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

B.P. Harrison[a], M. Dorigo[b], C.K. Reynolds[a], L.A. Sinclair[c], J. Dijkstra[d] and P.P. Ray[a*],

[a]Department of Animal Sciences, School of Agriculture, Policy and Development, University of Reading, Reading, RG6 6EU, UK

[b]AHDB Dairy, Agriculture and Horticulture Development Board, Stoneleigh Park, Kenilworth, Warwickshire, CV8 2TL, UK

[c]Department of Agriculture and the Environment, Harper Adams University, Shropshire, TF10 8NB, UK

[d]Animal Nutrition Group, Wageningen University & Research, 6700 AH Wageningen, Netherlands

* Corresponding author: p.p.ray@reading.ac.uk

ABSTRACT

CONTEXT

Identifying the determinants of phosphorus (P) balance and use efficiency (PUE) is critical to improving the sustainability of dairy farming in countries operating diverse dairy farming systems because each system contributes to eutrophication through different pathways. However, information about P balance and PUE across diverse dairy farming systems is scarce.

OBJECTIVE

The current study aimed to use a novel approach to determine P balance and PUE, and identify their key determinants across diverse dairy farming systems in GB.

METHODS

Data from 29 dairy farms representing systems with differing feeding approaches and production levels was collected from farm records or generated by quantifying P concentration in feed, manure, and soil samples. The methodology of the nutrient management tool ‘Planning for Land Application of Nutrients for Efficiency and the environmenT (PLANET) and the principles of ‘Annual Nutrient Cycling Assessment’ (ANCA) were used to calculate farm-gate P balance (FPB) and soil-surface P balance (SPB), respectively. Differences in P balance and PUE between dairy farming systems were investigated using ANOVA. Determinants of P balance and PUE were identified using multiple stepwise linear regressions.

RESULTS AND CONCLUSIONS

The current study demonstrated a novel approach of calculating FPB and SPB that captures differences in the P concentration of manure and milk between systems.

Phosphorus surplus was higher and PUE was lower in housed systems compared to pasture-based systems (except for a Spring-calving system grazing $\geq$ 274 days/year) primarily because of greater import of concentrate feed, highlighting the importance of reducing concentrate feed import into housed systems to minimise P import. Farms with greater inclusion rate of home-grown feed (primarily forages) in their herds' diet had higher PUE and lower P surplus. Thus, pasture-based systems could improve PUE by increasing the inclusion rate of home-grown feeds in the herd diet only if they maintain a stocking rate that matches the feed demand of the herd to the availability of home-grown feeds. In conclusion, the assessment of PUE and strategies to improve it should consider system classification beyond strict housed and pasture-based systems.

SIGNIFICANCE

The current study demonstrated the foundations of an approach to calculate FPB and SPB that could be more robust compared to using standard P coefficients particularly in countries that operate diverse dairy farming systems. With further development, this approach could be adopted and could change the way GB dairy farmers and advisers calculate P balances in diverse systems.

Keywords: diverse dairy farming systems, phosphorus balance, phosphorus use efficiency, sustainable intensification, phosphorus

1. INTRODUCTION

Dairy farming in many world regions is intensifying by increasing milk output and feed import without acquiring additional land, primarily to improve economic efficiency (Clay *et al.*, 2019). However, regions densely stocked with dairy cattle are associated with phosphorus (P) imbalances, as a large amount of concentrate feed is imported into the region with the P-rich manure subsequently being generated and applied on nearby land, in addition to imported fertiliser (Svanback *et al.*, 2019). Land application of this P-rich manure often leads to application of P in excess of the crops' requirement, which leads to accumulation of P in the soil and P loss from agricultural land to waterbodies, consequently contributing to eutrophication (Adenuga *et al.*, 2018). Therefore, improving P use efficiency (PUE) is important for sustainable dairy production systems because it can lower the risk of P loss and increase a farm's net profit through more precise feed and fertiliser purchases (Mihailescu *et al.*, 2015, Adenuga *et al.*, 2018). In recent years, research has begun to suggest that an all-year housed system may be less efficient in P use than a pasture-based system on a per unit of milk solids or per ha basis based on a small number of research farms (O'Brien *et* al 2012; March *et al.* 2016) and 24 commercial farms in Switzerland (Akert *et* al. 2020). However, in countries such as GB, dairy production is so diverse that a simple classification into strict pasture-based and housed systems would not reflect an accurate representation of the diversification. For example, five classifications of dairy production system have been proposed to explore feed efficiency in GB dairy farming (Garnsworthy *et al.* 2019). However, currently no research has investigated the PUE of commercial farms reflective of current GB practice across such diverse dairy farming systems, which contain multiple classes of pasture-based systems. An indepth comparison of the PUE and P flows between such dairy farming systems may provide new insight into developing strategies to improve PUE or at least will confirm which existing strategies can improve PUE in commercial dairy production system that is more diverse than a system simply classified into two types *i.e.* strict pasture-based and housed.

The PUE of dairy farms is often assessed by calculating farm-gate P balance (FPB) or soil-surface P balance (SPB) (Oenema *et al.*, 2003, Thomas *et al.*, 2020). A surplus indicates a long-term risk of P accumulating in soil and subsequently being lost to waterbodies (Mihailescu *et al.*, 2015), although a P deficit can also be unsustainable as depletion of soil P reserves can lead to reduced soil fertility (Thomas *et al.*, 2020). Principally, FPB and SPB should match, and although both FPB and SPB follow a similar trend, SPB is observed to be lower than FPB (Adenuga *et al.*, 2018). This is likely because FPB cannot explicitly represent the build-up, depletion and consumption of internal stock (i.e. harvested crop and silage that has been stored on farm and not exported or fed to herd in the given year). Additionally, SPB may underestimate the manure P import into soil, as the extant energy systems that SPB relies on can under-predict the energy requirement of dairy cattle (Dijkstra, 2008, Moraes, 2015).

However, SPB provides information on the internal flow of P that is not captured in a FPB but is important in identifying strategies to improve PUE. Therefore, both FPB and SPB are important to provide a meaningful assessment of the risk posed by a dairy farm to the aquatic environment.

There is no information available on the SPB of dairy farms reflective of current GB commercial dairy farming practice, likely because of the difficulty in calculating manure P import into soil and grazed grass P export out of soil (Adenuga *et al.* 2018). An approach to calculate SPB has been previously employed to assess the total soil nutrient balance of agricultural land in England (Defra 2019) and more specifically dairy farms in Northern Ireland (Adenuga et al 2018). However, these approaches use a standard coefficient to calculate manure P import into soil and milk P concertation. Milk P concentration largely influences FPB and the deposition of dietary P in the herd, which is used to calculate manure P import into soil. Consequently previous approaches to calculate FPB and SPB used in GB dairy farms may be unable to consider how key differences (e.g. different feeding approaches) between diverse dairy farming systems operating in GB truly influence P balances in each system. Therefore, the current study is the first to use P concentrations measured in farm samples and apply the principles of the Annual Nutrient Cycling Assessment (ANCA) to capture important differences in the internal flow of P between commercial dairy farming systems reflective of diverse GB practice. In addition, currently available information about P balance on commercial dairy farms (Withers *et al.*, 1999, Withers *et al.*, 2001, Raison *et al.*, 2006) are not reflective of modern GB dairy farming practice because there has been an increase in the prevalence of housed dairy farming systems in recent years (March *et al.*, 2014). Therefore, the approach used in the current study to recruit a balanced number of dairy farms operating a housed and various pasture-based systems is important in indicating potential differences between these GB dairy farming systems. Furthermore, identifying an approach to calculate P balance that is able to capture important differences between modern GB and North-European dairy farming systems is required for more accurate and robust assessment of the risk of P loss from modern diverse GB and North-European dairy farms.

Great Britain and multiple North-European countries have large soil P reserves but no specific legislation directly limiting P feeding and land application of P via manure (Amery and Schoumans, 2014). Strategies to improve PUE in dairy farming are largely based on countries where either strict housed (Knowlton and Ray, 2013, Cela *et al.*, 2014) or strict pasture-based dairy farming systems (Gourley and Weaver, 2012, Mihailescu *et al.*, 2015) are prominent or where P-based legislations are in place (The Netherlands Environmental Assessment Agency, 2016). However, the literature on strategies to improve PUE in a wide assortment of GB dairy farming systems characterised by diverse calving patterns, varying amounts of concentrate feeding and grazing days (Garnsworthy *et al.*, 2019) is limited. Indeed, a previous study has reported the phosphorus inputs, flows and outputs from three self-contained research dairy farms of contrasting systems in Southern England based on actual measured data from multiple sampling over 3 years (Withers *et al.*, 1999). However, such previous research used a limited number of research farms over 2 decades ago and consequently could be considered not representative of current practice of commercial farms. Identifying strategies to improve PUE across diverse dairy farming systems representative of commercial farms operating in GB is important because previous research suggests that GB dairy farmers feed P in excess of the NRC (2001) recommended dietary P concentration (Sinclair and Atkins, 2015). According to our previous finding, GB dairy farmers and feed advisers are reported to use minimal precision P feeding strategies ((Harrison *et al.*, 2021)). In addition, strategies to reduce P loss from GB dairy farms largely focus on ‘rear-end’ solutions and rarely consider source solutions (*i.e.* P feeding management). Consequently, there is a gap in the literature regarding information on strategies to improve PUE in diverse dairy farming systems such as the ones operating in GB.

While P balance data is useful to determine potential P loss from dairy farms, efficient strategies to improve PUE cannot be developed without understanding the factors that influence P balance and PUE. The determinants of FPB have previously been investigated in strict Irish pasture-based dairy farming systems (Mihailescu *et al.* 2015). However, the data on the major determinants of FPB and SPB considered across diverse dairy farming systems is scarce, likely because of the lack of approaches available to robustly assess such information across diverse dairy farming systems. Therefore, the current study aims to demonstrate the foundations of an approach adapted from the ANCA tool to calculate FPB and SPB that can consider important differences between dairy farming systems (i.e. concentrations of P in milk and manure). Using this approach, the current study further aims to identify the differences in, and the determinants of FPB, SPB and PUE across a range of dairy farming systems representative of current practices adopted by commercial dairy farms operating in GB. The hypothesis is that the proposed approach will capture that pasture-based dairy farming systems will have a higher PUE than housed systems.

2. MATERIALS AND METHODS

2.1. Study farms and data collection

Dairy farms from across GB were recruited through advertisements by various stakeholders (acknowledgements). After the responding farms provided further information on their calving plan, grazing days and concentrate feeding approach, thirty dairy farms with no other livestock enterprise were selected (geographical spread in Figure 1) to ensure representation from farms within each of the five GB dairy farming classifications, which have been previously devised to assess feed efficiency (Garnsworthy *et al.*, 2019). Classification 1 farms adopt spring calving approach and graze cows ≥ 274 days a year with minimal feeding of concentrate supplements (Table S1). Classification 2, 3 and 4 farms adopt block or all year calving approach 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. The use of the five GB dairy classification approach in the current study provides an opportunity to investigate PUE not only in strict pasture-based (classification 1) and housed systems (classification 5) but in diverse pasture-based systems (classification 2, 3, and 4) as well.

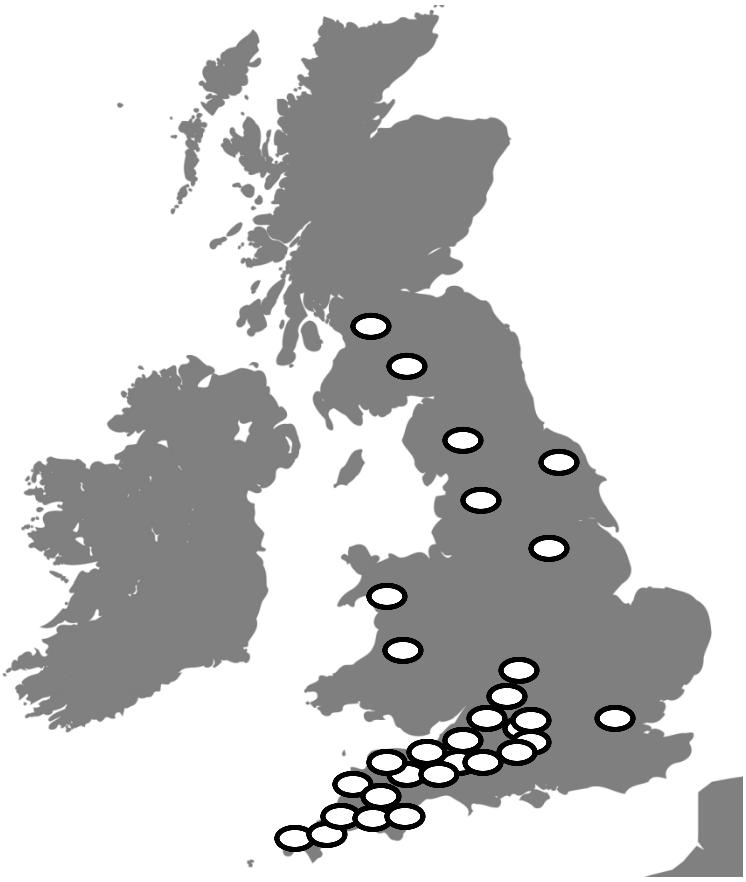

Figure 1. Map of the geographic spread of participating dairy farms in Great Britain

Participating farms completed a form to provide information about production characteristics (*i.e.* herd size, calving pattern, number of grazing days/year and land management) for the year 2018 / 2019. Data required for calculating FPB *e.g.* annual imports and exports and stocks at the start and end of the year (Table 1) was collected. Additional information was collected to calculate SPB, such as annual amounts of feed (excluding grazed grass) fed to the entire herd (including young stock), mineral fertiliser 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 between October 2018 and March 2019 to collect feed, manure, and soil samples for the determination of P concentration, which allowed more accurate calculations of P balances both at the farm-gate and soil surface level.

2.2. Sample Collection

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 for grassland and arable land, an Edelman Combination Soil Auger (Eijkelkamp, The Netherlands) was used to collect ≥10 and ≥15 soil cores (100 mm depth, 50 mm diameter), respectively, in a 'W' pattern with the additional five soil cores taken from the un-trafficked borders of the arable land (Landwise, 2019). For each farm, soil cores from a sampling area were mixed to generate 2 to 5 representative samples (~1 kg) and stored at -20°C until further analysis.

Individual feed ingredient samples were collected from each farm when P concentration of a feed was not available from recent farm records or product labels. Sub-samples of each clamp and big bale silage were collected in a 'W' pattern from the face (Sinclair, 2006), mixed and a representative sample (~1 kg) of each silage was collected. Twelve grab samples of any parlour concentrate fed were also collected, bulked, mixed and a representative (~500 g) sample was collected. All representative samples were 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 collected. 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 collected. All samples were stored at -20°C until further analysis.

2.3. 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 P 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).

2.4. Calculation of phosphorus balances 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 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).

Table 1. Formulae used to calculate farm-gate and soil-surface phosphorus (P) balances and use efficiencies on 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] + Exported milk P + 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)
Milk P content (g/kg)	0.24 + (0.0220 × milk crude protein (g/kg))[1] (Klop *et al.*, 2014)
Manure P (kg) (including from grazing livestock)	(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 to entire herd by each silage	(Herd requirement (VEM) - Purchased feed (VEM)) × original proportions (%) of VEM supplied by grazed grass plus silages made from home-grown forages
VEM supplied to entire herd by grazed grass	Fresh grass (VEM) based on amount of fresh grass grazed adjusted using ANCA's coefficients of grazing[5] as proportion of fresh grass plus silages made from home-grown forages in the remaining requirement (Herd requirement (VEM) - Purchased feed (VEM)) (Groor, 2016) (Groor, 2016) (Groor, 2016) (Groor, 2016) (Groor, 2016) (Groor, 2016) (Groor, 2016) (Groor, 2016)

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[1] Concentrations of P from product label, farm records or 'Planning for Land Application of Nutrients for Efficiency and the environmenT' (PLANET) tool, [2] Concentrations of P from product label, farm records 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.

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 1) of the ‘Annual Nutrient Cycling Assessment; ANCA; KringloopWijzer’ (Aarts *et al.*, 2015). To the authors’ knowledge, this is the first instance that ANCA’s principles have been employed in a study to calculate SPB for commercial dairy farms in GB. Briefly, in ANCA, the amount of energy supplied in grazed grass and home-grown silages is calculated by subtracting the energy supplied to the herd as feeds (other than fresh grass and home-grown silages) from the herd’s energy requirement. The proportion of grazed grass and home-grown silages in this remaining energy supply is then calculated based on the ratio of the amounts of home-grown silages provided by the farmer, and of the amount of fresh grass grazed using validated coefficients that consider type of grazing system, grazing days, hours of grazing and size of the cow breed (Groor, 2016). 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 in the current study, the ME (MJ/kg DM) of feed was converted to VEM using equation 1 (Wageningen UR, 2016):

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

2.5. 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).

3. RESULTS

3.1. 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 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 amount of concentrate supplements (classifications 1 and 2), and milk protein and P concentration 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 from home-grown feeds (primarily forages) compared to participating farms operating a housed system (classification 5). The mean P concentration of the herd's annual diet 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 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]	3	5	1	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}	$10{,}268^{a}$	1555	≤ 0.01
Annual concentrate intake (kg DM/Livestock Unit)	856.0^{b}	1072^{b}	1625^{ab}	3125^{a}	2524^{a}	673.6	≤ 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
Milk P content (g/kg)	1.03^{a}	0.98^{ab}	0.98^{ab}	0.98^{ab}	0.95^{b}	0.026	≤ 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)[5]	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] Required for the principles of ANCA, [4] Inclusion rate of home-grown feed (primarily forages) in the herd diet, [5]Annual dietary P intake of the entire herd including young stock (kg)/annual dietary dry matter intake of the entire herd (kg) × 1000, [a-b] Means in a row without a common superscript letter differ ($P \leq 0.05$)

3.2. 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 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 amount of concentrate supplements (classification 2). Across all systems, milk accounted for the major proportion (72 to 97%) of annual P export but milk P export did not differ between systems. 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 amount of concentrate supplements (classification 2). Across all systems, the FPB ranged from -6.04 to 32.7 kg/ha with a deficit on eight farms, a surplus on the remainder and a mean P surplus of 9.58 kg/ha. The mean farm-gate PUE across all systems was 75.2%.

Table 3. 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	8.87	10.2	11.2	7.06	15.7	4.48	0.12
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	9.12	13.0	15.6	8.10	21.7	8.41	0.20
Farm-gate P balance (kg/ha)	10.7^{ab}	3.21^{b}	9.13^{b}	8.64^{ab}	25.2^{a}	7.86	≤ 0.01
Farm-gate P use efficiency (%)	47.4^{ab}	$101^{a, 2}$	71.4^{ab}	49.3^{ab}	46.1^{b}	33.6	0.02
Farm-gate P balance (kg/Livestock Unit)	7.18^{ab}	1.35^{b}	4.24^{b}	6.26^{ab}	11.02^{a}	3.81	≤ 0.01
Farm-gate P balance (kg/t milk)	1.38^{ab}	0.31^{b}	0.75^{ab}	1.43^{ab}	1.61^{a}	0.68	≤ 0.01

[1] Based on calving pattern, concentrate supplements provided 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, $^{a\text{-}b}$ Means in a row without a common superscript letter differ ($P \leq 0.05$),

3.3. 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 inclusion rate of home-grown feed in the herd diet and RR (Table 4). Milk P export positively correlated with a farm’s SR. The FPB was negatively associated with the inclusion rate of home-grown feed in the herd’s diet but was positively correlated with mineral fertiliser P import, whilst a farm’s PUE and feed P import were negatively associated.

Table 4. Determinants of farm-gate phosphorus (P) balance in a diverse dairy farming system

Response	Significant variables^1	R^2
LgFdP =	$2.4\ (\pm0.37) + 0.18\ (\pm0.076) \times SR{*} - 0.018\ (\pm0.0035) \times PHF{**} - 1.7\ (\pm0.77) \times RR{*}$	0.67
MPE =	$-21\ (\pm6.8) + 4.4\ (\pm0.64) \times SR{**} + 7.2\ (\pm2.1) \times LgMS{**})$	0.73
FPB =	$40\ (\pm5.3\ ) - 0.47\ (\pm0.073) \times PHF{**} + 8.3\ (\pm2.6) \times LgFI{**}$	0.66
LgFPUE	$1.2\ (\pm0.15\ ) - 0.47\ (\pm0.13) \times LgFdP{**}$	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 + βLgFA + βLgFdP + βPHF + βSTPo + βSTPt + σ_{est} (βLgFA and βLgFdP were not considered when they were the dependent variable) , ^{2} Investigated variables = μ + βSR + βLgMS + βGD + βPHF + βSPB + βLgFI + βMPI + βGgP + βGsP + σ_{est}

3.4. 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%) of P import, but the mean annual P import was not different between systems (Table 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 system (classification 1) tended (P = 0.05) to export the greatest amount of P from the soil-surface via grazed grass. 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 -7.08 to 31.3 kg/ha, with a P deficit on nine farms, a surplus on the remainder and a mean surplus of 7.47 kg/ha. The mean soil-surface PUE across all systems was 81.0%.

Table 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	21.0	25.7	28.4	16.4	39.7	13.7	0.22
Mineral fertiliser	6.39	3.37	7.42	0.00	3.31	6.30	0.52
Total	27.3	29.1	35.8	16.4	43.0	15.6	0.27
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)	8.70^{ab}	2.06^{b}	5.68^{b}	7.84^{ab}	22.1^{a}	7.98	≤ 0.01
Soil-surface P use efficiency (%)	67.0^{ab}	98.5^{a}	90.3^{a}	52.1^{ab}	46.1^{b}	21.9	≤ 0.01

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

3.5. 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 6). Phosphorus export via grazed grass positively correlated with SR, number of grazing days/year, the inclusion rate of home-grown feed in the herd diet and soil Olsen P concentrations. The SPB was negatively associated with the inclusion rate of home-grown feed in the herd diet but positively correlated with SR. The soil-surface PUE and the inclusion rate of home-grown feed in the herd diet were positively associated. Soil Olsen P concentration was negatively correlated with the number of grazing days but was positively correlated with P export via grazed grass.

Table 6. Determinants of soil-surface phosphorus (P) balance in a diverse dairy farming system.

Response	Significant	R^2
$LgFI^1$ =	$-0.40\ (\pm 0.247) + 0.34\ (\pm 0.107) \times SR^{**}$	0.29
MPI^1 =	$4.5\ (\pm 6.34\ ) + 11\ (\pm 2.75) \times SR^{**}$	0.41
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 =	$27\ (\pm 6.0\ ) + 3.7\ (\pm 1.44\ ) \times SR^{*} - 0.39\ (\pm 0.065) \times PHF^{**}$	0.67
$SsPUE^1$ =	$-10\ (\pm 15.8) + 1.3\ (\pm 0.21) \times PHF^{**}$	0.61
$STPo^2$ =	$39\ (\pm 5.4) - 0.084\ (\pm 0.0323) \times GD^{*} + 1.7\ (\pm 0.33) \times GgP^{**}$	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 = $\mu + \beta SR + \beta LgMS + \beta GD + \beta PHF + \beta STPo + \beta STPt + \sigma_{est}$

4. DISCUSSION

4.1. *Production characteristics of participating dairy farming systems*

The farms in the current study had larger herds compared to the herd size of 165 lactating cows typical for commercial 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 commercial GB dairy farms (AHDB, 2019). 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 import of greater amount of concentrate feed and relatively lower inclusion rate of home-grown forages in the housed system. It is difficult to meet the elevated energy demand of high yielding cows typically raised in housed systems by feeding high-forage diets (March *et al.*, 2014) and hence the import of large amount of concentrate feed. This increased import of concentrate feed into 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, considerable differences in feeding practices between systems resulted in significant differences in P imports. However, dietary P concentration in all systems was higher than what is recommended to support the level of milk production in each system (NRC, 2001).

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

In the current study, the mean FPB of 9.58 kg P/ha across all systems was lower than the FPB of 15.3 kg P/ha previously reported for dairy farms in South-West England (Raison *et al.*, 2006) but indicates that on average the environmental sustainability of participant farms could be improved, with the suggested optimal P balance at 5 kg P/ha (DAERA, 2016, Rothwell *et al.*, 2020). This difference was attributed to less mineral fertiliser P import and greater milk P export observed in the current study, despite a greater feed P import. The increased feed P import and milk P export reported in the current study may be because the current study recruited farms to ensure representation from each system. Consequently, there was likely an increased number of housed systems used in the current study compared to previous studies, which is important to capture when considering that there is an increased number of housed dairy farming systems operating in GB more recently (March *et al.*, 2014). Therefore, the current study provides much needed FPB information] on commercial dairy farms representative of each classification of modern GB dairy farming system, which indicated the importance of considering system-specific P balance information in countries that operate modern diverse systems. In particular, the current study raises the question 'has reductions in mineral fertiliser P simply been replaced by increased feed P import at a national scale?' Greater P surplus in the housed system compared to the blended pasture-based systems (classifications 2 and 3) in the current study supports that housed systems are relatively less efficient in using P than pasture-based systems (March *et al.*, 2016, Akert *et al.*, 2020). However, the current study goes further than these previous studies to suggest that 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 of numerically lower total export of P in the longest grazing pasture-based system compared to other pasture-based systems. Therefore, this first-time comparison of P balances for commercial dairy farms across the 5 GB dairy classifications allowed the current study to provide results that suggest that pasture-based systems with minimal imports of P may not be more efficient in P use than housed systems because of the subsequent lower export of P in the minimal import pasture-based system. Largely, this is potentially because of the use of smaller dairy cow breeds, which lowered annual milk yield in the minimal import pasture based system.

In the current study, mean FPB across most pasture-based systems was within the range (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 FPB of 3.21 kg P/ha for classification 2 was below this range, most likely because two farms that participated in the current study 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 may be because the approach used in the current study captured a lower P concentration in milk for dairy cows in the housed system compared to the pasture-based system (Classification 1), which may not have been captured by the previous study which used standard coefficients for milk P concentration. Consequently, a lower export of milk P may have been captured in the housed system in the current study, leading to a higher P surplus. Overall, considering that the semi-voluntary approach used to recruit farms for the current study may have resulted in the recruitment of farms more interested in P management and consequently provided a better reflection of P management than the national situation. Therefore, the use of the approach used in the current study to calculate P balance would need to be employed on a larger sample size of dairy farms across GB to confirm the finding from the current study that indicate that there is scope to further improve PUE in GB dairy farming, particularly in housed systems.

4.3. 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 required to import 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 confirmed that the opportunity to reduce FPB and therefore, improve PUE still exists in dairy farms representative of current dairy farming practice if farmers reduce feed P import (Withers *et al.*, 1999),by reducing the import of P-rich feeds and suggests there is a similar opportunity by maintaining a SR that matches the availability of home-grown forages. On the other hand, the positive relationship between milk P export (a major source of P export from a farm) 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 be used as a strategy to lower FPB and increase PUE (Mihailescu *et al.*, 2015). However, in the current study, the benefit of greater milk P export in the housed system was outweighed by increased feed P import. Therefore, the current study suggests that a simplified approach to maximising a farm's milk P export by increasing SR of lactating cows, as usually seen in housed systems or maximising home-grown forage intake by reducing SR and with a reduction in total and per cow milk production, as could be expected in a strict pasture-based system, may not provide an opportunity to maximise the PUE in a dairy production system. This suggestion is, partly if not fully, supported by the observation in the current study that both P balance and use efficiency at the farm-gate level were relatively better in systems (classifications 2 and 3), which were not strict pasture-based and housed systems.

Since farms with a greater reliance on home-grown feed (primarily forages) had lower P surplus and improved PUE in the current study, increasing the inclusion rate of home-grown forages in the herd diet could improve PUE on dairy farms. 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, cows in the housed system in the current study were allowed diets with a mean P concentration that is 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 and importing high-P feeds could reduce P surplus and improve PUE by formulating diets with a P concentration closer to the cows' requirement and importing low-P concentrates.

4.4. 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. However, the mean SPB across all systems in the current study was lower compared to pasture-based systems in Northern Ireland (7.47 vs 11.0 kg P/ha) (Adenuga *et al.*, 2018), primarily because of lower mineral fertiliser P import and greater crop P export from pasture-based systems participating in the current study. Therefore, this supports that increased crop production could be a viable strategy 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 in the current study was well above the optimal 16 to 25 mg/kg range (AHDB, 2018), most systems could further reduce mineral fertiliser P import by relying on accumulated P in soil (Withers *et al.*, 2017). To the authors' knowledge, the approach demonstrated in the current study allowed this study to be the first to provide SPB values for commercial dairy farms that are representative of the current diverse practices for GB dairy farming using measured P concentrations of feed and manure and the capturing of variation in P concentrations milk and manure between systems as opposed to using standard coefficient for manure P import onto soil. This novel approach allowed the current study to report differences in SPB between diverse dairy farming systems.

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

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 and consequently, grazed grass P export was not a determinant of SPB. Therefore, extending the grazing season may not always be a 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 was associated with an increased soil Olsen P concentration, 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, the number of 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.

Housed systems can lower SPB by formulating diets that closely matches cows' P requirement and hence reduced import of P in concentrate feeds (Adenuga *et al.*, 2018). In addition, SPB could be reduced by replacing high-P home-grown forages (grass silage) with low-P home-grown feeds (maize silage). Considering that the housed system in the current study fed P that is 32% more than the mean P concentration of 3.4 g P/kg DM recommended (NRC 2001) for dairy cows, farms in the housed system could have reduced mean herd dietary P intake from ~53.3 kg P/ha to ~40.4 kg P/ha by feeding P that closely matches the recommended dietary P requirement for dairy cows (NRC, 2001). Therefore, the findings of the current study suggest that feeding dairy cows P that closely matches the recommended dietary P requirement would allow the housed system to achieve a SPB more similar to pasture-based systems (9.2 kg P/ha), after considering a reduction of manure P import into soil by 12.9 kg P/ha. Similarly, 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 and mineral fertiliser P import (Lukács *et al.*, 2019), and such measures represent a major opportunity for GB dairy farming to reduce soil-surface P surplus.

4.6. Limitations

Despite the data collection on the stock of the farms that was stored at the start and end of the year being considered, the results of the current study should be used with caution because the data collection did not occur over multiple years. The number of dairy farms used in the current study was smaller compared to other studies calculating P balances (Adenuga et al 2018), which might have contributed to an imbalance in the number of farms in each classification. However, the number of farms in each classification followed a similar trend to previous research that has used this classification system, with most farms representative of Classification 2 (Harrison et al. 2020), likely because it reflects practices typical of a GB dairy farm. Additionally, the use of a smaller sample size in the current study was a conscious trade-off to allow the current study to be the first to provide P balance values that are reflective of modern GB dairy farming systems by using quantified concentrations of P in feed, manure and soil samples collected from the participant farms. However, a caveat of caution should be provided because when samples were collected, sampling only occurred on a single day for each farm, but controlling the sample size to capture systems reflective of each classification allowed the current study to demonstrate an easily implementable SPB approach that considered key differences in farm-gate and soil-surface level P flows between GB dairy farming systems. Since the participating farms in the current study were semi-volunteered, the lower P balance values reported in the current study compared to previous studies may partly be because the participating farms were representative of farms more interested in P management.

5. CONCLUSIONS

The results indicate large P surpluses and consequently large soil P reserves across all participating dairy farming systems. Considering that the semi self-selective approach for recruiting farms in the current study may have skewed the results towards being reflective of farms more interested in P management, the findings of the current study could consequently reflect a better than actual national situation. To the authors' knowledge, the current study is the first to consider differences across dairy farming systems that operate in GB when calculating FPB and SPB. This was achieved by implementing a novel approach to calculating the FPB and SPB that captures differences in the P concentration of manure and milk between systems as opposed to previous studies for dairy farms outside of GB that have used standard coefficients for these imports and exports. Subsequently, the current study also provided the demonstration of the foundations of an approach to calculate P balances that could be more robust for dairy farmers operating diverse dairy farming systems than using standard coefficients. With further development, this approach could be easily adopted and could change the way GB dairy farmers and advisers calculate P balances in diverse systems to inform on system-specific strategies to improve their PUE. Using this novel approach, the current study was able to provide much needed in depth information on P flows between dairy farming systems that are reflective of current commercial practices in GB dairy farming. Such information is important to contribute toward developing system-specific P management strategies to meet the need for more sustainable dairy production systems. In general, the high soil P concentration across all systems and the positive association between mineral fertiliser P application and P surplus confirmed 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. In particular, the issue of relatively high P surplus and poor PUE at both farm-gate and soil-surface level in participating farms operating a housed system could be reduced by importing less P in concentrates, or by using home-grown feeds with lower P content. The current study demonstrated that precision P feeding P to match cow's P requirement could allow some housed systems implementing similar practices to housed systems participating in the current study to achieve a P balance more similar to that of pasture-based systems. Whereas, increasing farm-level milk production by increasing SR will improve PUE in pasture-based systems but only if SR is such that availability of home-grown forages is not limited. Therefore, the current study was able to provide findings that could suggest that countries operating dairy production which is more diverse than having a simple classification into strict pasture-based or housed systems may achieve relatively higher PUE in systems that are in between two extreme systems *i.e.* strict pasture-based and housed systems This information provides an important contribution towards the development of strategies to improve the sustainability of dairy production in regard to P use.

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