GB operates a diverse dairy farming system, but such information is limited. Therefore, this project aimed to: investigate current P feeding practices, determine P balance and P use efficiency (PUE) and simulate least-cost suites of methods to mitigate environmental P loading across a range of GB dairy farming systems.

- Firstly, surveys of 139 dairy farmers and 31 feed advisers were conducted to investigate current P feeding practices and identify barriers to, and motivators for minimising P feeding in a diverse dairy farming system. Findings indicated that minimising P feeding is required in GB dairy farming to reduce the concentration of P in dairy manure, which will minimise risk of P being applied beyond crops' requirement. Additionally, the survey recommended that strategies to minimise P feeding would benefit from being system-specific.

- Secondly, the farm-gate and soil-surface P balance and PUE were determined for 30 dairy farms representing a range of GB dairy farming systems. Findings indicated that large mean P surpluses on a farm-gate (10.2 kg/ha) and a soil-surface (7.51 kg/ha) level and consequently large soil P reserves occurred across all systems. However, the housed system had higher P surplus per hectare and lower PUE compared to pasture-based systems, primarily because of greater import of concentrate feed.

- Thirdly, FARMSCOPER was used to simulate environmental P loading and optimise a suite of least-cost methods to mitigate environmental P loading from a model farm representative of a housed and pasture-based system (using data from 7 and 20 dairy farms, respectively). Findings indicated that greater environmental P loading was simulated from the housed system than the pasture-based system. Additionally, mitigating environmental P loading showed financial savings for both systems, but particularly in the housed system.

In conclusion, the current project highlighted strategies to improve P management in diverse GB dairy farming systems would benefit from a more system-specific approach. Additionally, the current project recommends a number of system-specific strategies to minimise P feeding, reduce P surplus and improve PUE and to cost-effectively mitigate environmental P loading. Such strategies could be implemented by dairy farmers, recommended to farmers by farm advisory services and considered by policy-makers in future policies.

2. Introduction

Phosphorus surplus on a dairy farm indicates the long-term risk of P accumulating in soil and subsequently being lost to waterbodies to accelerate eutrophication (Mihailescu *et al.*, 2015). The process of eutrophication degrades water quality and reduces aquatic biodiversity, annually costing the UK an estimated minimum of £229 million (Moxey, 2012). Phosphorus lost from agricultural land that has been applied in excess of the crops' ability to uptake P from the soil, is a major source of eutrophication in waterbodies (Adenuga *et al.*, 2018). Therefore, reducing P surplus and subsequently improving P use efficiency (PUE) in dairy farming is important to improve the sustainability of dairy farming in regard to P use. Furthermore, on a farm-level improved PUE can provide a financial saving to farmers by more precisely purchasing feed and mineral fertiliser (Mihailescu *et al.*, 2015). On a national scale, improved PUE in dairy farming could strengthen national food security and reduce dairy farmers' vulnerability to trade prices for many countries where food demand is dependent on the import of mineral fertiliser P to sustain crop yields (March *et al.*, 2016). On a global scale, improved PUE in dairy farming contributes towards slowing the depletion of limited global P reserves (Cordell *et al.*, 2011).

The PUE of a dairy farm is widely assessed by farmers, policy-makers and scientists by calculating farm-gate P balance (FPB) and soil-surface P balance (SPB) (Oenema *et al.*, 2003, Thomas *et al.*, 2020). Dairy farmers are required to calculate a P balance as a license to produce milk in some states in the US (Knowlton and Ray, 2013), in the Netherlands (Aarts *et al.*, 2015) and Northern Ireland when farmers request a N derogation (Northern Ireland Environment Agency, 2019). However, GB along with other European countries have no specific P legislation despite having large soil P reserves (Amery and Schoumans, 2014). Therefore, recommended strategies to improve PUE of dairy farms are largely based on research from countries where housed (Cela *et al.*, 2014) or pasture-based dairy farming systems are predominant (Gourley and Weaver, 2012, Mihailescu *et al.*, 2015) and the Netherlands where unique regulations such as phosphate rights and reduced P concentration in feeds are in place (The Netherlands Environmental Assessment Agency, 2016). However, GB has a wide assortment of dairy farming systems characterised by diverse calving patterns and varying amounts of concentrate feeding and grazing days (Garnsworthy *et al.*, 2019). Housed and pasture-based dairy farming systems contribute to eutrophication differently from one another (O'Brien *et al.*, 2012, Akert *et al.*, 2020) and the feasibility of implementing practices can differ between dairy farming systems (March *et al.*, 2014). Therefore, current strategies to improve PUE in dairy farming may not be appropriate for countries operating diverse dairy farming systems.

There is limited information on the P feeding practices (Sinclair and Atkins, 2015), P balance and PUE (Raison *et al.*, 2006, Withers and Foy, 2006) and environmental P loading (Zhang *et al.*, 2012, Lynch *et al.*, 2018, Micha *et al.*, 2018) of modern GB dairy farming. Furthermore, none of the above considered the wide range of dairy farming systems that operate in GB. However, such information is critical in minimising P feeding, reducing P surpluses, improving PUE and mitigating environmental P loading of dairy farming in countries operative diverse dairy farming systems. Therefore, there is a need for information on the P feeding practices, P balance and PUE and environmental P loading in a range of dairy farming systems in order to develop strategies to improve the sustainability of dairy farming in countries operating diverse dairy farming systems.

2.1. Aims and Objectives

1. Phosphorus feeding practices, barriers to and motivators for minimising phosphorus feeding in diverse dairy farming systems

    i. to assess the current P feeding practices used in diverse dairy farming systems.

    ii. to identify barriers to and motivators for minimising P feeding in diverse dairy farming systems.

2. Determinants of phosphorus balance and use efficiency in diverse dairy farming systems

    i. to determine FPB, SPB and PUE in diverse dairy farming systems.

    ii. to identify the key determinants of FPB, SPB and PUE in diverse dairy farming systems.

3. Assessing the environmental phosphorus loading from, and identifying least-cost suites of mitigations methods for, a pasture-based and housed dairy farming system (Chapter 5)

    i. Quantify EPL from dairy farms using FARMSCOPER specific input data collected directly from dairy farmers using a tailored approach

    ii. Compare EPL data simulated from FARMSCOPER for housed and pasture-based dairy farming systems

    iii. Identify a least-cost suite of mitigation methods to reduce EPL from both housed and pasture-based dairy farming systems

3. Objective 1

3.1. Materials and methods

3.1.1. Questionnaire survey: Great Britain dairy farmers

A list of 6780 anonymised dairy farms was obtained from the Agriculture and Horticulture Development Board (AHDB), the dairy farmer levy body in GB, and farms were grouped by herd size and region. Two-thousand dairy farms were then randomly selected using a stratified sampling approach and sent a copy of the survey by post in 2019. Additionally, an online version of the same anonymous survey was created using Qualtrics (https://www.qualtrics.com) and a link was distributed by relevant stakeholders (AHDB Dairy, British Grassland Society, Scottish Dairy Hub, Soil Association, Society of Feed Technologists, Feed Adviser Register and Agricology). The questionnaire consisted of 42 questions (10 open-ended and 32 closed), with multiple choices when applicable (Supplementary Table S1). Questions were developed from the literature and using contributions from relevant experts.

The questionnaire collected information on farm management practices including precision P feeding practices and farmers' attitudes towards feeding lower dietary P concentrations to dairy cows. Farms were categorized into GB region (England, Scotland and Wales), whether or not they relied on a feed professional (nutritionist, feed supplier or veterinary) and farm classification (Supplementary table 7.2). The five farm classifications are based on calving pattern, days of access to grazing and concentrate supplementation (Garnsworthy *et al.*, 2019). Classification 1 farms adopt spring calving and graze > 274 days a year with limited supplements. Classification 2, 3 and 4 farms adopt block or all year calving with increasing use of concentrate supplement as grazing days reduce. Classification 5 farms adopt all year round calving in a housed-system with the greatest supplement use fed as a total mix ration (TMR). The questionnaire was piloted on 5 dairy farms and revised prior to distribution.

3.1.2. Questionnaire survey: Feed advisers to Great Britain dairy farms

A questionnaire survey of dairy feed advisers was adapted from the farmer questionnaire. The feed adviser questionnaire was created on Qualtrics (https://www.qualtrics.com) with the anonymous link distributed by the same stakeholders used for the farmer survey. Paper copies were also distributed to relevant alumni of Harper Adams University and attendees of the Annual General Meet of the Society of Feed Technologists, 2019. Advisers were instructed to use one client farm when reporting practices throughout the survey.

3.1.3. Statistical analysis

The data from two questionnaire surveys were statistically analysed independent from one another. Not all respondents answered every question; therefore, the percentage of responses was calculated using the number of responses to the questions not the number of survey respondents. The dietary P concentration reported by the respondents was compared against recommended levels advised by the NRC (2001) using DM intake predictions (Kebreab *et al.*, 2013) based on the annual milk yield stated by respondents.

For each survey, ANOVA and mean separation by Tukey's test was carried out using Minitab (Version 2019) to investigate the effect of 'farm classification', 'region', and 'feed professional advice' on 'herd size', 'annual milk yield' and 'annual concentrate fed'. Chi-square tests were used to investigate associations between farm characteristics and whether or not respondents reported being aware of P pollution issues and implemented P feeding and management practices. A binary logistic regression model was used to evaluate the relationship between 'herd size' and whether or not respondents reported being aware of P pollution issues and implemented P feeding and management practices.

3.2. Results

3.2.1. Herd demographics

A total of 139 responses (126 postal and 13 online) were returned from the farmer survey with a mean herd size of 257 (range: 7 to 2500 cows). Housed systems (classification 5) managed larger herds than pasture-based systems feeding some concentrate supplements (classifications 2 and 3; Table 3.1). The mean annual milk yield of participating farms was 7956 kg/cow, with housed systems managing higher producing cows than pasture-based systems (Table 3.1). The mean annual amount of concentrate fed was 2036 kg/cow. Pasture-based systems that relied most on grazing (classification 1) fed the least amount of concentrate and housed systems feeding TMR (classification 5) fed more concentrate than pasture-based systems (classifications 1, 2 and 3; Table 3.1). Farms that used advice from feed advisers fed more concentrate to their cows and had greater milk yield compared to farms that did not have a feed professional (Table 3.1).

Table 3.1 Differences in the mean herd size, annual milk yield and the amount of concentrate fed to dairy cows between dairy farms from different regions, dairy classifications and with or without feed professional presence

Category	Sub Category	Respondents	Herd size (cow number)	Annual milk yield (kg/cow)	Concentrate fed (kg/cow/year)
Region					
	England	80/139	271	7630^{A}	1996
	Scotland	39/139	254	8866^{B}	2190
	Wales	20	205	7560^{AB}	1898
			(330)	(2051)	(1184)
Classification[1]					
	1	21/139	393^{AB}	5662^{C}	1003^{C}
	2	55/139	182^{BC}	7479^{B}	1752^{B}
	3	41/139	153^{C}	8159^{B}	2245^{B}
	4	4/139	363^{ABC}	10888^{A}	2943^{AB}
	5	18/139	539^{A}	10831^{A}	3466^{A}
			(303)	(1512)	(963)
Feed professional					
	Yes	96/138	248	8396^{A}	2235^{A}
	No	42/138	260	6849^{B}	1562^{B}
			(331)	(1971)	(1143)
			P values		
Region			$P > 0.005$	$P < 0.001$	$P > 0.005$
Classification			$P < 0.001$	$P < 0.001$	$P < 0.001$
Feed professional			$P > 0.005$	$P < 0.001$	$P < 0.01$

[1]Dairy farm classification based on calving and feeding approach (Garnsworthy *et al.*, 2019), Values in parenthesis indicate pooled standard deviations, $^{A\text{-}C}$ In a column, means within a category not sharing same superscripts differ ($P < 0.05$)

3.2.2. Farmers' knowledge of the phosphorus concentration in lactating cows' diet

More than two-thirds of farmers were unaware of the dietary P concentration in their lactating cows' diet (Table 3.2). A third of farmers who stated that they knew the dietary P concentration, offered diets with an estimated concentration greater than recommended by the NRC (2001), but a smaller proportion offered diets in excess of what the Agricultural and Food Research Council (AFRC, 1991) recommend (Figure 3.1). Two-thirds (62/93 [67%]) of farmers that did not know the dietary P concentration relied on a feed professional but the remainder presumably formulated diets with no knowledge of its P concentration. Only a small proportion of farmers stated that they formulated diets to a recognised P feeding recommendation, and these farmers either followed the NRC (2001) recommendations (10/25 [40%]) or the AFRC (1991) recommendations (6/25 [24%]) with the remainder following various unrecognised recommendations.

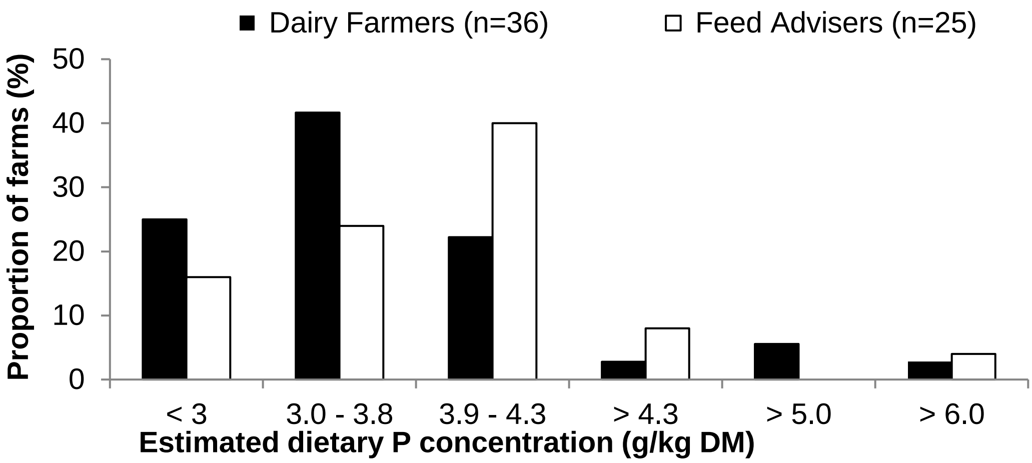

Figure 3.1 Dietary phosphorus (P) concentrations (g/kg DM) estimated by dairy farmers and feed advisers in Great Britain. Recommended average P concentration in dairy cow diet: 3.5 g/kg DM (NRC, 2001) or 4.1 g/kg DM (AFRC, 1991), based on a cow annually producing 7956 kg milk (average for participating farmers in this study).

3.2.3. Precision phosphorus feeding and management practices used by dairy farmers

Three-quarters of farmers fed a single diet to their entire milking herd (Table 3.2), primarily because it was an easier feeding strategy to adopt (45/98 [46%]). Just over a third of all farmers stated that they used forage P test results when formulating diets (Table 3.2). Many farmers included inorganic P supplements in lactating cow diets (Table 3.2) but almost two-thirds of farmers gave no consideration to P concentration when purchasing feed ingredients (Table 3.2). Manure was not analysed for P by two thirds of farmers (Table 3.2). Almost three quarters of farmers stated that sufficient training on P management was not available to them (Table 3.2).

Table 3.2 Responses of Great Britain dairy farmers (n = 139) and feed advisers (n = 31) involved in a survey of phosphorus (P) feeding and management practices and attitudes towards P feeding.

Characteristics	No. of Farmers (%)	No. of Advisers (%)
Aware of dietary P concentration		
Yes	36/129 (28)	25/30 (83)
No	93/129 (72)	5/30 (17)
Blanks	10	1
Feed P in excess of recommendations[1]		
Yes	12/36 (33)	13/25 (52)
No	24/36 (67)	12/25 (48)
Blanks	103	6
Use a feed professional		
Yes	96/138 (70)	NA
No	42/138 (30)	NA
Blanks	1	
Follow a recommendation for P feeding		
Yes	25/136 (18)	22/26 (85)
No	48/136 (35)	3/26 (12)
Don’t know	63/136 (46)	1/26 (4)
Blanks	3	5
Formulate a single diet for the milking herd		
Yes	98/132 (74)	26/31 (84)
No	34/132 (26)	5/31 (16)
Blanks	7	-
Formulate diets using forage P test results		
Yes	49/131 (37)	23/31 (74)
No	71/131 (54)	8/31 (26)
Don’t know	11/131 (8)	-
Blanks	8	-
Use inorganic P supplements		
Yes	114/138 (83)	26/28 (93)
No	24/138 (17)	2/28 (7)
Blanks	1	3
Consider P when buying feed ingredients		
Yes	49/129 (38)	N/A
No	80/129 (62)	N/A
Blanks	10	N/A
Analyse manure for P		
Yes	43/135 (32)	10/31 (32)
No	92/135 (68)	18/31 (58)
Don’t know	-	3/31 (10)
Blanks	4	-
Aware of P pollution issues		
Yes	92/134 (69)	25/26 (96)
No	42/134 (31)	1/26 (4)
Blanks	5	5
Satisfied with available P management training		
Yes	10/132 (8)	6/31 (19)
No	97/132 (73)	21/31 (68)
Don’t know	25/132 (19)	4/31 (13)
Blanks	7	-

[1]Calculated by comparing the dietary P concentration stated by respondents with the NRC (2001) recommended concentration. Recommended concentration was determined using the DMI predicted from milk yield stated by respondents.

3.2.4. Factors influencing farmers' awareness of phosphorus pollution and phosphorus feeding and management practices

Pasture-based systems were less likely to use a feed professional compared to housed systems feeding TMR (Table 3.3). The use of a feed professional increased the likelihood that a farm analyses forage for P but also tended to increase the likelihood that a farm uses inorganic P supplements (Table 3.3). Farmers operating larger herds were more aware of P pollution issues and more likely to analyse manure for P, but were more likely to feed P in excess of the NRC (2001) recommendations (Table 3.4). Pasture-based systems were also less likely than housed systems to test their herd's manure for P. Almost all farmers (133/139 [96%]) were willing to reduce the dietary P concentration of their cows diet if it was determined that they were feeding excess P. This willingness was driven by the prospect of improved environmental and economic sustainability but farmers were prevented by the uncertainty of P availability in different feed ingredients, concerns over reduced cow fertility and lack of information on the P concentration of feed ingredients (Table 3.5).

Table 3.2 Association of phosphorus (P) feeding and management practices that dairy farms adopt with regions, dairy farm classifications and use of a feed professional's advice.

Hypothesis H_o	Result	*P* value
Associations with regions		
Use inorganic P supplements	$X^2(2, n = 136) = 9.901$	0.007
Associations with dairy farm classifications		
Analyse manure for P	$X^2(4, n = 136) = 11.84$	0.019
Feed professional presence	$X^2(4, n = 138) = 15.90$	0.003
Associations with feed professional		
Formulate diets using forage P test results	$X^2(1, n = 119) = 5.09$	0.024
Use inorganic P supplements	$X^2(1, n = 136) = 3.05$	0.081

Table 3.3 Association between a dairy farm's herd size and tendency towards adopting certain phosphorus (P) feeding and management practices

Characteristics	*P* value	Odds ratio	95% CI
Feed P in excess of recommendations[1]	< 0.001	1.0072	1.0006 – 1.0138
Analyse manure for P	< 0.001	1.0049	1.0025 – 1.0074
Awareness of P pollution issues	< 0.001	1.0053	1.0016 - 1.0090

[1]Calculated by comparing the dietary P concentration stated by respondents with the NRC (2001) recommended concentration. Recommended concentration was determined using the DMI predicted from milk yield stated by respondents.

Table 3.4 The barriers to and motivators for reducing dietary phosphorus (P) concentration in lactating cow diets fed on Great Britain dairy farms[1]

Barriers and Motivators	No. of Farmers[2] (%)	No. of Feed Advisers[3] (%)
Barriers		
Uncertainty of P availability	49/166 (30)	11/42 (26)
Reduced cow fertility	36/166 (22)	6/42 (14)
Limited feed P concentration data	25/166 (15)	9/42 (21)
Did not know	23/166 (14)	-
Reduced cow productivity	15/166 (9)	9/42 (21)
Complicate system	11/166 (7)	1/42 (2)
Nothing	4/166 (2)	-
Nutritionist advises against	2/166 (1)	N/A
Farmers' non-compliance	N/A	6/42 (14)
Motivators		
Environmental benefit	76/276 (28)	14/37 (38)
Reduce feed costs	74/276 (27)	14/37 (38)
Nutritionist advises it	70/276 (25)	N/A
Meeting regulations	37/276 (13)	7/37 (19)
Incentive programme	17/276 (6)	1/37 (3)
Animal health	2/276 (1)	1/37 (3)

[1]Respondents could select multiple barriers and motivators and so the percentage of responses was calculated using the number of responses to each barrier and motivator not the number of survey respondents, [2]n = 139, [3]n = 31

3.2.5. Survey of feed advisers to dairy farms

There were 31 responses to the feed adviser questionnaire. The mean herd size of their client farms was 357, with a mean annual milk yield of 9560 kg/cow and a mean annual amount of concentrate fed at 2529 kg/cow. More than half of the client farms that the feed advisers provided advice to formulated diets with a P concentration in excess of NRC (2001) recommendations (Figure 3.1). Almost half of the feed advisers (10/22 [45%]) stated that they followed the NRC (2001) recommendations and many feed advisers stated that they used forage P analysis when formulating diets and used inorganic P supplements (Table 3.2). Over two-thirds of the feed advisers were not satisfied with the amount of P management training available to them (Table 3.2). All feed advisers surveyed were willing to formulate diets with a lower P concentration, if it was determined that they were feeding P in excess of the cow's requirement. Feed adviser's shared similar motivators and barriers to reducing dietary P concentration as dairy farmers (Table 3.5).

3.3. Discussion

3.3.1. Herd demographics

The herds of the respondents in the farmer survey had an annual milk yield similar to the UK average of 7889 kg/cow (AHDB, 2019c) but were larger than the UK average of 148 cows (AHDB, 2019b). Despite the respondents in the farmer survey covering a wide range of herd sizes, just over half of respondents operated farms larger than the UK average (AHDB, 2019b). Larger herds were associated with being more aware of P pollution issues in the current survey and in the US (Dou *et al.*, 2003). Therefore, respondents from the current study may be representative of farmers that are relatively more interested in P feeding management. Housed systems operated the largest herds and fed the greatest amount of concentrates per cow to support higher producing cows, which was expected because large herds of high producing cows are easier to manage in housed systems, in regard to controlling the diet, acquiring a stable labour force, reducing the uncertainty of grass supply and practical difficulties such as walking distance (March *et al.*, 2014).

3.3.2. Farmers' knowledge of the phosphorus concentration in lactating cow's diet

Farmers were not aware of how much P they feed or should be feeding to their cows and instead feed professionals were largely relied upon for P feeding. Thereby highlighting the importance of feed professionals in minimising P feeding on dairy farms (Dou *et al.*, 2003). The 36 farmers in the current study that were able to report the P concentration of the diet they feed to their lactating dairy cows may in some cases have underestimated the P concentration. In England, an average forage mix provides 3.5 g P/kg DM before adding parlour concentrates (Sinclair and Atkins, 2015). Therefore, it is likely that farmers did not consider P supplied by all dietary sources when reporting dietary P concentration in the current survey, particularly for the farmers estimating feeding less than 3 g P/kg DM. A smaller proportion of farmers fed P in excess of the AFRC (1991) recommended concentration than the NRC (2001), because the AFRC (1991) assumes a higher net P requirement for maintenance (Valk and Baynen, 2003) and a single value for the absorption of P (Cottrill *et al.*, 2008). The need for reappraisal of the AFRC (1991) likely explains why the majority of farmers in the current study that used a recognised P feeding recommendation followed the NRC (2001). However, the NRC (2001) recommendations are based on data from the US, which may not accurately estimate the availability of P in forages and concentrates grown under UK conditions due to differences in the species grown and the status of the soil they are grown in (Cottrill *et al.*, 2008). The lack of uniformity in the following of recognised P feeding recommendations observed in the current study highlights a need for the reappraisal of national P feeding recommendations to minimise excess P feeding resulting from inconsistent advice.

3.3.3. Precision phosphorus feeding and management practices used by dairy farmers

A cow's P requirement changes during the stage of growth, lactation and gestation and an opportunity exists to lower dietary P concentration by accounting for the accretion and resorption of bone P throughout lactation (Kebreab *et al.*, 2013).The strategy of formulating diets for groups of cows with similar milk yields or in the same lactation stage could be useful in more precisely formulating diets that will match cows' P requirement (Kebreab *et al.*, 2013). However, most farmers in the current survey did not implement a group feeding strategy, primarily because it would complicate their feeding system. The ease of a feeding system is an important consideration for farmers when choosing management practices and is a primary reason for the increased number of housed systems in GB (March *et al.*, 2014). A group feeding strategy can be simple to adopt in a housed system because diets can be easily controlled. However, group feeding could also be adopted in pasture-based systems by the careful grouping of cows, for example via a spring block calving. Therefore, promoting group feeding strategies could facilitate the sustainable use of P in diverse dairy farming systems by reducing the excess purchasing of P supplements.

In the current survey, less than half of the farmers that formulated their own diets considered the actual forage P concentration during diet formulation whilst the remaining farmers presumably used book values. However, book values can inaccurately estimate the P concentration of forages, as the concentration varies with forage maturity and soil P levels, leading to imprecise dietary P supply to dairy cows (Cerosaletti *et al.*, 2004). The farms that underestimated forage P concentrations by using book values could feed excess P in the form of supplements, and indicates an opportunity to minimise P feeding to cows and reduce the purchasing of excess inorganic P supplements (Kebreab *et al.*, 2008). Inversely, forage P analysis can reduce the risk of overestimating the P supplied from forage, subsequently resulting in a P deficient diet being formulated. The contribution of P from forages is critical in pasture-based systems because cows are primarily fed forages. However, regular forage P testing whenever parlour concentrates or inorganic mineral supplements is fed to cows is crucial to minimise P feeding.

3.3.4. Factors influencing farmers' awareness of phosphorus pollution and phosphorus feeding and management practices

In the current study, farms with a feed professional were more likely to regularly analyse their forages for P than farms without a feed professional. However, the lesser reliance on feed professionals by farmers operating pasture-based systems compared to housed systems highlights that alternative strategies are required to encourage forage P analysis in pasture-based systems. Such strategies could be implemented on a governmental scale by subsidizing sample analyses and by increasing farmers' knowledge of precise P management through farm advisory services (Knowlton, 2011, Svanback *et al.*, 2019). Minimising P feeding in pasture-based system is important because the number of housed systems should eventually stabilise due to consumer's preference for pasture-based systems (March *et al.*, 2014). Inversely, the increasing number of housed systems in GB (March *et al.*, 2014), highlights the increasing importance of feed professionals in minimising P feeding in dairy farms in the future. However, the current study indicates that the influence that feed professionals have over P feeding practice could be better utilized to minimise P feeding, since farms that used advice from a feed professional tended to use inorganic P supplements more than farms without a feed professional, which in many cases may not be necessary.

The current survey revealed that most farmers never tested manure for P content. Farmers can acquire information on their manure P content by sending representative manure samples to laboratories. Wet chemistry laboratory methods remain the gold standard for quantifying total P in manure, however a number of colorimetric test kits for manure P are commercially available. Although such rapid tests cannot replace laboratory methods, they can be useful in improving the accuracy of manure application rates by providing timely information on manure P concentration. Therefore, the farmers feeding P in excess of cows' dietary P requirement and adjusting mineral fertiliser P application rates based on standard values for manure P were not crediting manure P accurately and therefore, not reducing mineral fertiliser P application accordingly. Manure P analysis could help farmers credit the amount of manure P more accurately and therefore, is a good practice to adopt specially by farms generating P-rich manure as a result of feeding excess P (Svanback *et al.*, 2019). However, the cost-effective solution to the challenge of managing P-rich manure remains to be the minimising of P feeding because in areas with a high soil P index farmers may not be allowed to apply manure to the nearby land, which may incur additional cost as a result of manure transportation to further lands (Knowlton, 2011). Although, encouraging manure P analysis remains important for minimising P feeding because it provides farmers with an indication of the relative degree of excess P feeding on their farms (Nordqvist *et al.*, 2013). In the current study, farmers of smaller herds were particularly less likely to analyse their manure P than larger herds. However, it is important to ensure effective manure management in large herds, particularly in densely stocked herds (Svanback *et al.*, 2019), because of the greater quantities of manure they generate compared to the land available for manure spreading. In the current survey, the higher tendency for manure P testing in larger herds was also important because larger herds showed a greater tendency to feed P in excess of NRC (2001) recommendations. This was despite farmers of larger herds being more aware of P pollution issues than smaller herds in the current study and in the US (Dou *et al.*, 2003). Therefore, caution should be taken when deciding which farming system poses a greater eutrophic risk based on limited parameters (O'Brien *et al.*, 2012). Regardless of dairy farming system, the current survey identified that increasing the availability of P management training is an effective strategy to raise farmers' awareness of P pollution issues and promote precision P feeding practices

3.3.5. Barriers to and motivators for dairy farmers to reduce excess phosphorus feeding

The current survey highlighted that emphasising the benefit of reduced feed costs and water pollution associated with minimising P feeding (Kebreab *et al.*, 2008), would motivate farmers to lower dietary P concentrations. However, in order to minimise P feeding, the current study demonstrates that the uncertainty of P availability in feed ingredients needs to be addressed. This is a particular problem in pasture-based systems where the P availability of grazed forages varies with soil and fertiliser P concentrations and precipitation, environmental conditions and management practices employed (Karn, 2001). The variation in digestibility and absorption of P by dairy cows influenced by various feed and animal factors (NRC, 2001, Ray *et al.*, 2013) has led farmers and feed advisers in the US to formulate diets following NRC (2001) recommendations but with the addition of a safety margin (Sansinena *et al.*, 1999, Harrison *et al.*, 2012). However, the NRC (2001) recommendations already include a modest safety margin to accommodate the high variability in P availability between individual feed ingredients within each feed type (forages, concentrations, and inorganic supplements). Therefore, formulating diets following NRC (2001) recommendations could minimise P feeding, but more precise P feeding could be achieved by determining P availability in individual feed ingredients (Feng *et al.*, 2016). However, more research is required to further understand P utilisation in dairy cows and to determine P availability in feed ingredients.

The many farmers in the current study selecting fertility as a barrier to minimising P feeding may be an overestimate of the relative importance of this barrier, since the presence of 'fertility' as a multiple choice option may have had some influence over farmer selection. However, fertility concerns has similarly caused farmers and feed professionals in the US to resist efforts to minimise P feeding (Dou *et al.*, 2003, Harrison *et al.*, 2012).The concerns over fertility amongst dairy farmers when lowering dietary P concentrations, are possibly related to earlier research that reported the feeding of a dietary

P concentration of 2 g/kg DM impaired cow fertility (Knowlton *et al.*, 2004). Indeed a dietary P concentration of 3.1 g/kg DM is considered borderline deficient for high producing dairy cows (Wu *et al.*, 2000). However, feeding P within the NRC (2001) recommended range has no adverse effect on fertility or productivity (Ferris *et al.*, 2009).Therefore farmers should be educated on the most recent findings on the effects of dietary P concentration on cow fertility.

3.3.6. Survey of Feed Advisers to Dairy Farms

The larger and higher milk producing client farms of the responding feed advisers compared to the UK average supports the finding from the farmer survey that feed advisers were more common in housed systems, since housed systems were associated with larger herds and higher producing cows in the farmer survey. Despite the feed advisers generally demonstrating a greater knowledge of P feeding than the average farmer survey respondent, over half of the feed advisers' client farms formulated lactating cow diets with a P concentration in excess of NRC (2001) recommended concentrations. Since most of the advisers stated that they followed NRC (2001) recommendations and formulated diets based on forage P test results, it is possible that a safety margin was included into P concentrations via inorganic P supplements (Kebreab *et al.*, 2013). Increased knowledge transfer could encourage feed advisers to reduce or remove these safety margins because feed advisers were similarly unsatisfied with the amount of P management training available to them as dairy farmers. This knowledge transfer should utilise the feed advisers' motivators for minimising P feeding and address their barriers to minimising P feeding, which were similar to the dairy farmers.

3.4. Conclusions

The current survey emphasised that most dairy farmers were not aware of how much P they are feeding or how much they should be feeding to their cows and instead relied on feed professionals. The results highlighted that feed professionals have an influence over P feeding practice, particularly so for the housed system. Therefore, the better utilisation of feed professionals influence over P feeding to minimise P feeding is increasingly important, as the number of housed systems in GB increases. Furthermore, the study findings demonstrate the importance of considering type of dairy production systems when developing precision P feeding strategies. Farmers were willing to reduce dietary P concentrations but to facilitate judicious use of P and ensure sustainable progress of the dairy industry, policymakers and research agencies should consider the following strategies: 1) increase the availability of P management education to emphasize the benefits of precision P feeding, 2) more effectively utilize feed 136 professionals' influence over P feeding practices on dairy farms to promote precision P feeding practices and lower dietary P concentrations in formulated diets and 3) draw farmers attention towards current P feeding requirements and increase the motivation of farmers and feed advisers to work towards these minimum requirements.

4. Objective 2

4.1. Materials and methods

4.1.1. Study farms and data collection

Dairy farms from across GB were recruited through advertisements by various stakeholders (acknowledgements). Thirty solely dairy farms were selected to ensure representation from a range of dairy farming systems (Garnsworthy *et al.*, 2019). Classification 1 farms adopt spring calving and graze ≥ 274 days a year with minimal feeding of concentrate supplements. Classification 2, 3 and 4 farms adopt block or all year calving with increasing use of concentrate supplements as grazing days reduce. Classification 5 farms adopt year-round calving in a housed system with the greatest amount of concentrate use within a total mixed ration.

Participating farms completed a form to collect information about production characteristics for the year 2018 / 2019 (*i.e.* herd size, calving pattern, number of grazing days/year and land management). Data required for calculating FPB was also collected *e.g.* annual imports and exports of feed, mineral fertiliser, manure, bedding, crop, livestock, and milk. Additional information was collected to calculate SPB, such as annual amounts of feed (excluding grazed grass) fed to the herd, mineral fertilizer applied to land, crops harvested and herd characteristics required to calculate herd energy requirement (*i.e.* livestock type, age, breed size, and replacement rate [RR]). The Utilised Agriculture Area (UAA) was calculated as the hectares (ha) of grass and arable land involved in milk production. Stocking rate (SR) was calculated as livestock unit (LU) per ha of UAA (Eurostat, 2013). Participant farms were visited once to collect feed, manure, and soil samples for the determination of P concentration, which was used in calculating P balances.

4.1.2. Sample Collection

Two to five soil samples were collected from each farm (100 mm depth, 50 mm diameter) using an Edelman Combination Soil Auger (Eijkelkamp, The Netherlands). Sampling areas were evenly distributed across each farm, ensuring representation of different land management practices and the exclusion of high traffic spots (Mihailescu *et al.*, 2015). In each sampling area, ≥10 soil cores were taken in a ‘W’ pattern, with an additional five soil cores situated on the un-trafficked borders taken on arable land (Landwise, 2019). Soil cores from a sampling area were mixed and a representative sample (~1 kg) was stored at - 20°C until further analysis.

Mixed rations and individual feed ingredient samples were collected from each farm. Samples were not collected if P concentration of a feed was available from recent farm records. Mixed rations were sampled ≤ 10 minutes of feeding by collecting 12 grab samples along the feed trough (Sinclair and Atkins, 2015). Grab samples were mixed and a representative sample (~1 kg) was stored at - 20°C until further analysis. Sub-samples of each clamp and big bale silage were collected (Sinclair, 2006), mixed and a representative sample (~1 kg) of each silage was stored at - 20°C until further analysis. Twelve grab samples of any parlour concentrate fed were also collected, bulked and mixed and a representative (~500 g) sample was stored at - 20°C until further analysis.

On each farm that imported or exported manure, five to 10 subsamples of slurry were randomly collected from different locations in the manure storage facility and were bulked, mixed and a representative (~2 L) sample was stored at - 20°C until further analysis. Samples of manure were collected at six to eight inches depth from the face of the storage heap in a 'W' shape (Spears *et al.*, 2003) and were bulked, mixed and a representative sample (~1 kg) was stored at - 20°C until further analysis.

4.1.3. Sample analysis

Feed, manure and soil samples were dried at 60°C until a constant weight was achieved. Dried feed and manure samples were ground (1 mm mill; Cyclotec CT293, Foss, Warrington, GB) and dried soil samples were sieved (2 mm screen; Endcotts Limited, London, England). Processed samples of feed, manure and soil were sent to Lancrop laboratories (Yara analytical services, York, UK) for analysis. The total P concentration of all samples was determined via microwave assisted Aqua Regia digestion using nitric and hydrochloric acid for soil and manure samples and using nitric acid for feed samples. Olsen P extraction was used to analyse plant-available P (sodium bicarbonate-extractable P) in soil samples (Sims, 2000). Inductively coupled plasma-optical emission spectrometry (Varian Agilent ICP-OES 5110; California, United States) was used to quantify total and plant-available P concentrations (Withers *et al.*, 1999, Jahanzad *et al.*, 2019).

4.1.4. Calculation of phosphorus balances, benchmarks and use efficiencies

The current study calculated FPB by employing the 'Planning for Land Application of Nutrients for Efficiency and the environmenT' (PLANET; http://www.planet4farmers.co.uk) methodology (Table 4.1). PLANET is a validated tool that has been effectively used to explore nutrient management in the UK (Norton *et al.*, 2012, Gibbons *et al.*, 2014). A general benchmark that dairy farms across all systems in the current study should operate below was established by identifying the FPB (kg/ha) that 75% of participating farms operated below. Optimal zones for milk production and animal density that participating dairy farms should aim towards operating within were also determined by further considering the FPB (kg/ton of milk) and (kg/LU) that 50% of participant farms could achieve. This approach has been used to propose nutrient balance benchmarks for dairy farms in other countries (Nevens *et al.*, 2006, Cela *et al.*, 2014).

The challenge in calculating SPB due to the difficulty in determining P export from soil via grazed grass was overcome in the current study by employing the principles (Table 4.1) of the 'Annual Nutrient Cycling Assessment; ANCA; KringloopWijzer' (Aarts *et al.*, 2015). This is the first instance that ANCA's principles have been employed to calculate SPB for GB dairy farms. In ANCA, cows' energy requirement is calculated using the Netherlands' net energy system of VEM (feed unit of lactation). To effectively use the principles of ANCA to estimate P export from soil as grazed grass in the current study, the ME (MJ/kg DM) of feed was converted to VEM using the following equation (Wageningen UR, 2016):

$$VEM = 0.6 \times (1 + 0.004 \times ([ME / GE \times 100] - 57)) \times 0.9752 \times ME / 6.9 \text{ kJ} \times 1000 = (0.0003392 \times [ME / GE \times 100] + 0.0654656) \times ME \times 1000.$$

Table 4.1 Formulae used to calculate farm-gate and soil-surface phosphorus (P) balances and use efficiencies of dairy farms

Terms	Calculation
Farm-gate P import (kg)	Livestock P`[1] + Feed P[2] + Mineral fertiliser P[1] + Manure P[2] + Bedding P[1]
Farm-gate P export (kg)	Exported livestock P[1] + Exported manure P[2] + Milk sold P[1] + Exported crop P[1]
Farm-gate P balance (kg P/ha)	(Farm-gate P import – Farm-gate P export) / Utilised agricultural area (ha)
Farm-gate P use efficiency (%)	(Farm-gate P export / Farm-gate P import)
Soil-surface P import[3] (kg)	Manure P + Mineral fertiliser P[1]
Soil-surface P export (kg)	Harvested silages P[2] + Grazed grass P + Other harvested crop P[1]
Soil-surface P balance (kg P/ha)	(Soil-surface P import – Soil-surface P export) / Utilised agricultural area (ha)
Soil-surface P use efficiency (%)	(Soil-surface P export / Soil-surface P import)
Manure P (kg)	(Herd dietary P intake – Herd P deposition[4]) – Exported manure P[2] + Imported manure P[2]
Grazed grass P (kg)	((Grass silage P[2] / VEM supplied by grass silage) × 1.05)× VEM supplied by grazed grass
VEM supplied by each silage	Herd requirement (VEM) - Purchased feed (VEM) /original diet's proportions of silages VEM (%)
VEM supplied by grazed grass	VEM supplied by grass silage adjusted using ANCA's coefficients of grazing[5]

[1] Concentrations of P from product label or 'Planning for Land Application of Nutrients for Efficiency and the environmenT' (PLANET) tool (Livestock = 7.1 g P/kg, milk = 0.97 g P/kg), [2] Concentrations of P from product label or determined by inductively coupled plasma-optical emission spectrometry (ICP-OES) after acid digestion, [3]Atmospheric and seed residue P negligible, [4] Deposition for milk, pregnancy and young stock (Groor, 2016), [5] type of grazing system, grazing days, hours of grazing and size of the cow breed

4.1.5. Statistical analysis

Data was analysed using Minitab (2019), with one outlier farm (classification 1) removed from analysis due to an abnormally large herd size, land size (ha) and annual milk yield (kg/cow) for its classification. The normality of residuals distribution was tested using the Ryan-Joiner test ($P \leq 0.05$ indicating abnormal distribution). Log-transformation ($y = \log10(x)$) was required to ensure homogeneity of variance (Mihailescu *et al.*, 2015) for; 'milk sold/year', 'feed P import', 'farm-gate PUE' and 'mineral fertiliser P import'. Fixed effects of differences in production characteristics, FPB, and SPB variables (import, export, balance and PUE) between systems were investigated using ANOVA with Tukey's test ($P \leq 0.05$ indicating significantly different means). Multiple stepwise linear regressions were undertaken with acceptance of new terms set to $P \leq 0.05$, to investigate relationships between both FPB and SPB variables (import, export, balances and PUE) and potential determinants, which were selected based on their likely significance to the dependent variable (Mihailescu *et al.*, 2015).

4.2. Results

4.2.1. Production characteristics of dairy farming systems

The mean herd size of the participating farms was 222 lactating cows with a mean UAA of 177 ha, SR of 2.18 LU/ha and annual milk yield of 7677 kg/cow (Table 4.2). Dairy cows in the housed system (classification 5) had a higher annual milk yield and a lower milk fat content compared to pasture-based systems feeding limited concentrate supplements (classifications 1 and 2), and milk protein content in the housed system was lower than in the longest grazing pasture-based system (classification 1). Pasture-based systems feeding some concentrate supplements (classifications 2 and 3) had a higher percentage of their herd's diet compromised from home-grown feeds (primarily forages) compared to a housed system (classification 5). The mean dietary P concentration fed across systems was 3.8 g/kg DM, but the housed system (classification 5) fed diets with the highest P concentration. The mean concentrations of Olsen P and total P in the soil across all systems were 43.3 and 959 mg/kg, respectively, and were not different between systems.

Table 4.2 Production characteristics of dairy farming systems

	Dairy farming system[1]					SE	*P* values
	1	2	3	4	5		
Number of farms	3[2]	12	7	2	5		
Farms using a breed ≤ 500 kg mature weight[3] (%)	100	42	14	0	0		
Herd size (lactating cows)	217	211	247	262	202	123	0.95
Utilised agriculture area (ha)	129	160	237	263	129	134	0.50
Stocking rate (Livestock Unit/ha)	2.28	2.13	2.21	1.41	2.48	0.82	0.64
Annual milk yield (kg/cow)	5281^{b}	7204^{b}	7683^{ab}	7617^{ab}	10268^{a}	1555	≤ 0.01
Milk fat content (%)	4.42^{a}	4.28^{a}	4.08^{ab}	4.09^{ab}	3.97^{b}	0.181	≤ 0.01
Milk protein content (%)	3.58^{a}	3.37^{ab}	3.37^{ab}	3.38^{ab}	3.22^{b}	0.119	≤ 0.01
Annual replacement rate (%)	0.20	0.29	0.27	0.27	0.28	0.08	0.57
Proportion of home-grown feed[4] (%)	77.2^{ab}	79.4^{a}	78.7^{a}	58.0^{ab}	48.6^{b}	0.14	≤ 0.01
Dietary phosphorus (P) concentration (g/kg DM)	3.43^{ab}	3.72^{ab}	3.56^{b}	3.75^{ab}	4.52^{a}	0.53	0.03
Soil Olsen P concentration (mg/kg)	33.3	44.4	49.4	32.5	42.3	19.4	0.71
Soil total P concentration (mg/kg)	1037	1013	934	481	1051	298	0.23

[1] Based on calving pattern, concentrate supplements provided and number of grazing days (Garnsworthy *et al.*, 2019), [2]One outlier farm removed from analysis, [3] Remaining farms used breed ≥ 500 kg mature weight, [4]Percentage of the herd's diet from home-grown feed (primarily forages), [a-b] Means in a row without a common superscript letter differ ($P \leq 0.05$)

4.2.2. Balance and use efficiency of farm-gate phosphorus in dairy farming systems

Across all systems, purchased feed accounted for a major proportion (46 to 79%) of annual P import onto a farm (Table 4.3). However, the housed system (classification 5) imported more feed P compared to pasture-based systems (classifications 1, 2 and 3). Subsequently, the mean annual P import was greater in the housed system (classification 5) compared to a pasture-based system feeding limited concentrate supplements (classification 2). Across all systems, milk accounted for the main proportion (72 to 97%) of annual P export. The housed system (classification 5) tended (P = 0.09) to export more milk P than other systems. Furthermore, the housed system (classification 5) exported more livestock P than a pasture-based system feeding some concentrate supplements (classification 3). However, the mean annual P export was not different between systems. Subsequently, the housed system (classification 5) had a higher mean P surplus compared to pasture-based systems that fed some concentrate supplements (classifications 2 and 3).

Consequently, the housed system (classification 5) had a lower PUE than a pasture-based system feeding limited concentrate supplements (classification 2). Across all systems the FPB ranged from -5.81 to 32.1 kg/ha with a deficit on eight farms, a surplus on the remainder and a mean P surplus of 9.65 kg/ha. The mean farm-gate PUE across all systems was 0.74.

Table 4.2 Differences in farm-gate phosphorus (P) import, export, balance and use efficiency between dairy farming systems

	Dairy farming system[1]					SE	*P* values
	1	2	3	4	5		
Farm-gate P import (kg/ha)							
Feeds	10.4[b]	11.3[b]	12.2[b]	16.0[ab]	37.0[a]	10.5	≤ 0.01
Mineral fertiliser	6.39	3.37	7.42	0.00	3.31	6.29	0.51
Livestock	0.00	0.17	0.00	0.29	2.01	1.71	0.30
Bedding	0.27	0.48	0.79	0.44	0.34	0.63	0.69
Manure	2.73	0.93	4.26	0.00	4.19	7.15	0.82
Total	19.8[ab]	16.3[b]	24.8[ab]	16.7[ab]	46.9[a]	13.3	≤ 0.01
Farm-gate P export (kg/ha)							
Milk	8.38	10.1	11.1	6.96	16.2	4.58	0.09
Livestock	0.25[ab]	1.53[ab]	0.26[b]	1.04[ab]	3.45[a]	1.70	0.04
Crop	0.00	1.02	0.12	0.00	2.50	2.49	0.49
Manure	0.00	0.22	4.08	0.00	0.00	5.31	0.57
Total	8.62	12.9	15.5	8.00	22.1	8.45	0.16
Farm-gate P balance (kg/ha)	11.2[ab]	3.34[b]	9.25[b]	8.74[ab]	24.8[a]	7.76	≤ 0.01
Farm-gate P use efficiency	0.45[ab]	0.99[a, 2]	0.71[ab]	0.49[ab]	0.47[b]	0.33	0.02

[1] Based on calving pattern, concentrate supplements feeding approach and number of grazing days (Garnsworthy *et al.*, 2019), [2] One farm reduced their herd size and one farm produced and exported a large amount of crop for the year of interest, [a-b] Means in a row without a common superscript letter differ ($P \leq 0.05$)

4.2.3. Determinants of balance and use efficiency of farm-gate phosphorus

Feed P import positively correlated with a farm's SR and negatively correlated with the percentage of a herd's diet from home-grown feed and cow RR (Table 4.4). Milk P export positively correlated with a farm's SR. The FPB was negatively associated with the percentage of a herd's diet from home-grown feed but was positively correlated with mineral fertiliser P import, whilst a farm's PUE and feed P import were negatively associated.

Table 4.3 Determinants of farm-gate phosphorus (P) balance in a diverse dairy farming system

Response	Significant variables[1]	R^2
LgFdP =	2.6 (±0.37) + 0.18 (±0.076) × *SR** – 0.018 (±0.0035) × *PHF*** – 1.7 (±0.77) × *RR**	0.67
MPE =	$-20\ (\pm 6.9) + 4.2(\pm 0.65) \times SR^{**} + 6.9\ (\pm 2.17) \times LgMS^{**})$	0.63
FPB =	$40\ (\pm 5.4\ ) - 0.47\ (\pm 0.073) \times PHF^{**} + 8.6\ (\pm 2.60) \times LgFI^{**}$	0.66
LgFPUE	$0.063\ (\pm 0.0783\ ) - 0.25\ (\pm 0.071) \times LgFdP^{**}$	0.34

FPB, farm-gate P balance (kg/ha); GD, grazing days; LgFdP, log-transformed feed P import (kg/ha); LgFI, log-transformed mineral fertiliser P import (kg/ha); LgFPUE, log-transformed farm-gate P use efficiency (%); LgMS, log-transformed milk sold/year (tons); MPE, Milk P export (kg/ha); PHF, percentage of herd's diet from home-grown feeds (%); RR, replacement rate (%); SR, stocking rate (Livestock Unit/ha); STPo, soil test Olsen P (mg/kg); STPt, soil test total P (mg/kg); * $P \leq 0.05$, ** $P \leq 0.01$. [1]Investigated variables = μ + βSR + βRR + βLgMS + βGD + βLgFI + βLgFdP + βPHF + βSTPo + βSTPt + σ_{est} (βLgFI and βLgFdP were not considered when they were the dependent variable)

4.2.4. Optimal zone for milk production and animal density

Seventy-five percent of participant farms operated below 15.9 kg P/ha and 50% operated below 0.87 kg P/ton of milk and 4.6 kg P/LU (Figure 4.1). Farms operating a pasture-based system feeding limited concentrate supplements (classification 2) were most commonly located within the optimal zone for milk production (≤ 15.9 kg P/ha and ≤ 0.87 kg P/ton of milk) and animal density (≤ 15.9 kg P/ha and ≤ 4.6 kg P/LU) but no benchmark was achieved by a housed system (classification 5).

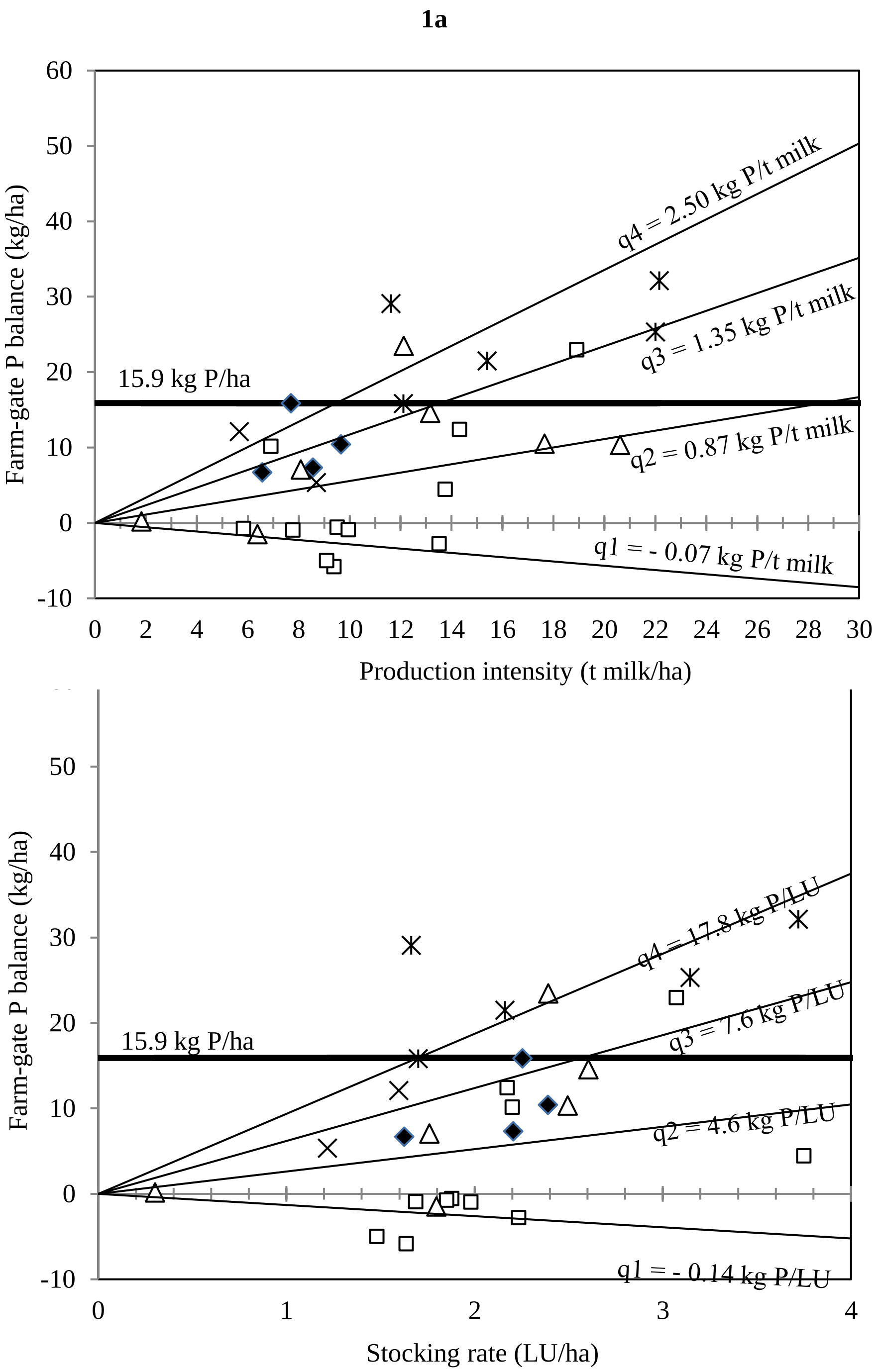

Figure 4.1 The Farm-gate phosphorus (P) balance per hectare (ha) as a function of (1a) production intensity (tons [t] of milk/ha) and (1b) animal density (livestock unit [LU]/ha) for 29 dairy farms across dairy farming systems (Garnsworthy *et al.*, 2019). Dairy farming system 1 (black diamonds), 2 (white squares), 3 (white triangles), 4 (×) and 5 (× with a vertical line). Bold horizontal line indicates farm-gate P balance (kg/ha) that 75% of farms achieved and sloped lines represent the quartile of farms achieving a kg P/LU and kg P/t milk

4.2.5. Balance and use efficiency of soil-surface phosphorus in dairy farming systems

Across all systems manure P accounted for all or a major proportion (77 to 100%) of annual P import onto the soil-surface, whereas mineral fertiliser accounted for a smaller proportion (0 to 23%), but the mean annual P import was not different between systems (Table 4.5). A large proportion of annual P export from the soil-surface was accounted for by grazed grass (41 to 83%) in pasture-based systems (classifications 1, 2 and 3) and silages (47 to 55%) in predominantly housed systems (classifications 4 and 5). The longest grazing pasture-based systems (classification 1) tended (P = 0.05) to export the greatest amount of P from the soil-surface via grazed grass. Subsequently, pasture-based systems feeding some concentrate supplements (classifications 2 and 3) had a lower mean P surplus and higher PUE than the housed system (classification 5). Across all systems, the SPB ranged from -6.92 to 30.7 kg/ha, with a P deficit on nine farms, a surplus on the remainder and a mean surplus of 7.51 kg/ha. The mean soil-surface PUE across all systems was 0.81.

Table 4. 5 Differences in soil-surface phosphorus (P) import, export, balance and use efficiency between dairy farming systems

	Dairy farming system[1]					SE	*P* values
	1	2	3	4	5		
Soil-surface P import (kg/ha)							
Manure	21.5	25.8	28.5	16.5	39.3	13.7	0.25
Mineral fertiliser	6.39	3.37	7.42	0.00	3.31	6.30	0.52
Total	27.8	29.1	35.9	16.5	42.6	15.6	0.29
Soil-surface P export (kg/ha)							
Grazed grass	15.4	13.8	12.5	0.67	2.44[2]	8.22	0.05
Grass silage	2.83	7.30	9.78	1.56	8.58	5.28	0.21
Other silages	0.14	1.58	1.80	2.51	2.82	1.78	0.34
Harvested concentrate	0.32	2.88	4.69	3.53	1.98	4.26	0.63
Other crop (bedding and cash crop)	0.00	1.46	1.36	0.33	5.09	4.76	0.53
Total	18.7	27.0	30.1	8.60	20.9	13.5	0.29
Soil-surface P balance (kg/ha)	9.19[ab]	2.12[b]	5.80[b]	7.94[ab]	21.7[a]	7.86	≤ 0.01
Soil-surface P use efficiency (%)	0.66[ab]	0.98[a]	0.90[a]	0.52[ab]	0.46[b]	0.22	≤ 0.01

[1] Based on calving pattern, concentrate supplements feeding approach and number of grazing days (Garnsworthy *et al.*, 2019), [2] grazing from young stock and heifers only, [a-b] means in a row without a common superscript letter differ ($P \leq 0.05$)

4.2.6. Determinants of balance and use efficiency of soil-surface phosphorus

Mineral fertiliser P import positively correlated with a farm's SR whereas manure P import positively correlated with SR and annual amount of milk sold (Table 4.6). Phosphorus export via grazed grass positively correlated with SR, number of grazing days/year, percentage of the herd's diet from home-grown feed and soil Olsen P concentrations. The SPB was negatively associated with the percentage of a herd's diet from home-grown feed but positively correlated with SR. The soil-surface PUE and the percentage of a herd's diet from home-grown feed were positively associated. Soil Olsen P concentration negatively correlated with grazing days but positively correlated with P export via grazed grass, whereas no significant relationships were determined for soil total P concentration.

Table 4.4 Determinants of soil-surface phosphorus (P) balance in a diverse dairy farming system

Response	Significant	R^2
LgFI[1] =	$-0.39\ (\pm 0.247) + 0.34\ (\pm 0.107) \times SR^{**}$	0.29
MPI[1] =	$4.6\ (\pm 6.21\ ) + 10\ (\pm 2.69) \times SR^{**}$	0.39
GgP[1] =	$-25\ (\pm 4.9) + 3.7\ (\pm 1.25) \times SR^{**} + 0.029\ (\pm 0.0127) \times GD^{*} + 0.18\ (\pm 0.067) \times PHF^{**} + 0.24\ (\pm 0.055) \times STPo^{**}$	0.80
SPB[1] =	$26\ (\pm 6.1\ ) + 3.7\ (\pm 1.45\ ) \times SR^{*} - 0.38\ (\pm 0.065) \times PHF^{**}$	0.66
SsPUE[1] =	$-10\ (\pm 15.9) + 1.3\ (\pm 0.21) \times PHF^{**}$	0.60
STPo[2] =	$39\ (\pm 5.4) - 0.084\ (\pm 0.0323) \times GD^{*} + 1.7\ (\pm 0.33) \times GgP^{**}$	0.53
STPt[2] =	NS	

GD, grazing days; GgP, grazed grass P export (kg/ha); GsP, grass silage P export (kg/ha); LgFI, log-transformed mineral fertiliser P import (kg/ha); LgMS. log-transformed annual milk sold (tons); MPI, manure P import (kg/ha); PHF, proportion of home-grown forage (%); SPB, soil-surface P balance (kg/ha); SsPUE, Soil-surface P use efficiency (%); STPo, soil test Olsen P (mg/kg); STPt, soil test total P (mg/kg); SR, stocking rate (livestock unit/ha); NS = not significant, * $P \leq 0.05$, ** $P \leq 0.01$, [1]Investigated variables = μ + βSR + βLgMS + βGD + βPHF + βSTPo + βSTPt + σ_{est} , [2] Investigated variables = μ + βSR + βLgMS + βGD + βPHF + βSPB + βLgFA + βMPI + βGgP + βGsP + σ_{est}

4.3. Discussion

4.3.1. Production characteristics of dairy farming systems

The farms in the current study had larger herds than the 165 lactating cows typical for GB dairy farms (DEFRA, 2020). However, the mean UAA and annual milk yield across all systems were similar to the national averages (154 ha and 7889 kg/cow, respectively) of GB dairy farms (AHDB, 2019a). In the current study, there was a higher annual milk yield for cows in the housed system compared to pasture-based systems, attributed to greater use of maize silage, larger breeds and the greater import of concentrate feed and relatively lower use of home-grown forages in the housed system. It is difficult to meet the elevated energy demand of high yielding cows typically used in housed systems by feeding high-forage diets (March *et al.*, 2014). This increased feed P import in the housed system explains why dietary P concentration was greatest in this system, because concentrate supplements in GB usually contain 50% more P compared to grass herbages (Withers *et al.*, 2001). Therefore, important differences in feeding practices between systems resulted in significant differences in P imports.

The milk P content can vary between 0.7 and 1.3 g/kg (Pfeffer *et al.*, 2005) but was assumed to be constant for farms in the current study. Determination of milk P may improve the accuracy of P balances in future studies. However in the current study, the greater milk protein content in the longest grazing pasture-based system compared to the housed system, suggests the P content of milk export is likely greater in pasture-based systems than estimated here, since milk P positively relates to milk protein (Klop *et al.*, 2014).

4.3.2. Comparison of farm-gate balance and use efficiency of phosphorus between dairy farming systems

The mean FPB across all systems in the current study of 9.65 kg P/ha was lower than the 15.3 kg P/ha previously reported for dairy farms in South-West England (Raison *et al.*, 2006). This difference could be attributed to less mineral fertiliser P import and greater milk P export in the current study, despite a greater feed P import. Such an increase in feed P import and milk P export is primarily attributed to the increased prevalence of housed systems in GB dairy farming (March *et al.*, 2014). Greater P surplus in the housed system compared to pasture-based systems (classifications 2 and 3) in the current study, supports that housed systems are relatively less efficient in utilising P (March *et al.*, 2016, Akert *et al.*, 2020). However, differences in P balance and PUE between the housed system and the longest grazing pasture-based system (classification 1) were not observed in the current study, likely because numerically lower export of P in the longest grazing pasture-based system compared to other pasture-based systems (classifications 2 and 3).

In the current study, mean FPB across all pasture-based systems was within the 5.09 to 17.2 kg P/ha reported for pasture-based systems in Ireland (Mihailescu *et al.*, 2015, Adenuga *et al.*, 2018). However, the mean 3.85 kg P/ha for classification 2 was below this range, likely because two farms exported large amounts of livestock or crop. Conversely, the housed system in the current study had a greater P surplus compared to the 10.00 kg P/ha for similar systems in the US (Cela *et al.*, 2014). This finding therefore indicates that there is scope to further improve PUE in GB dairy farming, particularly in housed systems.

4.3.3. Determinants of farm-gate balance and use efficiency of phosphorus

In the current study, the positive association between feed P import and SR was likely because densely stocked farms are associated with the import of a large amount of feed (Mihailescu *et al.*, 2015) as the availability of land for grazing and home-grown feed production is often limited (March *et al.*, 2014). Therefore, results of the current study suggest that FPB could be reduced and PUE could be improved if farmers reduce feed P import by either, reducing the P content of imported feeds or maintaining a SR that matches the availability of home-grown forages.

Since milk was the major source of P export from a farm, the positive relationship between milk P export and SR in the current study suggests that maintaining a lower than optimal SR of lactating cows would increase P surplus, due to the lower milk production. Therefore, increasing a farm's SR of lactating cows to increase milk P export could lower FPB and increase PUE (Mihailescu *et al.*, 2015). However, in the current study the greater milk P export in the housed system was outweighed by increased feed P import. Therefore, the current study suggests that increasing a farm's milk P export by increasing SR of lactating cows can lower a FPB, if the farm either uses feeds with a lower P content or does not increase SR such that the availability of home-grown feed becomes limited. However, selecting cows of genetic merit for higher milk yields and milk contents can also improve PUE (March *et al.*, 2016) and likely contributed to differences in feed import and milk export between systems in the current study.

Since farms with a greater reliance on home-grown feed (primarily forages) had reduced P surplus and improved PUE in the current study, increasing the reliance on home-grown forages could improve PUE. However, this strategy may not be appropriate for housed systems that have limited land availability. In the current study, the greater amount of feed P import likely contributed to greater P surpluses in housed systems compared to pasture-based systems (O'Brien *et al.*, 2012). Furthermore, the housed system fed diets with a mean P concentration 132% of the mean 3.4 g P/kg DM recommended (NRC, 2001) to support the relative milk production and DM intake (Kebreab *et al.*, 2013). Therefore, housed systems with limited land availability importing high P feeds could reduce P surplus and improve PUE by formulating diets and importing concentrates with a P concentration closer to the cows' requirement.

4.3.4. Optimal zone for milk production and animal density

The feasible benchmark of 15.9 kg P/ha calculated in the current study was greater than the 9 to 13 kg P/ha proposed in other countries (Cela *et al.*, 2014). Whereas, the 0.87 kg P/t of milk was lower than 1.1 kg P/t of milk in New York (Cela *et al.*, 2014). Since no benchmark was achieved by farms in the housed system, the current study recommends that system-specific benchmarks are required for countries operating diverse dairy farming systems. Furthermore, the pasture-based system (classification 3) annually producing 21 t of milk/ha operating within the optimal zone for milk production in the current study illustrated that a high producing dairy farm can be highly eco-efficient with P.

4.3.5. Comparison of balance and use efficiency of soil-surface phosphorus between dairy farming systems

In the current study, the housed system (classification 5) had higher P surplus and lower soil PUE compared to pasture-based systems (classifications 2 and 3), partly because the housed system tended to have lower grazed grass P export. This finding supports that a housed system poses a greater eutrophication risk than pasture-based systems (O'Brien *et al.*, 2012). However, the mean 7.51 kg P/ha SPB across all systems in the current study was lower than 11.0 kg P/ha in pasture-based systems in Northern Ireland (Adenuga *et al.*, 2018), primarily because of lower mineral fertiliser P import and greater crop P export. This therefore suggests that accurately applying mineral P fertiliser based on crop requirements and increased crop production may be strategies to reduce SPB in systems where increasing P export via grazed grass is not feasible. Additionally, since mean soil Olsen P concentration across all systems was well above the optimal 16 to 25 mg/kg agronomic range (AHDB, 2018), most systems could further reduce mineral fertiliser P import by relying on accumulated P in soil, thereby providing an economic saving to farmers (Withers *et al.*, 2017).

4.3.6. Determinants of balance and use efficiency of soil-surface phosphorus

In the current study, the lower SPB in pasture-based systems (classifications 2 and 3) compared to the housed system was partly due to the greater amount of P export via grazed grass in pasture-based systems. Extending the grazing season may lower SPB in pasture-based systems (Adenuga *et al.*, 2018) and provide an opportunity to reduce the import of high-P concentrate feeds (Mihailescu *et al.*, 2015). However, in the current study farms with increased grazing had decreased silage and crop P export. Consequently, grazed grass P export was not a determinant of SPB and therefore extending the grazing season may not be a viable strategy to lower SPB.

Lowering SPB by reducing feed P import may be nullified by the need for increased import of mineral fertiliser P required to increase the production of home-grown feed (O'Brien *et al.*, 2012, Adenuga *et al.*, 2018). Conversely, in the current study increased grazed grass P export increased the concentration of P in the soil utilisable by forages, likely because of greater P cycling and direct deposition of faecal P onto the soil by grazing cows (Baron *et al.*, 2001, Gourley *et al.*, 2011). However, increases in P export via grazed grass would need to be achieved without increasing grazing days, since grazing days negatively correlated with soil Olsen P concentration. Therefore, the current study recommends that soil PUE could be improved by increasing P export via grazed grass by increasing a farm's SR, whilst appropriately considering associated increases in manure and mineral fertiliser P import. Alternatively, housed systems can lower SPB by more precisely formulating diets to reduce excess P import in concentrate feeds (Adenuga *et al.*, 2018) or partly replacing high-P home-grown forages (grass silage) with low-P home-grown feeds (maize silage). Dairy farms in the Netherlands have improved SPB from an average 5.1 kg/ha (2010-2013) to -0.8 kg/ha (2014-2017), largely by reducing feed P content (Lukács *et al.*, 2019), such a measure represents a major opportunity for GB dairy farming to improve SPB.

4.4. Conclusions

Large P surpluses and consequently large soil P reserves across all systems highlight the potential to improve PUE in GB dairy farming. This high soil P concentration across all systems and the positive association between mineral fertiliser P application and P surplus indicate that most systems could lower the risk of P loss and improve PUE by reducing fertiliser P import through accurate crediting of P in soil and manure. The issue of relatively high P surplus and poor PUE at both farm-gate and soil-surface level in housed systems could be reduced by importing less P in concentrates, or by or using home-grown feeds with lower P content, as the dietary P concentration in the housed system was more than the concentration recommended to meet requirements. Whereas, increasing the reliance on home-grown feed (primarily forages) and maintaining a SR to more closely match the availability of home-grown forages is suggested as a strategy to improve PUE in pasture-based systems. Therefore, strategies to reduce P surplus and improve PUE of dairy farming in countries that operate diverse dairy farming systems would benefit from a more system-specific approach.

5. Objective 3

5.1. Materials and methods

5.1.1. Participating dairy farms

Dairy farms from across GB were recruited through advertisements by various stakeholders (listed in acknowledgements). Twenty-seven solely dairy farms were selected to ensure representation from a range of dairy farming systems (Garnsworthy *et al.*, 2019). Classification one farms adopt spring calving and graze > 274 days a year with limited supplements. Classification two, three and four farms adopt block or all year calving with increasing use of concentrate supplement as grazing days reduce. Classification five farms adopt all year round calving in a housed system with the greatest amount of concentrate use as a total mix ration. For the current study, classifications one, two, three were deemed pasture-based (n = 20 farms) whereas classification four and five farms were deemed housed (n = seven farms). A similar number of dairy farms to previous studies (29 dairy farms) that collected data from large existing datasets (Lynch *et al.*, 2018) was achieved in the current study (27 dairy farms). However, the number of participant dairy farms in the current study was considerably more than the four dairy farms used by the only other research that similarly used a tailored approach to collect data specifically appropriate for FARMSCOPER directly from farmers (Firbank *et al.*, 2013). Such a tailored data collection approach reduces the number of assumptions required and generates a more reliably data set (Zhang *et al.*, 2012, Lynch *et al.*, 2018, Micha *et al.*, 2018).

Across all systems, the farms in the current study had larger mean herd size of 246 (78 to 920) lactating cows and utilised agricultural area (UAA) of 202 (64 to 920) ha, than the average 165 lactating cows and 154 ha UAA for typical GB dairy farms (DEFRA, 2020). However, the mean annual milk yield of 7824 (4706 to 12091) kg/cow across all farming systems was similar to the 7889 kg/cow national average of GB dairy farms (AHDB, 2019a). Therefore, since larger dairy farms (herd and land basis) are more aware of P pollution issues (Dou *et al.*, 2003), consequently the current study may be reflective of dairy farmers that are relatively more interested in P management and thus may be reflective of a 'best case' situation.

5.1.2. Data collection

Information on the farms' structure (i.e. livestock and cropping) and physical characteristics (i.e. soil type, rainfall) was collected during a visit using a pro-forma designed specifically to collect data appropriate for direct input into FARMSCOPER, thereby minimising the amount of assumptions required to be made. Additionally, the dominant soil type for each farm's location was derived from Soilscapes (Farewell *et al.*, 2011), with soil types classified in Soilscapes as freely draining considered as 'free draining' in FARMSCOPER. Slightly impermeable soils were considered as 'Drained for arable use', while impermeable soils were considered as 'Drained for grass and arable use'. Furthermore, rainfall data was determined for each farm's location using the same average precipitation data over 30 years that is used when calculating RB209 Nitrogen recommendations (AHDB, 2018).

5.1.3. Scenario analysis with FARMSCOPER

The FARMSCOPER tool is built on a suite of validated models that have been used in supporting UK policy-making (McDowell *et al.*, 2016). Since the focus of this study is on P, the PSYCHIC model - Phosphorus and Sediment Yield Characteri-sation in Catchments (Davison *et al.*, 2008, Strömqvist *et al.*, 2008), of FARMSCOPER is of particular importance. In the current study, FARMSCOPER was firstly used to simulate the annual EPL from each individual dairy farm by tailoring the customizable parameters in FARMSCOPER to match the farm's structure and physical characteristics of the farm. However, it is important to note that some variations in important farm practices (i.e. feeding) were fixed in FARMSCOPER. Environmental P loading for each farm was simulated under three scenarios (1) 'baseline scenario' –when no mitigation methods are implemented, (2) 'current scenario' – when mitigation methods are implemented at the current rate; simulated by FARMSCOPER using national averages on the implementation of mitigation methods under existing schemes and initiatives such as NVZs and the Countryside Stewardship Scheme (Anthony *et al.*, 2009) and (3) 'maximum scenario' – when all mitigation methods in the DEFRA user guide are implemented (Newell-Price *et al.*, 2011).

The 'maximum scenario' expresses the maximum potential mitigation of EPL but excludes feasibility in terms of cost. Therefore, the optimisation feature within FARMSCOPER was also used to identify the least-cost suite of methods to mitigate EPL by a minimum target of 5% of the baseline. FARMSCOPER optimises a selection of mitigation methods from within its library of mitigation methods which are characterised by their annual impact on pollutant loading and capital and operational costs. Optimisation occurs following the elitist NSGA-II genetic algorithm (Deb *et al.*, 2001). In FARMSCOPER, the algorithm is used to select the best solutions for maximum pollutant reduction at minimum cost. The parents of each child solution are generated by tournament selection and solutions on the same Pareto front are given a higher probability of being selected to reproduce and survive in to the next generation if neighbouring solutions are more distant (Zhang *et al.*, 2012).

5.1.4. Generation of model farms to closely represent a pasture-based and housed dairy farming system

To utilise the optimisation feature of FARMSCOPER, previous studies generate a representative farm that is typical of one of the 17 representative farm types derived from the DEFRA 'Robust Farm Type' classification scheme (Zhang *et al.*, 2012). However, for the first time the current study utilised the customizable parameters within FARMSCOPER to generate two model farms that closely represent either a pasture based or housed dairy farming system, by using averages of the farm structure and physical characteristics from the participating dairy farms from each system (Table 5.1). FARMSCOPER has received criticism for its use of fixed averages within each representative farm type, in particular a fixed grazing season of 117 days grazing/year for dairy cows (Willows and Whitehead, 2015). However, despite a fixed grazing season, FARMSCOPER may capture other important differences between pasture-based and housed dairy farming systems (i.e. differences in cropping, fertiliser, and manure and livestock management).

Table 3.2 Structure and physical characteristics of two model farms generated to closely represent a pasture-based and housed dairy farming system

Characteristic		Pasture-based[1]	Housed[2]
Livestock			
	Dairy cows	254	219
	Heifers	71	85
	Calves	120	98
Land use			
	Permanent pasture (ha)	128	109
	Rotational grazing (ha)	51	0
	Arable (ha)	39	59
Soil Type			
		Free draining	Free draining
Climate			
	Rainfall (mm)	900 - 1200	900 - 1200
Dirty water			
		Yard runoff and parlour washings sent to slurry store	Yard runoff and parlour washings sent to slurry store
Grazing option			
		Access to watercourses while grazing	None

[1]Generated using average data from 20 participating farms, [2]Generated using average data from seven participating farms

5.1.5. Statistical analysis

The EPL simulated for each farm in FARMSCOPER was summarised using descriptive statistics in Minitab (Version 2019). Since the average herd size and UAA of participant farms were greater than their respective national averages, EPL was calculated on a total basis (kg) but also relative to UAA (kg/ha) and milk yield (kg/ton milk). To compare EPL from previous studies, the EPL was also expressed as kg per unit of energy (GJ) produced from milk production (Firbank *et al.*, 2013, Lynch *et al.*, 2018). The energy content of milk was assumed to be 2.8 GJ of energy per 1000 litres of milk (Firbank *et al.*, 2013). A linear regression analysis was used to investigate the relationship between the annual EPL and annual milk production for the farms on a total (kg and ton, respectively) and a land use basis (kg/ha UAA and tons/ha UAA, respectively). The difference in mean EPL from farms operating a pasture-based vs housed system was investigated using ANOVA with mean separation by Tukey's test ($P \leq 0.05$ indicating significantly different means).

5.2. Results

5.2.1. Environmental phosphorus loading across all dairy farming systems under 'baseline', 'current' and 'maximum' scenarios

The mean annual EPL from all participant dairy farms (Fig. 5.1), regardless of system, in the 'baseline scenario' was 114.5 kg (range = 13.8 - 583.6, S.E.M = 27.2) which equated to 0.63 kg P/ha UAA (range = 0.04 - 3.47, SEM = 0.13). Assuming that the implementation rate of on-farm mitigation methods estimated by FARMSCOPER in the 'current' scenario are representative of the participant dairy farms in the current study, farmers might have achieved a reduction in EPL by only ~ 11% from the 'baseline', equating to a 'current' EPL of 0.56 kg P/ha UAA. However, the simulation under the 'maximum' scenario suggested the potential for a reduction in EPL of ~ 54% of the 'baseline', equating to a potential annual EPL of only 0.29 kg P/ha through the implementation of all the existing mitigation methods in the DEFRA list (Newell-Price *et al.*, 2011).

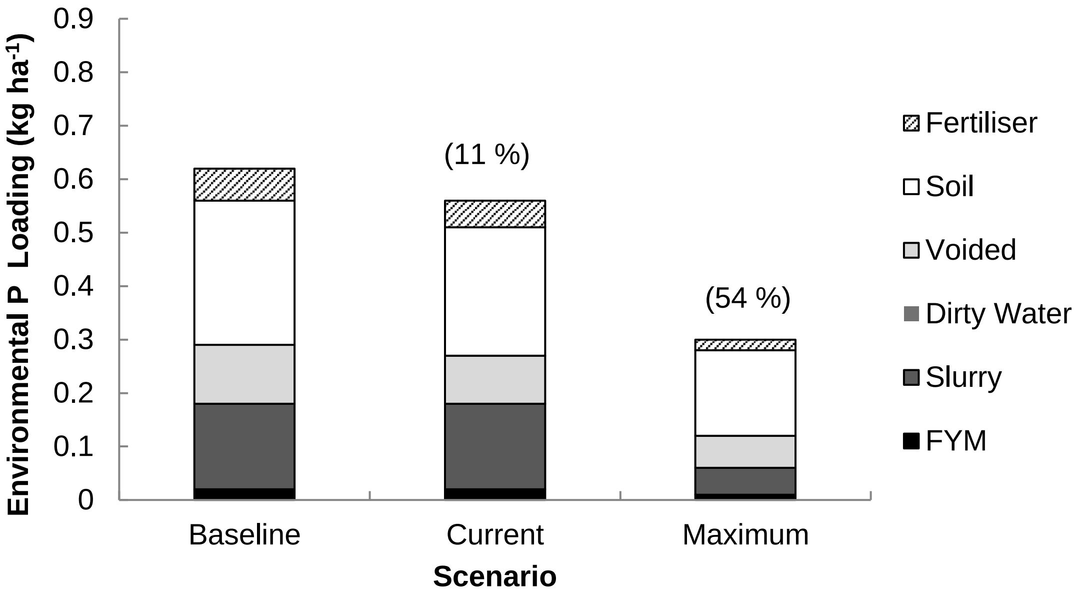

Figure 5.1 Mean source apportionment of the annual environmental phosphorus (P) loading simulated in FARMSCOPER for 27 dairy farms in Great Britain across all systems. 'Baseline' scenario - no mitigation methods implemented, 'Current' scenario –mitigation methods implemented at an estimated rate and 'Maximum' scenario - all mitigation methods in FARMSCOPER's library are implemented. Percentages (in parentheses) are further reductions in environmental P loading compared to the baseline scenario.

The mean annual EPLs under the 'baseline' scenario, per unit of milk and per unit of energy from milk were 0.057 kg//ton of milk (range = 0.007 - 0.176, SEM = 0.008) and 0.021 kg/GJ of milk per year (range = 0.003 - 0.065, SEM = 0.008), respectively. The mean annual EPLs under the 'current' scenario, per unit of milk 0.0004 (range = 0.00003 - 0.002; SEM = 0.0009) kg/ton of milk and per unit of energy from milk were 0.0001(range = 0.00001 - 0.0008, SEM = 0.0003) kg/GJ of milk per year, respectively. The annual EPL from all participating dairy farms under both the 'baseline' and 'current' scenarios, positively correlated with total annual milk yield (tons) and annual milk yield relative to land use (tons/ha UAA) (Figure 5.2).

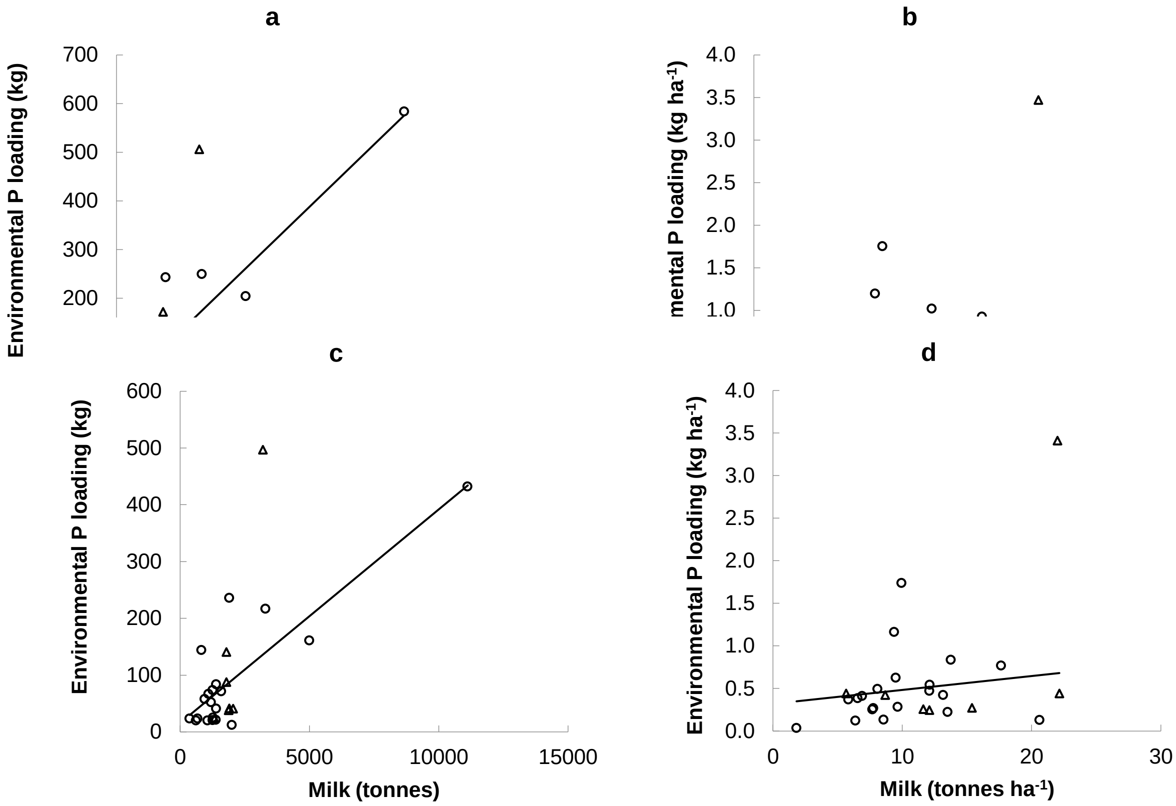

Figure 5.1 Relationships between annual milk production and the annual environmental phosphorus (P) loading simulated using FARMSCOPER under the 'baseline' scenario ((a) total milk yield ($P \leq 0.001$; $R^2 = 64.3$ %) and (b) milk yield relative to land use basis ($P = 0.026$, $R^2 = 18.1\%$)) and under the 'current' scenario ((c) total milk yield ($P \leq 0.001$; $R^2 = 49.39\%$) and (d) milk yield relative to land use basis ($P = 0.033$, $R^2 = 16.9\%$)). 'Baseline' scenario - no mitigation methods implemented and 'Current' scenario –mitigation methods implemented at an estimated rate. Pasture-based dairy farming system (white circle; n = 20), housed dairy farming system (white triangle; n = 7).

5.2.2. Environmental phosphorus loading from pasture-based and house dairy farming systems

A numerically lower mean EPL was predicted from the pasture-based system (Fig. 5.3) compared to the housed system (Fig. 5.4) under the 'baseline' (0.54 vs 0.84 kg P/ha, respectively), 'current' (0.49 vs 0.78 kg P/ha, respectively) and 'maximum' (0.25 vs 0.49 kg P/ha, respectively) scenarios. Consequently, equating to a 56, 59 and 96% greater mean EPL from farms using the housed compared to pasture-based system under the 'baseline', 'current' and 'maximum' scenarios, respectively. However, means were not statistically significantly different.

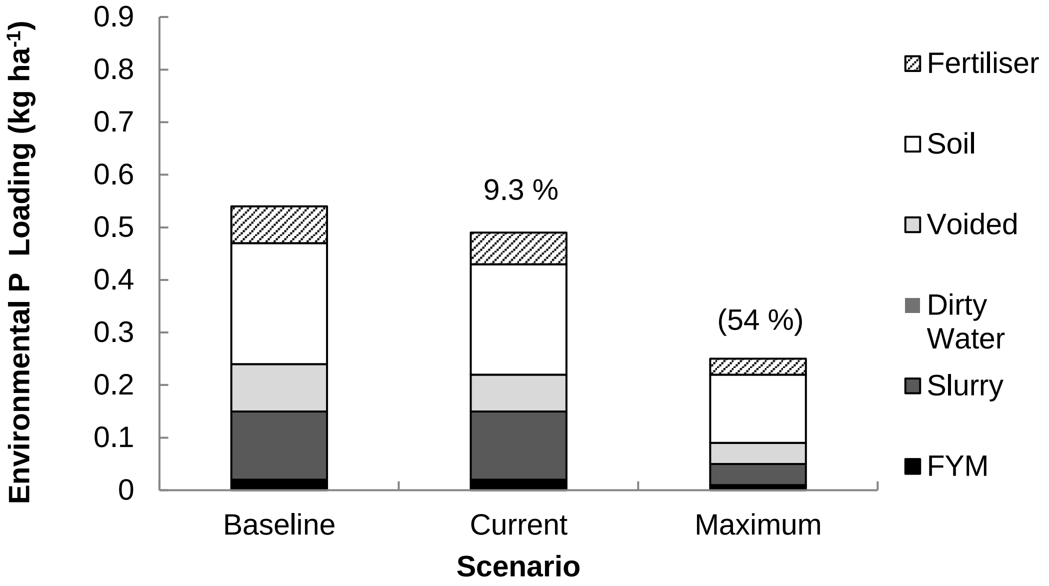

Figure 5.2 Mean source apportionment of the annual environmental phosphorus (P) loading simulated in FARMSCOPER for farms operating a pasture-based system (n = 20). ‘Baseline’ scenario - no mitigation methods implemented, ‘Current’ scenario –mitigation methods implemented at an estimated rate and ‘Maximum’ scenario - all mitigation methods in FARMSCOPER’s library are implemented. Percentages (in parentheses) are the reductions in environmental P loading from the baseline scenario.

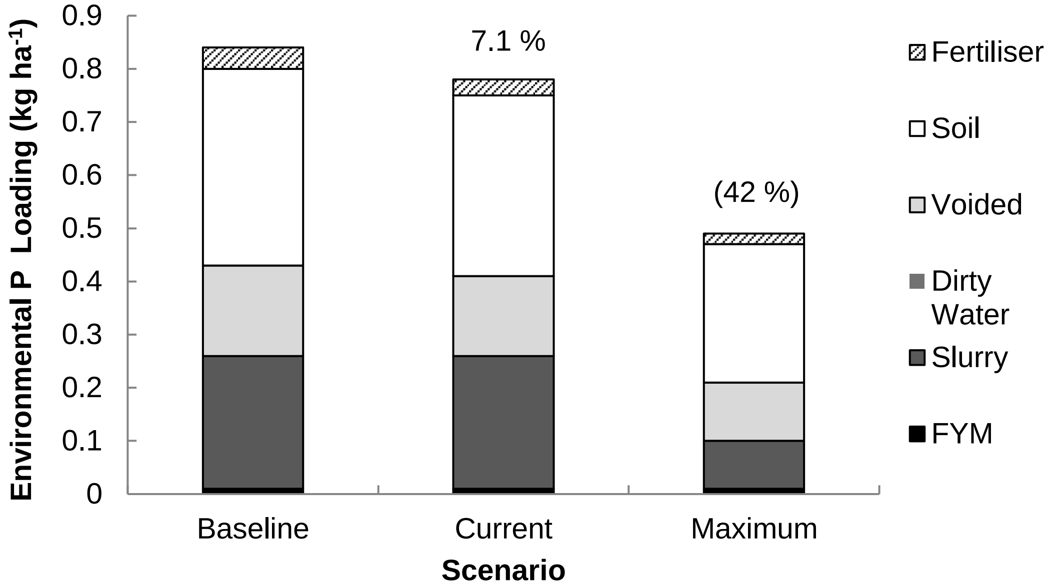

Figure 5.3 Mean source apportionment of the annual environmental phosphorus (P) loading simulated in FARMSCOPER for farms operating a housed dairy farming system (n = 7) in Great Britain. 'Baseline' scenario - no mitigation methods implemented, 'Current' scenario –mitigation methods implemented at an estimated rate and 'Maximum' scenario - all mitigation methods in FARMSCOPER's library are implemented. Percentages (in parentheses) are further reductions in environmental P loading compared to the baseline scenario

5.2.3. Identifying a suite of least-cost methods to mitigate environmental phosphorus loading from a pasture-based and housed dairy farming system

The optimization feature of FARMSCOPER was first used to identify a range of cost-effective suites of methods to mitigate EPL from both the pasture-based and housed dairy farming system (Fig. 5.5). The pasture-based system could potentially reduce EPL by ~ 50% of the 'baseline' without incurring annual financial losses, whereas the housed system could reduce EPL by ~ 60% without annual financial losses.

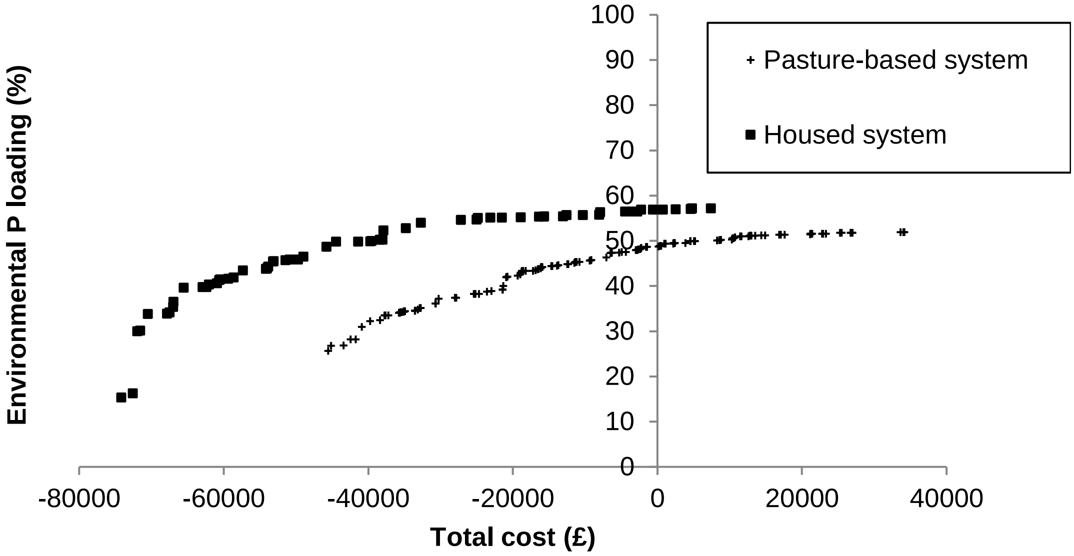

Figure 5.4 Suites of cost-effective mitigation methods following optimisation on environmental phosphorus loading for a minimum target reduction of five percent, for two model farms generated to closely represent either a pasture-based[1] or housed[2] dairy farming system. [1]Generated using average data of 20 participating farms, [2]Generated using average data of seven participating farms.

It was indicated that implementing the least-cost suite of 26 mitigation methods (Table 7.2) in the pasture-based system provided a potential annual saving of £45,578 and annual reduction of EPL by 25.6% (Table 5.2). In contrast, a potential annual financial saving of £74,176 and a reduction of 15.4% in EPL when implementing the least-cost suite of 14 mitigation methods (Table 7.3) was indicated in the housed system. Across both dairy farming systems, the same seven mitigation methods were selected for every optimal suite of mitigation methods (Table 5.3).

Table 5.1 Effects of the suites of least-cost mitigation methods that could achieve minimum target phosphorus reductions for a pasture-based and housed dairy farming system.

	Pasture-based[1]			Housed[2]		
Target reduction (%)	Cost (£)[3]	Reduction achieved (%)	No. methods	Cost (£)	Reduction achieved (%)	No. methods
5	-45,578	25.6	26	-74,176	15.4	14
10	-45,190	17.8	23	-64,788	34.6	24
15	-46,394	21.3	21	-60,097	32.7	25
20	-48,093	21.4	25	-69,430	28.3	22
25	-44,393	26.2	23	-68,926	37.5	26
30	-41,538	31.5	26	-67,854	34.7	21
35	-31,941	35.1	31	-59,119	39.6	31
40	-20,551	42.9	28	-53,872	40.8	29
45	-11,288	45.2	34	-55,114	45.2	29
50	2,790	50.0	34	-42,783	50.2	28
55	-	-	-	-17,643	55.6	31

[1]Generated using average data of 20 participating farms, [2]Generated using average data of seven participating farm, [3]total cost = capital cost + operational cost or saving

Table 5.2 Individual environmental and financial impact of the seven mitigation methods selected in all cost-effective suites of methods to mitigate environmental phosphorus (P) loading from both a pasture-based and housed dairy farming system.
[1]Total cost = capital cost - operational cost

	Pasture-based		Housed	
Mitigation method	Reduction (%)	Cost[1] (£)	Reduction (%)	Cost[1] (£)
Establish in-field grass buffer strips	3.5	176	8.0	271
Correctly-inflated low ground pressure tyres on machinery	1.3	-2,373	3.2	- 2438
Management of arable field corners	1.3	383	3.1	644
Do not apply P fertilisers to high P index soils	1.2	- 730	2.6	- 630
Make use of improved genetic resources in livestock	0.6	-25,586	0.5	-26,052
Management of in-field ponds	0.5	35	1.4	52
Integrate fertiliser and manure nutrient supply	0	-13,928	0	- 34,329

5.3. Discussion

5.3.1. Environmental phosphorus loading across all dairy farming systems under ‘baseline’, ‘current’ and ‘maximum’ scenarios

It was not within the scope of this study to validate the EPLs simulated by FARMSCOPER using on-farm measures, because the models within FARMSCOPER, in particular the PSYCHIC model (Davison *et al.*, 2008, Strömqvist *et al.*, 2008) are validated methodologies employed in previous studies (Zhang *et al.*, 2012). However, the broad range in EPL across all dairy farming systems under each scenario in the current study, suggested that the data collection approach sufficiently captured differences in farm structure and physical characteristics that were important in determining EPL. Furthermore, the mean annual EPL across all participating farms simulated for the ‘baseline’, ‘current’ and ‘maximum’ scenarios (0.63, 0.56 and 0.29 kg P/ha, respectively) were all similar to the EPL reported from dairy farms in the South of England in 2009 by Zhang *et al.* (2012) using the same scenarios (0.5, 0.44 and 0.19 kg P/ha). When considering the uncertainty associated with modelling scenarios, the EPL simulated in the current study under the ‘baseline’ scenario could be considered acceptable. However, the implementation rate of mitigation methods in the ‘current’ scenario is simulated using older averages on the implementation of mitigation methods under existing schemes and initiatives such as NVZs and the Countryside Stewardship Scheme (Anthony *et al.*, 2009).

Consequently, the reliability of simulated EPL under the 'current' scenario could be improved by updating the average data used by FARMSCOPER or by collecting additional information regarding the farm's actual implementation of mitigation methods (Zhang *et al.*, 2012).

The variation in EPL relative to milk production among the farms in the current study, supports that there are opportunities for some dairy farmers to intensify sustainably in regard to P (Lynch *et al.*, 2018), when considering that farms producing similar amounts of milk had varying amounts of EPL. The mean 0.021 kg P/GJ milk produced per year of EPL from across all farms under the 'baseline' scenario in the current study, was relatively lower than the 0.03 kg P/GJ milk produced per year reported for South-Western England dairy farms in 2012 using the same scenario (Lynch *et al.*, 2018). Furthermore, the positive correlation between the annual energy of milk produced per ha and EPL per ha in the current study (R^2 = 0.17) was weaker than the strength of the relative correlation (R^2 = 0.53) for dairy farms in South-Western England in 2012 (Lynch *et al.*, 2018). Therefore, the current study indicates that some progress has been made towards the sustainable intensification of GB dairy farming in regard phosphorus pollution from 2012 to 2019. However, the above discrepancies may partly be attributed to differences in the samples of dairy farms used or the transformation of data from an existing dataset into an appropriate format for input into FARMSCOPER by Lynch *et al*. (2018). Nevertheless, the finding in the current study that EPL from dairy farms remains to be positively correlated with energy of milk produced, emphasises the importance of mitigating EPL from dairy farms, as the prevalence of housed dairy farming systems has increased since 2004, as part of an ongoing intensification of dairy production (March *et al.*, 2014).

5.3.2. Environmental phosphorus loading from pasture-based and housed dairy farming systems

Housed dairy farming systems are associated with a denser stocking rate (O'Brien *et al.*, 2012). Densely stocked farms are associated with increased imports of purchased concentrates, which usually contain 50% more P than grass-based feeds in GB (Ruane *et al.*, 2013). Since, the P concentration of manure is highly and positively correlated with dietary P intake in dairy cattle, a large amount of P-rich manure can be generated in a housed dairy farming system, which is then applied to the same arable and grass land usually in excess of crops P requirement (O'Brien *et al.*, 2012, Svanback *et al.*, 2019). Consequently, applying P to land beyond the crops' requirement can result in soil P accumulation and subsequent environment P loading. Furthermore, more densely stocked farms have a greater soil compaction than less densely stocked farms, and subsequently a greater amount of EPL as surface runoff can be expected as a result of reduced water infiltration

(Johnston and Dawson, 2005). Therefore, it has been suggested that housed dairy farming systems may be a significantly greater risk to EPL than pasture-based systems (O'Brien *et al.*, 2012, March *et al.*, 2016, Akert *et al.*, 2020). Conversely, although the current study simulated a 59% greater mean annual EPL from the farms using the housed system compared to the pasture-based system under the ‘current’ scenario, this difference was not statistically significant. The chances of finding significance in the current study were likely reduced in the current study because of the small sample size and FARMSCOPER’s estimates exclude variations in important farm practices (i.e. feeding).

FARMSCOPER uses a fixed grazing season of 117 days/year for dairy farms, which was raised as unrealistic by farm advisors in 2012 (Willows and Whitehead, 2015). A shorter grazing season in a housed system results in greater reliance on purchased concentrates (Mihailescu *et al.*, 2015). Subsequently, the greater eutrophic risk associated with a housed system is largely attributed to their greater import of concentrate feed and subsequent greater manure P concentration (O'Brien *et al.*, 2012). FARMSCOPER’s fixed grazing season is based on data from between 2001 and 2007. However, the prevalence of the housed system amongst GB dairy farming has increased (March *et al.*, 2014). Therefore, the current study highlights the need for FARMSCOPER to enable the manipulation of many parameters in order for users to create a farming system that closely matches their practice, if it means to continue to support policy-makers in decision making by simulating information that is reflective of modern diverse dairy farming systems.

5.3.3. Identifying a suite of least-cost methods to mitigate environmental phosphorus loading from pasture-based and housed dairy farming systems

In the current study, the optimization feature of FARMSCOPER suggested that there is considerable scope to reduce EPL by at least 50% in both systems without annual financial losses (capital expenditure being recovered through annual operational savings in some cases). Similarly, previous studies investigating mitigation methods for various representative farm types using FARMSCOPER found dairy farming to have the most pronounced potential savings when mitigating EPL compared to other farm types (Zhang *et al.*, 2012, Collins *et al.*, 2017). In the current study, the same seven mitigation methods that were selected in every cost-effective suite of mitigation methods for both the pasture-based and housed system either targeted reducing nutrient input (i.e. integrating P concentration in manure and mineral fertiliser, make use of improved genetic resource and not applying mineral fertiliser P to high P index soils) to provide an operational saving or were easy to implement (establish grass buffer strips, use correctly inflated low pressure tyres, manage arable field corners). Since policy-makers are becoming increasingly interested in using voluntary approaches to influence positive environmental change because farmers tend to avert responsibility and resist enforced regulations (Collins *et al.*, 2017). They are also reported to have the most positive attitude towards changing practices that are associated with lower costs, i.e. practices that will reduce input use (Collins *et al.*, 2017, Micha *et al.*, 2018). Therefore, the findings of the current study suggests that more emphasis should be put on approaches to increase the implementation rate of existing mitigation methods, in particular the seven mitigation methods discussed in the current study, to reduce EPL, such as increasing knowledge transfer between farmers, advisers and researchers (Micha *et al.*, 2018).

The optimization of mitigation methods in FARMSCOPER is based solely on the environmental and financial impact given to each mitigation method in FARMSCOPER's library. Consequently, other important site-specific drivers of a mitigation method being selected were not considered, such as the farmer's personal preference, technological innovation, agri-environmental scheme incentives and farm typology and practice (Zhang *et al.*, 2012, Micha *et al.*, 2018). Therefore, the feasibility of implementing the mitigation methods selected in the least-cost suite may vary with farm typology (Micha *et al.*, 2018) and the economic saving for dairy farmers may also vary depending on factors such as agri-environmental incentives. In the current study, differences in the mitigation methods selected in the least-cost suites occurred between the pasture-based and housed dairy farming systems. For example, increasing the use of maize silage in the housed system could provide potential annual operational savings, whereas soil management was important in the pasture-based system but this was associated with an operational cost, consequently less annual financial savings occurred in the pasture-based system. Therefore, the current study suggests that the approaches used to increase the implementation rate of existing methods to mitigate EPL in GB dairy farming would benefit from a system-specific approach.

5.3.4. Opportunities to improve the accuracy of FARMSCOPER in predicting environmental P loading and identifying a least-cost suite of methods to mitigate environmental P loading'

Since FARMSCOPER is a decision support tool, which could be used to support policy-making, it is important to ensure that the results from FARMSCOPER simulation are accurate (McDowell *et al.*, 2016). In the current study, the greater potential financial saving associated with the least-cost suite of methods to mitigate EPL for the housed system compared to the pasture-based system, was largely attributed to the method of integrating the P concentration of manure and fertiliser when planning land application rates, because of the greater production of manure in the housed system. Indeed, accurately crediting the P concentration of manure can provide financial savings by allowing more precise purchasing of mineral fertiliser P relative to manure P concentration (Knowlton, 2011).

However, integrating manure and fertiliser P may not be the most cost effective solution to reduce EPL for farmers handling P-rich manure in areas with a high soil P index, because farms may incur a cost to transport manure to further grass and arable land to avoid the risk of applying P in excess of the crops P requirement in nearby land (Knowlton, 2011). Therefore, lowering the concentration of P in manure by minimising the feeding of P in excess of the cows' requirement, which is a common practice in many GB dairy farms (Sinclair and Atkins, 2015), is a recommended optimal strategy (Knowlton, 2011).

In the current study, FARMSCOPER only selected the method of 'reducing dietary P concentration' in ~ 25% of the cost-effective suites of methods to mitigate EPL. Largely because FARMSCOPER calculates the cost of reducing dietary P concentration by multiplying the number of dairy cows by a fixed factor of 0.02 and then multiplying this by an annual operating cost of £723. This calculation is devised from the assumption that more precise formulation of diets requires analytical data on forage P concentrations that is not readily available. Additionally, the calculation assumes that it is difficult to formulate low-cost, low-P diets because the P concentration in less expensive, protein-rich feed ingredients, which are commonly used in dairy cow diets, is considered high (Bateman *et al.*, 2008, Newell-Price *et al.*, 2011). However, in many cases P feeding could be minimised by simply eliminating or reducing the use of inorganic P supplements, which can provide financial savings (Kebreab *et al.*, 2008) and can minimise the water soluble fraction of manure P that is more prone to runoff (Dou *et al.*, 2002). Consequently, further research into the annual impacts on EPL and finances when reducing dietary P concentration in dairy farms would be beneficial to the accuracy of least-cost suites of mitigation methods optimized by FARMSCOPER.

Extending the grazing season was a selected method in the least-cost suite of methods to mitigate EPL for both the pasture-based and housed dairy farming system, largely because it provided a saving in operational costs for farmers in regard to reduced cost of silage production and manure management (Newell-Price *et al.*, 2011). Inversely, FARMSCOPER also estimated that an extended grazing season would increase EPL because of increased soil poaching from grazing livestock (Newell-Price *et al.*, 2011). Conversely, EPL attributed to an extended grazing season may be lower than that simulated by FARMSCOPER as FARMSCOPER does not consider the potential reduction in manure P concentration as a result of replacing a large amount of high P concentrate with grass-based feeds, which typically contain 50% less P than concentrates in GB (Withers *et al.*, 2001, Mihailescu *et al.*, 2015). Furthermore, the method of extending the grazing season may not be feasible for a housed system where land for grazing is often limited. Therefore, the current study highlights that further work into the annual environmental and financial impact from the method of extending the grazing season could be important to improve the prediction accuracy of

FARMSCOPER and subsequently FARMSCOPER's usefulness to policy makers. Furthermore, the current study supports that for decision support tools to be beneficial for policy-makers, they need to consider farm typologies to select the right measures at the farm-scale (Micha *et al.*, 2018).

5.4. Conclusions

Farms using the housed dairy farming system had a mean 'current' potential EPL ~ 59% greater than farms using the pasture-based system. However, statistical significance was not found, partly of a small sample size and because FARMSCOPER's estimates exclude variations in important farm practices (i.e. feeding). Furthermore, despite the current study indicating some progress may have been made towards achieving the sustainable intensification of dairy farming in the aspect of EPL, the current study indicates EPL from dairy farms may remain to be positively correlated with milk production on a total and land basis. Therefore, the current study emphasises the importance of ensuring effective mitigation of EPL as the prevalence of housed systems in GB dairy farming has increased. The current study demonstrates that there is considerable scope to reduce EPL by ~ 50% in a pasture-based dairy farming system and ~ 60% in a housed system without incurring annual financial losses. These considerable reductions can be achieved by implementing existing mitigation methods. Therefore, the current study leads to the recommendation that more emphasis should be put on approaches to increase the implementation rate of existing methods to mitigate EPL, such as increasing knowledge transfer between farmers, advisers and researchers. However, such approaches would benefit from a more system-specific approach. Further consideration of the environmental and financial impacts from minimising P feeding and the increased customizability of parameters in FARMSCOPER are recommended to ensure that the results from FARMSCOPER's simulations are reflective of modern GB dairy farming practice as to correctly advice policy-makers, farm advisers and farmers when developing strategies to mitigate EPL.

6. General discussion

In the P feeding survey (Objective 1), there was lower than optimal response rate and larger herds and UAAs than the typical 165 lactating cows and 154 ha for UK dairy farms (DEFRA, 2020). Subsequently, suggesting that the respondents were representative of farmers more interested in P feeding than the average farmer (Dou *et al.*, 2003), of who assumedly would be more aware of P feeding. Therefore, results from the survey are likely reflective of a 'best case' scenario and consequently, the national situation regarding P feeding in dairy farms is likely more concerning than reported here. Findings from the survey recommend that the apparent excess P feeding in diverse dairy farming systems could be minimised by increasing the availability of P management training to farmers and feed professionals, better utilizing the influence of feed professionals on P management

(Dou *et al.*, 2003) and encouraging the following of extant national P feeding recommendations to reduce the inconsistency in P feeding advice associated with lack of uniformity across all available P feeding recommendations (Knowlton, 2011). Furthermore, the current survey provides an indication that such recommended strategies to minimise P feeding in GB dairy farming would benefit from a more system-specific approach.

In the assessment of P balance and PUE (Objective 2), data was used from 30 dairy farms across GB which is a similar sample size to other studies that determined PUE on ~21 dairy farms (Mihailescu *et al.*, 2015). Even though the sample size may seem small, this study was one of the first to involve farmers that represented each of the proposed five different GB dairy farming systems (Garnsworthy *et al.*, 2019), one of the first to measure the concentration of P in import and export items and the first to propose an approach to calculate SPB on GB dairy farms. Therefore, the current study accurately demonstrated that housed dairy farming systems had greater farm-gate and soil-surface P surpluses and subsequently lower PUE compared to some pasture-based systems. Furthermore, representation from each dairy farming system allowed the opportunity to demonstrate that strategies to improve PUE on dairy farms should be system-specific. For example, it was evident both housed and pasture-based systems could improve PUE by increasing the inclusion rate of home-grown feed (primarily forages) into the herd's diet. However, it appeared that system-specific strategies were required to increase the use of home-grown feed in formulating the herd diets. Pasture-based systems could increase the reliance on home-grown feed by extending the grazing season (Mihailescu *et al.*, 2015) and maintaining a moderate stocking rate adjusted according to the availability of home-grown forage. Whereas, housed systems could increase the relative proportion of home-grown feed in the herds' diet by formulating dietary P concentration more closely to the cows P requirement by minimising excess import of P with concentrate feed, partly replacing high P forage (grass silage) with low P forage (maize) and by removing unnecessary inorganic P supplements from the diets (Kebreab *et al.*, 2008). However, large P surpluses and consequently high soil P index on participant dairy farms across all farming systems suggested that PUE in both housed and pasture-based dairy farming systems could be improved by accurately crediting P accumulated in the soil in the calculation of fertiliser application rates (Withers *et al.*, 2017). Additionally, regular analysis of manure P for accurate crediting of manure P in the calculation of mineral fertiliser application rates could reduce the over application of P to land (Svanback *et al.*, 2019), especially on farms that generate P-rich manure due to P overfeeding their herds NRC (2001).

In the simulation of environmental P loading (Objective 3), the positive association between milk production intensity and P loss from dairy farms agreed with previous studies (Firbank *et al.*, 2013).

However, the current study is the first to report this relationship using data that has been simulated from information collected directly from farmers as opposed to adapted from existing databases. Additionally, the current study was the first to use FARMSCOPER to simulate environmental P loading from both a housed and pasture-based dairy farming systems. Therefore, the current study was able to indicate that a housed dairy farming system had numerically higher environmental P loading and greater financial saving when mitigating environmental P loading, compared to pasture-based systems. However, statistical significance of these differences between farming systems was not found and consequently, suggested that FARMSCOPER's current approach to defining representative farm types may not capture important differences between dairy farming systems (Willows and Whitehead, 2015). Therefore, there is a need to improve the customizability of the parameters within FARMSCOPER such that it can continue supporting stakeholders and policy-makers by making predictions of environmental P loading and optimising mitigation methods that are more accurately reflective of GB dairy farming systems.

Future research perspectives

i. Simulate the FPB and SPB on farms feeding diets manipulated to contain a high and low P concentration and compare their financial and environmental impact using a within-farm or between-farm approach.
ii. Further adapt the SPB principles using UK values to produce a more UK-specific model that could be integrated into widely employed farm advisory software, such as PLANET.
iii. Further investigate net benefit of extended grazing season in terms of EPL from dairy farms: increased EPL attributed to increased soil compaction vs. reduced EPL attributed to reduced manure P concentration as a result of feeding more home-grown feed (primarily forages) which is expected to be low in P concentration compared to concentrates.
iv. Further investigate strategies to implement the improvements to FARMSCOPER recommended from this project to ensure output is reflective of modern GB dairy farming systems (i.e. increased customizability of farm parameters to create a model farm more closely representing a farming system).

Conclusions and recommendations

In conclusion, improving P management in diverse dairy farming systems is increasingly important as the prevalence of housed dairy farming systems increases, with these housed systems having greater P surpluses and lower PUE than some pasture-based systems. Real practical cost-effective opportunities to mitigate EPL at a financial saving for farmers exist and largely involve minimising mineral fertiliser and purchased feed P and employing mobilisation management practices. However, strategies to cost-effectively reduce EPL from dairy farms in countries operating diverse dairy farming systems should be system-specific. A further reduction in EPL from dairy farms in the future largely relies on minimising P feeding.

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8. Appendix

Supplementary table S2 Classifications of Great Britain dairy farms adapted from Garnsworthy, *et al.* (2019)

Characteristic	Classification				
	1	2	3	4	5
Calving approach	Spring	Block / all year	Block / all year	All year	All year
Days grazing	> 274 days	183 to 274 days	92 to 182 days	0 to 90 days	Housed
Feeding approach	Limited supplements	More use of supplements	Mixed ration supplements	Mostly mixed ration	Total mixed ration

Table 8.1 Questions included in a questionnaire on phosphorus feeding distributed to Great Britain dairy farmers and feed advisers

No.	Question	Type
1	What are the first 3 digits of your postcode?	Open
2	On average how many lactating cows are milked annually?	Open
3	What is your rolling annual average milk yield per cow?	Open
4	How many days do you allow for lactating cows grazing?	Open
4.1	What percentage of your whole herd is grazed?	Open
5	Which calving system do you use?	Open
5.1	If block calving, please circle which months cover the block	Closed
6	Is your farm organic?	Closed
7	Who is responsible for the nutrition of your herd?	Closed
8	What is your annual amount of concentrates per cow (kg)?	Open
8.1	When do you feed these concentrates?	Closed
9	How do you feed your lactating cows with inorganic phosphorus (Phosphate) supplements?	Closed
9.1	Is your current supplement practice different from that followed 5 years ago?	Closed
10	Currently, which official recommendation (nutritional guidelines or computer rationing programmes) for feeding dietary phosphorus to dairy cows do you (or your nutrition advisor) follow?	Closed
10.1	If you do not follow any recommendation, why is this?	Closed
11	Do you consider dietary phosphorus concentration when deciding on which feed ingredient to buy?	Closed
12	On a scale of 0-10 how much of a priority do you give the consideration of phosphorus when formulating your diets? (10 being top priority and 0 being 'I don't consider it when formulating diets')	Closed

13	Please tick the most appropriate option for your feeding strategy	Closed
13.1	If all milking cows are fed the same dietary phosphorus concentration, why have you chosen this option?	Closed
14	How confident are you in the accuracy of your diet mixing? (training and accuracy of people responsible for feeding and scale accuracy)	Closed
15	Do you have any systems in place to monitor the accuracy of adding feed ingredients to a mix?	Closed
16	How regularly do you analyse forage phosphorus content?	Closed
16.1	Do you use this forage phosphorus content when you formulate rations?	Closed
16.2	If you do not analyse your forage phosphorus content, what is the reason for this?	Closed
17	What do you think phosphorus is required for in the diet?	Closed
18	Which level of dietary phosphorus [as % diet Dry Matter] do you think will over-feed phosphorus?	Closed
19	How important is it to you to make sure your cows are eating enough phosphorus?	Closed
20	What level of dietary phosphorus [as % diet Dry Matter] are your cows offered in total?	Closed
21	If you were found to be overfeeding phosphorus, would you be willing to reduce dietary phosphorus concentration?	Closed
21.1	What would prevent you from reducing phosphorus overfeeding?	Closed
22	What would be your reasons for reducing phosphorus content if you were overfeeding?	Closed
23	Are you aware of the environmental impact of diffuse phosphorus loss from dairy farms in the UK?	Closed
24	Are you aware of any UK environmental legislation relating to phosphorus use in animal agriculture?	Open
24.1	If yes, where did you hear about this information?	Closed
25	Are you aware of how phosphorus has impacted dairy farm management in other countries (such as the Netherlands)?	Closed
26	Are you aware of the close link between phosphorus overfeeding and diffuse phosphorus loss to the environment	Closed
26.1	If yes, have you changed your practice to reduce phosphorus overfeeding?	Closed
26.2	If yes, what have you done?	Closed
27	How regularly do you have your manure/ slurry analysed for phosphorus?	Closed
27.1	If yes, what do you do with this information?	Open
28	Do you feel there is enough training and education on phosphorus pollution management available to you	Closed
29	Do you need any new information or do you want any information to be updated in order to assist you in balancing diets for phosphorus or to adopt precision phosphorus feeding? If yes, then please specify.	Open

Table 8.2 The 26 mitigation methods selected to achieve the minimum target of 5% reduction in environmental phosphorus (P) loading from a model farm generated to closely represent a pasture-based dairy farming system[1]

Mitigation method	P loss reduction (%)	Total Cost[2] (£)
Use correctly-inflated low ground pressure tyres on machinery	1.3	-2373
Leave out winter stubbles	0.7	344
Unfertilised cereal headlands	0.0	380
Management of arable field corners	1.3	383
Management of in-field ponds	0.5	35
Establish new hedges	0.0	279
Do not spread FYM at hgih risk times	0.8	16
Do not spread slurry or poultry manure at high-risk times	4.0	16
Do not apply manure to high-risk area	0.0	0.0
Cover solid manure stores with sheeting	0.3	171
Store solid manure heaps on an impermeable base and collect effluent	1.4	1348
Extend the grazing season	-7.0	-9506
Do not apply P fertiliser to high index soils	1.2	-730
Use manafactured fertiliser placement technology	0.0	-143
Integrate fertilise and manure nutrient supply	0.0	-13928
Use a fertiliser recommendation systems	0.0	-427
Make use of improved genetics in livestock	0.6	-25586
Loosen compacted soils in grassland fields	12.5	2417
Establish in-feild grass buffer strips	3.5	176
Manage over winter tramlines	0.1	7
Leave autumn seedbeds rough	0.0	151
Cultivate and drill across the slope	0.2	58
Unfertilised cereal headlands	0	380
Cultivate compacted tillage soils	3.7	421

Construct troughs with concrete base	3.6	726
Farm track management	0	46
Total[3]	**28.7**	**- 45339**

[1]Generated using average data of 20 participating farms, [2]Total cost is the sum of capital and operational costs, [3]Total cost and reduction in environmental P loading may vary when evaluating mitigation methods individually compared to together

Table 8.3 The 14 mitigation methods selected to achieve the minimum target of 5% reduction in environmental phosphorus (P) loading from a model farm generated to closely represent a housed dairy farming system[1]

Mitigation method	P loss reduction (%)	Total Cost[2] (£)
Increase use of maize silage	- 0.3	-1665
Use correctly-inflated low ground pressure tyres on machinery	3.2	-2438
Management of arable field corners	3.1	644
Management of in-field ponds	1.4	53
Do not spread slurry or poultry manure at high-risk times	0.3	62
Construct water troughs with concrete base	2.3	451
Extend the grazing season	-6.2	-9613
Do not apply P fertiliser to high index soils	2.6	-630
Integrate fertiliser and manure nutrient supply	0.0	-34329
Use a fertiliser recommendation systems	0.2	-1548
Make use of improved genetics in livestock	0.5	-26052
Establish riparian buffer strips	3.8	183
Leave autumn seedbeds rough	0.2	522
Establish in-feild grass buffer strips	8.0	271
Total[3]	**19.1**	**-74089**

[1]Generated using average data of seven participating farms