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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

Thesis submitted for the degree Doctor of Philosophy

School of Agriculture, Policy and Development

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February 2021

Declaration of Original Ownership

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

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ABSTRACT

Improving the sustainability of dairy farming in countries operating diverse dairy farming systems (*i.e.* Great Britain (GB)) requires information on phosphorus (P) management considered across multiple systems. Such information is currently limited in GB. Therefore, throughout this thesis the flow and management of P has been considered system-specifically. Furthermore, the current status of P balance on dairy farms needs to be determined to identify mitigation strategies to reduce P loss from dairy farms. In Experiment 1, questionnaire surveys of dairy farmers (n = 139) and feed advisers (n = 31) were conducted to provide new information on P feeding practices. The survey revealed most farmers (72%) did not know the P concentration in their lactating cow's diet and did not commonly adopt precision P feeding practices, indicating P feeding in excess of the amount recommended optimum to support certain level of milk production. Regardless of system, farmers largely relied on a feed professional (70%), and these farmers were more likely to analyse forage P ($P = 0.02$), but farmers of pasture-based systems relied less on feed professionals ($P < 0.05$). Both farmers (73%) and feed advisers (68%) were unsatisfied with the amount of training on P management available. Therefore, feed advisers' influence over P feeding should be better utilised, particularly in a housed system via training and other strategies need to be adopted to promote forage P analysis in pasture-based systems. In experiment 2, the farm-gate (FPB) and soil-surface P balance (SPB) and P use efficiency (PUE) were calculated for 29 dairy farms using the principles of the Annual Nutrient Cycling Assessment Tool, which allowed the capture of important differences in P flows between systems (*i.e.* P concentration in milk and manure). Additionally, the main determinants of P balance were investigated using regressions. The mean FPB and SPB of 9.58 kg/ha and 7.47 kg/ha, respectively, across all systems indicated opportunity to improve PUE. Blended pasture-based systems (classification 2 and 3) had higher PUE than the strict housed system (Classification 5; $P < 0.05$). The study findings confirmed that formulating dairy cow diets with a P concentration that closely matches dietary P requirement of dairy cows will reduce the amount of P import via concentrates, which will eventually improve PUE in housed systems. However, increasing the inclusion rate of home-grown feeds into a herd's diet would improve PUE in pasture-based systems. Experiment 3 was the first to use data collected directly from farmers in FARMSCOPER to simulate environmental P loading and identify a cost-effective suite of mitigation methods for housed ($n = 20$) and pasture-based ($n = 7$) dairy farms. Across both systems, 'current' implementation of mitigation methods was simulated to have minimally reduced environmental P loading from a mean 'baseline' of 0.63 to 0.56 kg P/ha (11%). The environmental P loading in the 'baseline' and 'current' scenarios positively correlated with milk production on a kg and kg/ha basis ($P \leq 0.001$ and $P = 0.033$, respectively). Therefore, the current study highlights the importance of mitigating environmental P loading from GB dairy farming especially considering the increasing prevalence of higher yielding herds and housed production systems. Simulated environmental P loading was reduced by ~50% and ~60% without incurring annual financial losses by implementing different existing mitigation methods for pasture-based and housed systems, respectively. Therefore, emphasis should be put on increasing the system-specific implementation of existing methods to mitigate environmental P loading (*i.e.* knowledge transfer). In conclusion, the current thesis provided much needed new information across diverse dairy farming systems in GB on 1) P management and flows, 2) the current status of PUE and 3) a suite of cost-effective mitigation methods to reduce environmental P loading. Collectively, this information will contribute towards developing system-specific strategies to improve the sustainability of GB dairy farming in regard to P use.

ACKNOWLEDGEMENTS

This project was funded by the Agriculture and Horticulture Development Board (AHDB) Dairy Studentship 41110062.

I would like to thank my supervisors, Dr. Partha Ray and Professor Chris Reynolds at the University of Reading, Professor Liam Sinclair at Harper Adams University and Dr Martina Dorigo at the AHDB Dairy. However, I would particularly like to thank Partha on an additional personal level, for his continued support throughout the project.

I further want to express my gratitude to Dr Jan Djikstra at Wageningen University for his patience, enthusiasm and support during my international research fellowship (WIAS) at Wageningen University, Netherlands.

I am also grateful to all the researchers, industry people and societies that continuously helped me with the projects recruitment, engagement and data collection.

I would lastly like to acknowledge my closest friends, family and in particular partner, who provided endless support and encouragement throughout.

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List of Abbreviations

Abbreviation	Definition
AFRC	Agriculture and Food Research Council
AHDB	Agriculture and Horticulture Development Board
Al	Aluminium
ANCA	Annual Nutrient Cycling Assessment
ANOVA	Analysis of Variance
ATP	Adenosine Triphosphate
Ca	Calcium
CAP	Common Agricultural Policy
CP	Crude protein
CSF	Catchment Sensitive Farming
CSFO	Catchment Sensitive Farming Officers
DEFRA	Department of Environment, Food and Rural Affairs
DM	Dry matter
DMI	Dry matter intake
DRP	Dissolved reactive phosphorus
EPL	Environmental phosphorus loading
EU	European Union
FARMSCOPER	Farm SCale Optimisation of Pollutant Emission Reductions
Fe	Iron
FPB	Farm-gate phosphorus balance
GAP	Good Agriculture for Protection of water

GB	Great Britain
GD	Grazing days
GE	Gross energy
GgP	Grazed grass P export
GsP	Grass silage P export
$H_2PO_4^-$ or HPO_4^{2-}	Orthophosphate anions
ICP-OES	Inductively coupled plasma-optimal spectrometry
LgFdP,	Log-transformed feed P import
LgFI	Log-transformed mineral fertiliser P import
LgMS	Log-transformed milk sold/year
LgPUE	Log-transformed farm-gate P use efficiency
LU	Livestock unit
ME	Metabolisable energy
MPI	Manure P import
N	Nitrogen
$NaHCO_3$	Sodium bicarbonate
NDF	Neutral detergent fibre
NE	Net energy
NRC	National Research Council
NVZ	Nitrate Vulnerable Zones
P	Phosphorus
PHF	Proportion of home-grown forage
Pi	Inorganic phosphorus
PLANET	Planning for Land Application of Nutrients for the EnvironmenT
Po	Organic phosphorus

PSYCHIC	Phosphorus and Sediment Yield Characteri-sation in Catchments
PUE	Phosphorus use efficiency
RR	Replacement rate
SPB	Soil-surface phosphorus balance
SR	Stocking rate
SRP	Soluble reactive phosphorus
SsPUE	Soil-surface PUE
STPo	Soil test phosphorus (Olsen P)
STPt	Soil test phosphorus (total P)
TMR	Total mixed ration
TP	Total phosphorus
UAA	Utilised agricultural area
VEM	Feed unit of milk, in Dutch; Voedereenheid Melk
WFD	Water Framework Directive

1 INTRODUCTION

1.1 GENERAL INTRODUCTION

Dairy farming in many regions across the globe is intensifying by increasing milk output and feed import without farmers acquiring additional land, primarily to improve economic efficiency (Clay *et al.*, 2019). In particular, dairy farming in Great Britain (GB) and many European countries that have predominantly produced milk using pasture-based systems with a long grazing season, is seeing an increasing number of housed dairy farming systems (March *et al.*, 2014). However, regions densely stocked with dairy cattle are associated with phosphorus (P) imbalances as a large proportion of concentrate feed is imported into the region, with the P-rich manure subsequently being produced applied on nearby arable and grass land, often in excess of the crops' P requirement (Svanback *et al.*, 2019). Land application of this manure often leads to application of P in excess of the crops' requirement, particularly in countries where the application of P is indirectly regulated by limits on the land application of nitrogen (N) via livestock (European Commission, 1991).

A P surplus on a dairy farm suggests a 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-scale improved PUE can provide financial benefit to farmers by more precisely purchasing feed and mineral fertiliser (Mihailescu *et al.*, 2015). On a national scale, in countries where there is no supply of phosphate rock (*i.e.* GB), improved PUE in dairy farming could strengthen national food security and reduce dairy farmers' vulnerability to trade prices (March *et al.*, 2016). This is because in countries with no phosphate rock supply the national food demand is dependent on the import of mineral fertiliser P from other countries to sustain crop yields. 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 from the Nitrates Directive (Northern Ireland Environment Agency, 2019). However, GB along with Poland, France and other European countries have no specific legislation directed at P (*i.e.* limits on P concentration in feeds or land application) 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 the US (Cela *et al.*, 2014) where strict housed dairy farming systems are predominant, from Ireland (Mihailescu *et al.*, 2015) and a lesser extent New Zealand

(Gourley and Weaver, 2012) where strict pasture-based systems are predominant 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) and the feasibility of implementing practices can differ between dairy farming systems (March *et al.*, 2014). Consequently, current strategies to improve PUE in dairy farming may not be appropriate for countries operating dairy farming systems that are more diverse than a simple classification of strict pasture-based or housed systems, and instead operate multiple classifications of pasture-based systems.

System-specific information on P balance and PUE between diverse dairy farming systems is required to develop strategies to reduce P surplus in diverse dairy farming systems. However, such information is scarce (March *et al.*, 2016). Furthermore, only a limited number of studies have calculated FPB using measured P concentrations of P import and export items. No research has calculated SPB in GB dairy farming. Therefore, there is a need for an investigation into the FPB, SPB and PUE across dairy farming systems to develop strategies to improve the sustainability of dairy farming in countries that operate diverse dairy farming systems, in regard to P use.

Previous reports on FPB in GB dairy farming indicated that feed P import via purchased feed replaced mineral fertiliser P import as the main source of P import into GB dairy farms (Raison *et al.*, 2006, Withers and Foy, 2006). However, this previous data is more than a decade old. Consequently, currently available data may not be reflective of modern GB dairy farming because there is an increased prevalence of housed dairy farming systems, which import a greater amount of concentrate feed than pasture-based systems to support high milk yield (March *et al.*, 2014). However, farmers are speculated to be unaware of how much P they are feeding to their cows (Withers *et al.*, 2006) and usually feed P in excess of the concentration recommended by the National Research Council (NRC, 2001) for optimal health and production (Sinclair and Atkins, 2015). Since faecal P excretion is highly and positively correlated with dietary P intake (Knowlton and Ray, 2013), feeding P in excess of the cow's P requirement generates P-rich manure that contains an imbalanced N:P ratio. This manure is almost impossible to apply to land based on crop N requirement without applying P beyond the crops' requirement (Knowlton and Ray, 2013). Conversely, minimising excess P feeding to closely match the dietary P concentration recommended relative to milk yield (NRC, 2001), reduces faecal P excretion without negative impacts on health, productivity or fertility with only minor reductions in bone P content in dairy cows (Ferris *et al.*, 2009, Wang *et al.*, 2014). Furthermore, in many cases excess P feeding could be minimised by reducing or eliminating the inclusion of inorganic P supplements to the diet (Knowlton *et al.*, 2004). Reduced inorganic P supplementation can additionally reduce feed costs (Kebreab *et al.*, 2008) and minimise the water soluble fraction of manure P that is more prone to be lost via surface runoff (Dou *et al.*, 2002). Therefore, the sustainability of dairy farming in GB and throughout Europe needs to be improved by improving how efficiently feed nutrients, including P, are utilised (Augère-Granier, 2018).

Most research into reducing P feeding in dairy farming is based in the US, where strict housed systems are predominant (Dou et al., 2003, Harrison et al., 2012). However, the feasibility of implementing certain feeding practices differ between housed and pasture-based systems (March *et al.*, 2014). Consequently, such US-based strategies may not be appropriate for many North-Western and Central European countries that operate diverse dairy farming systems. No information is available on the P feeding practices that farmers and feed advisers implement and the barriers to and motivators for farmers to reduce their P feeding in diverse dairy farming systems. However, such information is critical in developing strategies to reduce P feeding to dairy cows and subsequently reduce feed P import into dairy farms. Therefore, information on how dairy farmers and feed advisers feed P in a diverse range of dairy farming systems is required to develop strategies to minimise excess feed P import into dairy farms to reduce P surplus in countries operating diverse dairy farming systems.

Indeed P surplus remains important in suggesting the long-term risk of P accumulation in soil and subsequent loss to waterbodies (Mihailescu *et al.*, 2015). However, P surplus cannot determine the amount or pathways of environmental P loading. To overcome the considerable costs in time, labour and money of directly measuring environmental P loading from dairy farms, models of agricultural systems such as the ‘Farm Scale Optimisation of Pollutant Emission Reductions’ (FARMSCOPER) model have been used to simulate environmental P loading (Lynch *et al.*, 2018). FARMSCOPER is used to support farmers’ and advisers’ decisions on land management and policy-makers’ decisions on policies to address the environmental nutrient loading from agricultural land (McDowell *et al.*, 2016). However, previous studies simulating environmental P loading from dairy farms using FARMSCOPER tend to use data that has been transformed from existing datasets (Zhang *et al.*, 2012, Lynch *et al.*, 2018, Micha *et al.*, 2018). Therefore, a more reliable data set generated from data collected directly from farmers is required to: assess GB dairy farming's progress towards improving sustainability, to assess environmental P loading in different dairy farming systems and to identify a suite of least-cost methods to mitigate environmental P loading for each system. Furthermore, FARMSCOPER uses a restrictive broad representative farm type approach. FARMSCOPER has received criticism for this approach because of its use of fixed averages, in particular a fixed grazing season (Willows and Whitehead, 2015). Therefore, there is a need to assess whether FARMSCOPER can consider important differences between housed and pasture-based dairy farming systems when simulating environmental P loading and optimizing mitigation methods for each system.

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) for modern GB dairy farming. Furthermore, none of the above literature considered the wide range of dairy farming systems that operate in GB despite different systems likely contributing to eutrophication differently (O'Brien *et al.*, 2012) and the feasibility of implementing practices varying between systems (March *et al.*, 2014). However, such information is critical in minimising excess P feeding, reducing P surpluses, improving PUE and mitigating environmental P loading of dairy farming in countries operating diverse dairy farming systems. Therefore, there is a need for system-specific information on the P feeding practices, P balance and use efficiency 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.

1.2 AIMS AND OBJECTIVES

1. Phosphorus feeding practices, barriers to and motivators for reducing phosphorus feeding in diverse dairy farming systems (Chapter 3)

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

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

2. Determinants of phosphorus balance and use efficiency in diverse dairy farming systems (Chapter 4)

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 environmental P loading from dairy farms using FARMSCOPER specific input data collected directly from dairy farmers using a tailored approach

ii. compare environmental P loading data simulated from FARMSCOPER for housed and pasture-based dairy farming systems

iii. identify a least-cost suite of mitigation methods to reduce environmental P loading from both housed and pasture-based dairy farming systems

1.3 THESIS LAYOUT

The thesis is comprised of six chapters, with each chapter ending with a list of references pertaining to that chapter. Following on from this introductory chapter, Chapter 2 provides a review of literature on diverse dairy farming systems in GB, the typical cycles of P (through the soil, the dairy cow and the dairy farm) and the need for strategies to mitigate environmental P loading from dairy farms in countries operating diverse dairy farming systems. Chapter 3 assessed the current P feeding practices implemented by farmers and feed advisers in diverse dairy farming systems and investigated the barriers to and motivators for reducing P feeding to dairy cows. Chapter 4 demonstrated a novel approach able to calculate the FPB, SPB and PUE across diverse dairy farming systems and investigated the key determinants of FPB, SPB and PUE in diverse dairy farming systems. Chapter 5 compared the simulated environmental P loading from pasture-based and housed dairy farming systems and investigated a suite of least-cost methods to mitigate environmental P loading from both pasture-based and housed dairy farming systems. Chapter 6 concludes the thesis with a general discussion (key findings, outcomes and limitations), future research perspectives and conclusions.

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2 LITERATURE REVIEW

2.1 DIVERSE DAIRY FARMING SYSTEMS IN EUROPE

The European dairy sector is one of the most profitable sectors of European agriculture. It accounts for up to 26% of milk supply towards the global milk market (906 million tonnes), which is the second largest single share at 236 million tonnes (FAO, 2021). Despite this large contribution of milk, European dairy herds are considered small compared to larger dairy operations in the US and Saudi Arabia (March *et al.*, 2014). Dairy farming across Europe is comprised of four main management systems; high input: high output (housed system), low input: low output (pasture-based system), Alpine (mountain areas) and Mediterranean systems (Arendonk and Linamo, 2003). North-Western and central European countries (Germany, Italy, France, the Netherlands and until recently the UK) are the highest milk producing countries in Europe and produce milk by operating a similar wide assortment of highly specialised dairy farming systems (March *et al.*, 2014, Augère-Granier, 2018). Therefore, strategies to reduce environmental P loading from dairy farms in GB may be applicable to many European countries with similar farming systems.

2.1.1 Climate of Great Britain

Grass begins to grow when the soil temperature is above a minimum of 5.5°C and this growth is stimulated by warmer weather (Brown *et al.*, 2016). Therefore, peak grass growth in GB occurs in late spring and early summer months (July 2019: mean grass growth 79.3 kg DM/ha (AHDB, 2020)) where the climatic conditions (July 2019: mean temperature 17.6 °C, mean precipitation 84 mm (Tiseo, 2020b and 2020a)) are optimal for grass growth. However, wide variations in grass growth occur between years and regions with southern parts of GB reaching higher temperatures than northern regions (Rath and Peel, 2005). During the grass growing season, dairy farmers' aim is to harvest a sufficient amount of home-grown forage in preparation for the colder months in autumn and winter, when grass growth is restricted.

Agricultural land in GB is generally dominated by grassland, predominantly perennial grasses (*Lolium perenne),* but the climatic conditions suitable for growing grass can vary between regions (Qi *et al.*, 2018). The drier Eastern half of GB is more suitable for arable crops (*i.e.* cereal and potatoes) whereas the wetter Western regions of GB are dominated by grassland and dairy farms, because the wetter soil makes arable crop production more difficult (March *et al.*, 2016). However, there is no reported relationship between the grass productivity of a location and a specific type of dairy farming system (March *et al.*, 2014). Therefore, although South Western GB is dominated by dairy farms, a range of dairy farming systems can be found across GB, which is influenced by many influential factors in addition to climate.

2.1.2 Diverse dairy farming systems in Great Britain

The mild and moist maritime climate that is warmed by Atlantic and Gulf Stream drifts provides a long growing season for grass. Subsequently, some pasture-based dairy farming systems in parts of GB favourable for grass growth operate some of the longest grazing seasons reported in Europe (Rath and Peel, 2005). Therefore, similar to Ireland the amount of grazed grass in the diet of dairy cattle can be maximised to subsequently reduce the milk production costs by reducing the amount of concentrate feed purchased (Mihailescu, 2013). Consequently, a pasture-based dairy farming system that relies on grazing of grass in the warmer months and feeding concentrate and silage to housed cows during the colder months has been the traditional system for GB dairy farming (Shortall, 2019). However, Ireland has a more unified stricter pasture-based dairy farming system compared to the diverse dairy farming systems in GB. This is largely because Ireland allocated some of the strictest quotas for the EU Milk quota to reduce overproduction of milk and consequently Ireland had a research extension pushing low cost pasture-based systems (Shortall, 2019). Additionally, the large population of GB relative to Ireland's population was also partly responsible for the emergence of diverse dairy farming systems in GB because the volume of milk was more important than the solids in milk. Consequently, grass in the diet was less important (Shortall, 2019) because a higher proportion of grass in the diet is reported to be favourable for higher concentrations of protein and fat in milk (Alothman *et al.*, 2019).

The diverse dairy farming systems that adopt different calving patterns in GB are important in providing a year-long national supply of milk to the GB population (March *et al.*, 2014). An all-year-round calving pattern tends to be operated in a housed system, because labour can be more easily spread throughout the year with persistent high yielding cows that can lactate for up to 405 days. Whereas, a spring-calving pattern is usually adopted in a pasture-based system where cows calve close to a season when grass growth is relatively high (March *et al.*, 2014). Dairy farms in GB can be classified into one of five dairy classifications (Table 2.1) based on calving pattern, varying amounts of concentrate supplement and number of grazing days offered to cows (Garnsworthy *et al.*, 2019). Classification 1 farms adopt a spring calving pattern and graze ≥ 274 days a year with a minimal amount of concentrate supplement feeding. Classifications 2, 3 and 4 farms adopt block or year-round calving patterns with an increasing amount of concentrate supplement feeding as number of grazing days reduce. In classification 5 farms, calving is all-year-round in a housed system with the greatest amount of concentrate supplement use in a total mixed ration (TMR). Generally, the size of the herd, the amount of concentrate fed and the annual milk yield are reported to significantly increase from a pasture-based system in classification 1 through to a housed system in classification 5 (Garnsworthy *et al.*, 2019). However, the stocking rate (SR) does not vary with classifications, but shows a high variation between 1.95 to 2.57 Livestock Units (LU)/ha.

Table 2.1. Classification of dairy farming systems in Great Britain (Garnsworthy *et al.*, 2019).

	Classification				
Characteristics	1	2	3	4	5
Calving pattern	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	0
Feeding approach	Minimal supplements[1]	Limited supplements	Mixed ration supplements	Mostly mixed ration	Total mixed ration

[1] Concentrate supplements

An optimal SR of a dairy farm depends on the land resource and animal performance, with a heavier than optimal SR being detrimental to both land resource and animal productivity (Lyons and Machen, 2001). A SR that exceeds the availability of home-grown forage can see more productive, more palatable species of home-grown forages (green foliage) replaced with less productive, less palatable plants (*i.e.* dead and insufficient amounts of immature plants) that capture less rainfall. Consequently, a higher SR than optimal reduces soil moisture and increases the risk of soil being eroded into waterbodies (Lyons and Machen, 2001). Additionally, a SR that exceeds the availability of home-grown forage, without the import of purchased feed to supply the cow with missing nutrients, can reduce fertility, body condition score, milk yield and solids in milk of dairy cows (Farmers Weekly, 2019). A farm's net profit increases with the density of a SR until the optimal SR is reached, because of an increase in a farm's milk production (Farmers Weekly, 2019). However, a farm's net profits gradually decline as a SR exceeds the availability of home-grown forage increases. This is because an increase in the cost of milk production occurs in highly stocked farms due to the increased need to import purchased feed to replace the nutrients not provided by home-grown forage because the herd's dietary demand exceeds the farms availability of home-grown forage (Farmers Weekly, 2019). An increase in purchased feed import is estimated to increase the cost of milk production between 1.3 to 2.2 p/litre of milk for every 10% of extra import of purchased feed.

A wide variation in SR is observed across dairy farms in GB and many European countries. This is because the optimal SR for a farmer to establish is highly influenced by a wide range of financial and environmental factors (Lyons and Machen, 2001). The Nitrates Directive sets a limit on the SR, such that the land application of organic N is no more than 170 kg/ha (European Commission, 1991). Additionally, the code of Good Agricultural Practice (GAP) in the UK recommends farmers lower their SR if they see signs of soil erosion, insufficient grass cover of land and if manure cannot be applied to land within relevant N restrictions (DEFRA, 2009). In principle, SR should be important in determining the import of purchased feed into a farm and subsequently studies investigating P management in dairy farms usually consider SR (Mihailescu *et al.*, 2015, Adenuga *et al.*, 2018, Svanback *et al.*, 2019). However, limited research has considered the impact of SR in a range of dairy farming systems, despite the import of purchased feed being greater in a housed than pasture-based system (O'Brien *et al.*, 2012, March *et al.*, 2016). Therefore, there is a need for information on the effects that SR has on P management in a range of dairy farming systems.

2.1.3 Changes in dairy farming systems in Great Britain

An increasing prevalence of housed dairy farming systems in GB and across Europe (March *et al.*, 2014) has been largely attributed to the technically easier formulation of a diet for high yielding dairy cows. This is because of a greater control over the diet and a reduced impact from the uncertainty of grass supply throughout the year in a housed system (Van den Pol-van Dasselaar *et al.*, 2011). For example, in pasture-based systems using a spring calving pattern, a ‘slow spring’ means reduced intake of grass by dairy cattle during the early lactation period. This is because of poor growth rate of grass due to climatic conditions (Brown *et al.*, 2016). Reduced feed intake during early lactation will prolong the duration cows will be in negative nutrient balance, which will have negative impact on milk production (Goselink *et al.*, 2015). Conversely, a drier than optimal spring can reduce the amount of usable home-grown forage because of the increased prevalence of grassland weeds or poor growth of home-grown forages due to reduced moisture level in soil (Brown *et al.*, 2016).

Farmers’ decision to shift towards operating a larger herd in an all-year housed system is largely financially driven (March *et al.*, 2014). This is because the feeding of a relatively larger herd is easier to support by importing more purchased feed rather than acquiring more land to produce more home-grown forages. Furthermore, the likely increased occurrences of heatwaves associated with climate change could put pasture-based systems at a greater risk of financial losses in milk income. This is because pasture-based systems have less opportunity to mitigate the negative effects of heat stress on cow milk yield and fertility than housed systems (Fodor *et al.*, 2018). In the absence of mitigation methods, heat stress-related annual milk income loss by the end of this century in the South-West of England is estimated to reach on average £13.4 million (Fodor *et al.*, 2018). Therefore, ensuring effective P management in housed dairy farming systems is important to improve the sustainability of dairy farming in GB and across Europe, as the prevalence of housed dairy farming systems increases.

On the other hand, the increasing trend in the prevalence of housed dairy farming systems in GB will likely plateau in the longer-term because of consumers’ preference for pasture-based dairy farming systems (March *et al.*, 2014). Furthermore, a plateau in the prevalence of housed systems may also be influenced by the potential increase in the profitability of pasture-based systems which could occur as rising temperatures associated with climate change will likely increase the growth of grass in colder regions. Subsequently, rising temperatures could extend the grass growing season by 50 to 90 days by the year 2080 (Prado *et al.*, 2009). Currently, rising temperatures has led an increased selectivity towards growing drought-resistant forages and maize in GB dairy farming. This is because of a more optimal condition for the growth of such forages (Brown *et al.*, 2016). Furthermore, the environmental impact of pasture-based systems could be reduced, as decreased monthly rainfall is estimated to reduce soil poaching and erosion by grazing livestock but this may be counteracted by increases in extreme weather events (Prado *et al.*, 2009). Subsequently, milk production in GB and other European countries is likely to remain characterised by a diverse range of dairy farming systems in the future. Therefore, strategies proposed to reduce environmental P loading from modern diverse dairy farming systems is currently important and should remain effective in mitigating environmental P loading from dairy farms in countries operating diverse dairy farming systems for the long-term.

2.2 PHOSPHORUS CYCLING IN SOIL

Phosphorus is a vital component of Adenosine Triphosphate (ATP) and is fundamental to all living things, with a presence as cell wall (*e.g.* phospholipids) and cell components (*e.g.* phosphoproteins and nucleic acid). For plants in particular, ATP is the energy unit that is formed during photosynthesis, which is involved in many cellular processes vital for plant growth (Griffith, 2011). Therefore, ensuring a continuous supply of a sufficient amount of P in soil for crop production is critical for any dairy farming system that has some reliance on the contribution of home-grown feed to the nutrient supply of dairy cows.

2.2.1 Import of phosphorus into agricultural soils

Historically, P has been supplied to plants through the application of natural resources such as manure and crushed bones to agricultural land to increase crop yields (Samreen and Kausar, 2019). It is suggested that P played such a crucial role in crop production that it was an important limiting factor for the economic and social growth of Europe, because it determined the human population that was sustainable in nearby towns (Newman and Harvey, 1997). At around the year 1843, it was discovered that land application of the water soluble inorganic form of P (Pi) substantially increased crop yields compared to the land application of organic forms of P (Po). This was because Pi was largely readily available to the plant by root uptake (Johnstone and Poulton, 2019). Since then, factory production of mineral fertiliser P products started. Initially, sulfuric acid-treated bone ash was used to produce mineral fertiliser P products (Johnstone and Poulton, 2019). Consequently, mass production of such fertiliser P products quickly diminished the supply of available bone, which resulted in the commercial extraction of P from apatite phosphate rocks that consist of predominantly Pi (Samreen and Kausar, 2019).

The use of P in food production originates from the application of P to agricultural land, which is critical in sustaining crop production. However, only a small proportion (20%) of the total 19 million tonnes of extracted P that is used in agriculture each year is consumed by the global human population (Schroder *et al.*, 2011). A major loss of P from the food production process is P that is lost during the production and application of mineral fertiliser P products to land. Deposits of apatite rock extracted to make mineral fertiliser P are non-renewable and the total depletion of global P reserves is estimated in the next 50 to 100 years (Samreen and Kausar, 2019). However, this estimate only considers phosphate rock reserves and not P reserves in the soil. Therefore, improving the utilisation of P in mineral fertiliser and in soil is important to slow the depletion of global P reserves (Cordell *et al.*, 2011, Schroder *et al.*, 2011, Samreen and Kausar, 2019). Furthermore, deposits of apatite rock are unevenly distributed across the globe with less than one percent of global deposits situated in Europe (Samreen and Kausar, 2019). Therefore, improving the utilisation of P in mineral fertiliser and in soil is additionally important in strengthening food security in countries such as GB and throughout Europe that do not possess phosphate rocks and consequently rely entirely on the import of mineral fertiliser P.

2.2.2 Organic and inorganic forms of phosphorus in soil

Total P (TP) in soil includes both Po and Pi fractions (Figure 2.1). However, only Pi in the form of orthophosphate anions ($H_2PO_4^-$ or HPO_4^{2-}) can be taken up from the soil solution by diffusion into the roots of plants to be utilised for plant growth and development (Schneider *et al.*, 2016). Soil Po compounds are defined as phosphates which are associated with organic matter (George *et al.*, 2018) and many forms of Po exist in soil (monoesters, inositol phosphates, diesters and phosphonates). However, generally it is the inositol phosphates (such as phytate) that tend to be less labile and accumulate more in the terrestrial environment (George *et al.*, 2018). For plants and microbes to utilize Po compounds, they must first make them biologically available by hydrolysing the Po compounds with phosphatase enzymes into inorganic orthophosphates (George *et al.*, 2018). The little extractability of Po in routine soil analyses have led to research being focused primarily on the Pi fraction in soil rather than Po (Johnstone and Poulton, 2019). However, when plants and microbes are under Pi deficient conditions in soil, they can release extracellular phosphatase enzymes into their surroundings to convert Po into available Pi forms, *i.e.* mineralization (Schneider *et al.*, 2016, George *et al.*, 2018). Conversely, the process of immobilization, *i.e.* the conversion of bioavailable Pi compounds from microbial and root cells into Po forms in soil, occurs as crop residues decompose in soil (Ma *et al.*, 2020). Mineralization is highly influenced by many edaphic factors such as moisture, temperature, surface physio-chemical properties, and pH (Shen *et al.*, 2011). Subsequently, higher temperatures associated with climate change are predicted to increase the rate of Po mineralization in soils (Schoumans *et al.*, 2015). Therefore, Po reserves in soil may play an increasingly important role in improving PUE in soil by providing plant-available Pi.

The role that Po in agricultural soil plays in the context of improving PUE is much debated (George *et al.*, 2018). Researchers are increasingly investigating the possibility of further utilizing Po reserves in soil (Schneider *et al.*, 2016, Ma *et al.*, 2020). As much as 30% of TP in agricultural soils can be present in Po forms with an annual rate of mineralization between 7.7 to 8.5 kg P/ha in soils that have been ploughed out from permanent grassland soils or have received 100 t per hectare of farm yard manure (Johnstone and Poulton, 2019). Therefore, the concentration of TP in the soil of modern GB dairy farming is important to consider when investigating strategies to improve PUE and mitigate environmental P loading.

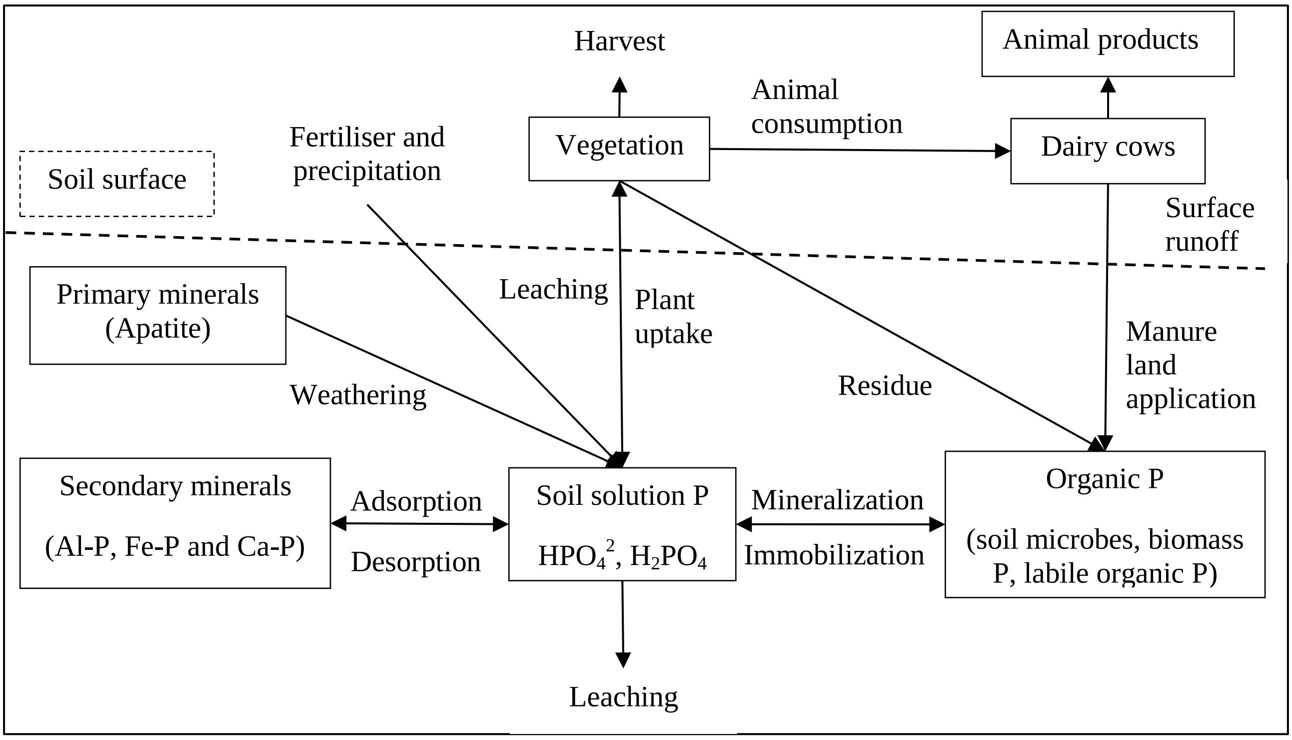

Figure 2.1 A simplified phosphorus (P) cycle in the soil of a dairy farm showing P inputs, losses and transformations. Adapted from Mullen (2005).

Soil Pi compounds can account for up to 70% of soil TP (Shen *et al.*, 2011) and are considered to be present in four pools of varying plant-availability (Table 2.2). The difference in plant availability of Pi between Pi pools depends on the physical association between the form of Pi and the oxides of Iron (Fe), Aluminium (Al) and Calcium (Ca) contained within soil particles (Shen *et al.*, 2011). Consequently, the concentration of phosphate ions in soil and the buffer capacity of the soil to replenish ions after crop uptake largely determines the ratio of TP to available Pi in the soil (Sattari *et al.*, 2012).The least amount of Pi is in the 1st pool (approximately 0.3 to 3 kg P/ha), which is immediately available for root uptake as it is in the soil solution, *i.e.* the liquid phase of soil (Johnston and Dawson, 2005). The analysis of P in soil using $NaHCO_3$ (Olsen P) tends to extract Pi from both immediately and readily available pools, but the extraction of Pi from pools 3 and 4 is very poor. Therefore, Olsen P is the routine soil analysis for soil P status of GB soils, because it measures the concentration of Pi that is available to be utilised by crops for production.

Table 2.2 The pools of inorganic phosphorus (Pi) present in soil, characterised by their form, plant availability and extractability. Adapted from Johnstone and Poulton (2019).

	Inorganic phosphorus pool			
	1st	2nd	3rd	4th
Forms of Pi	Soil solution	Surface-adsorbed	Strongly bonded or absorbed	Very strongly bonded or mineral or precipitated
Plant availability	Immediately available	Readily available	Less readily available	Very low availability
Extractability	In solution[1]	Readily extractable[1]	Low extractability	Very low extractability

[1] Extractable with $NaHCO_3$ (Olsen P) or other suitable reagents

When crops are harvested from land for human and animal consumption, large quantities of plant-available Pi are removed from the soil solution (1st pool). For example, winter wheat, a main arable crop gown in GB, can remove around 30 kg P/ha each year (Johnston and Dawson, 2005). Therefore, conventional wisdom has been that annual applications of mineral fertiliser P is essential to replace Pi removed from the soil solution during harvest to avoid soil P deficiency and associated reduced soil fertility. However, recent studies on the dynamics of P behaviour in soil led to the understanding that Pi is highly reverse-transferrable between the pools of Pi compounds of varying plant-availability over time (Johnstone and Poulton, 2019). So much so that a plot of land growing spring barley and winter wheat can recover 4 to 6 kg P/ha after 100 years of no application of mineral fertiliser P or farm yard manure (Johnstone and Poulton, 2019). Therefore, the concentration of TP in the soil of modern GB dairy farming is important to consider when investigating strategies to improve PUE and mitigate environmental P loading.

The physical association between the form of Pi and oxides in the soil influence how strongly Pi is adsorbed by the oxides of heavy metals (known as fixation) and therefore influences the desorption rate of Pi from heavy metal-oxides to become plant-available (Shen *et al.*, 2011, Thomas *et al.*, 2016). The 3rd pool of less readily available Pi is primarily Pi applied to land in excess of crops' requirement and is strongly bound to oxides in the soil with a very slow desorption into available Pi forms. Similarly, Pi in pool 4 is so strongly bound to oxides in the soil that it may only become plant available through weathering over many years. Consequently, minimal increases in plant-available Pi have been reported from routine soil analysis despite large quantities of mineral fertiliser P being applied (Johnston and Dawson, 2005). Increasing the reliance on soil P reserves in P saturated soils can draw down the P accumulated in soil to reduce the risk of environmental P loading (Stutter *et al.*, 2012, Withers *et al.*, 2014, Liu *et al.*, 2015) whilst also providing farmers financial savings by the reduced purchasing of mineral fertiliser P (Mihailescu *et al.*, 2015). However, limited data on the concentration of P in soils across modern GB dairy farming systems is available, despite such information being important in determining if there is an opportunity to minimise mineral fertiliser P import by increasing reliance on soil P reserves. Therefore, the determination of soil concentration of TP and Pi across GB dairy farming systems is required to contribute towards developing strategies to improve PUE and mitigate environmental P loading from GB dairy farms.

2.2.3 Soil phosphorus accumulation

Typically, less than 25% of Pi applied to soil is readily available and taken up by first crop after application, whilst approximately 10% is lost from soil as runoff and the remainder accumulates in soil as the legacy P fraction (Sattari *et al.*, 2012, Wang *et al.*, 2015, Wironen *et al.*, 2018). Research into the dynamics of legacy P in soil has increased over the years because legacy P in soils saturated with P can impair the effectiveness of nutrient management strategies' mitigation of environmental P loading from soils saturated with P (Sharpley *et al.*, 2013, Wironen *et al.*, 2018). Drawing down legacy P can be achieved by reducing P import into the soil to allow legacy P to be utilised by plants over time. However, the availability of legacy P in soil for plants can be largely influenced by a number of plant and soil factors (Frossard *et al.*, 2000). For example, soils containing a greater concentration of organic matter are reported to have increased P availability because lower concentrations of organic matter in soil can impair root growth and provide fewer sites of low bonding energies for P (Johnston and Dawson, 2005). Conversely, improving the concentration of organic matter in soil can increase the risk of N loss due to the production of water soluble N during the mineralization of soil organic matter. Therefore, further information on legacy P soils in soils is important in contributing towards understanding the dynamics of legacy P to improve the utilisation of legacy P by plants and subsequently mitigate environmental P loading.

Since legacy P represents a possible source of P supply to plants, strategies utilising legacy P could allow reduced rates of mineral fertiliser P application (Oliveira Filho and Pereira, 2020). For example, agricultural soils with considerable legacy P stores are estimated to be able to sustain wheat production for 15 years without any application of mineral fertiliser P (Johnston and Dawson, 2005). Subsequently, projections on the global amount of mineral fertiliser P required to produce crops for an increased global population in 2050 are reduced by up to 20% when re-calculated to consider the global reserves of legacy P in soils (Sattari *et al.*, 2012). Therefore, soils saturated with P provide the opportunity to utilise legacy P to reduce farmers' mineral fertiliser costs, minimise the risk of environmental P loading to waterbodies and improve PUE (Stutter *et al.*, 2012, Withers *et al.*, 2014, Liu *et al.*, 2015). However, there is limited information on the TP concentration of soils in GB dairy farming systems, despite such information being important in investigating if GB dairy farming systems need to draw down legacy P in soil. Therefore, information on the concentration of TP in soils across GB dairy farming systems is important to contribute towards devising strategies to mitigate environmental P loading from diverse dairy farming systems.

2.2.4 Phosphorus status of agricultural soils in Great Britain

National soil surveys show wide differences in GB soil types (loamy, sandy clay), pH status, hydrology and organic matter concentrations (Haygarth and Ritz, 2009). In England and Wales, agricultural soils are classified into one of nine indexes (Table 2.3) based on P concentration (mg P/litre), quantified routinely using the Olsen P method, which extracts readily available Pi from soil using $NaHCO_3$ (AHDB, 2018). Generally, the optimal agronomic concentration of readily available Pi in arable and grassland in GB is between 16 to 25 mg P/litre, *i.e.* soil P index 2. However, the ideal Pi concentration in soil for optimal agronomic performance is highly dependent on a number of soil properties. For example, a relatively higher rate of mineral fertiliser P application to maintain soil at an index above soil P index 2 may be required for alkaline (pH 7.5 to 8.5) and calcareous soils (where considerable quantities of available lime is present) because of low solubility of calcium phosphate (Ca-P) which is predominant in these soils (Hopkins and Ellsworth, 2005). However, farmers with arable land with a P concentration in excess of 16 to 25 mg/L (index 2), can utilise legacy P reserves in the soil by applying relatively less mineral fertiliser P to land. This concept is the process of ‘building up’ or ‘drawing down’ soil P indices. Soils with a higher P index than the agronomic optimal are associated with an increased risk of environmental P loading because a higher soil P index indicates that binding sites of the mineral components in soil are saturated with P, consequently any further application of P increases the likeliness of environmental P loading (Johnston and Dawson, 2005).

Table 2.3 Soil indices based on available phosphorus (Olsen P) concentrations in the soil. Adapted from the RB209 nutrient management guide (AHDB, 2018).

Soil index	Olsen P concentration (mg/L)
0	0-9
1	10-15
2	16-25
3	26-45
4	46-70
5	71-100
6	101-140
7	141-200
8	201-280
9	> 280

2.2.5 Environmental phosphorus loading from agricultural soils

The previous misconception that the fixation of Pi into an unavailable P form for plants is irreversible has historically encouraged heavy use of mineral fertiliser P (Sattari *et al.*, 2012). In Western Europe, the annual import of P into cropland soil as mineral fertiliser and manure (1115 kg P/ha) has regularly exceeded the crop's uptake of P (350 kg P/ha) from soil (Sattari *et al.*, 2012). Consequently, the application of P to soils that have gradually become saturated with surplus P is an environmental concern because of the risk of environmental P loading to waterbodies leading to eutrophication (Withers *et al.*, 1999). Eutrophication is the process of inorganic nutrients enriching waterbodies leading to uncontrolled growth of aquatic plants and algae (Environment Agency, 1998). Naturally, eutrophic symptoms of waterbodies become apparent over a number of centuries, but the enrichment of Pi is the key limiting factor that can accelerate this process to a matter of decades (Schnidler, 1977). Increased eutrophication is associated with the likely growth of cyanobacterial algal which poses problems for toxins, odour and drinking water quality (Withers *et al.*, 2001). Consequently, it is estimated that eutrophication annually costs the UK a minimum of £229 million (Moxey, 2012). These costs are a result of the increased expense for the treatment of drinking water and the reduced value of water dwellings, tourism and recreational activity (Pretty *et al.*, 2003). Therefore, ensuring the efficient use of P in dairy farming systems is important to mitigate environmental P loading in waterbodies and subsequently reduce the environmental and economic consequences associated with eutrophication.

Predicted increased frequencies of extreme weather events associated with climate change, such as heatwaves and precipitation events in Europe, is likely to increase the concentration of Pi in waterbodies (Schoumans *et al.*, 2015). Furthermore, similar to higher temperatures increasing the mineralization of Po into available Pi in soil, the conversion of Po into Pi in bottom sediment of warmer waterbodies will also increase, consequently promoting algal growth (Schoumans *et al.*, 2015). Therefore, strategizing the improved PUE of dairy farming systems is increasingly important to mitigate the environmental and economic consequences associated with eutrophication in countries operating diverse dairy farming systems.

The concentration of soluble reactive P (SRP) in waterbodies is measured to indicate the risk of eutrophication. Recommended P levels (Table 2.4) for a river to be considered in ‘good ecological status’ are between 0-50 µg SRP/L for rivers with less than 50 $CaCO_3$ mg/L alkalinity and 120 µg SRP/L for rivers with greater than 50 $CaCO_3$ mg/L alkalinity (Daldorph *et al.*, 2015). Differences in target SRP concentrations between rivers of varying alkalinity is based on the principle that river alkalinity generally tends to be from rock weathering and so is free from anthropogenic influences (Tappin *et al.*, 2018).

Table 2.4 Ecological status of each river type classified by altitude and alkalinity in the UK, based on annual mean concentrations of soluble reactive P (SRP). Adapted from Daldorph *et al.* (2015)

River type[1]	Altitude (m)	Alkalinity ($CaCO_3$ mg/L)	Ecological status			
			High	Good	Moderate	Poor
			SRP concentrations (µg P/L)			
1n	< 80	< 50	30	50	150	500
2n	> 80	< 50	20	40	150	500
3n	< 80	> 50	50	120	250	1000
4n	> 80	> 50	50	120	250	1000

[1] Used as an identifier based on altitude and alkalinity

Exceedance of the annual mean water SRP concentration standards set out by the Water Framework Directive (WFD) is the main cause of waterbodies in the UK not achieving ‘good’ ecological status (Daldorph *et al.*, 2015) (Muscutt and Withers, 1997). In 2016, only 14% of rivers in England were in ‘good’ ecological status and no improvement in the number of rivers in England achieving ‘good’ ecological status has been reported since (Environment Agency, 2020, Laville, 2020). Therefore, there is a clear need for strategies to mitigate environmental P loading in waterbodies.

The amount of environmental P loading in waterbodies attributed to ‘point sources’ such as sewage treatment works has been successfully reduced over the years. However, this has led to an increased proportion of environmental P loading in GB waterbodies being attributed to agricultural land (Johnston and Dawson, 2005). Therefore, environmental P loading from agricultural land needs to be mitigated in order to meet final objectives set out by the WFD (Schoumans *et al.*, 2015). The lingering dynamics of legacy P accumulated in agricultural soil, that has historically received P above crops’ requirement, can lead to century-long fluxes of environmental P loading into waterbodies (Sharpley *et al.*, 2013). This is true even with little to no additional import of P into soil (Withers *et al.*, 2014). For example, fluxes of SRP in the river Thames are suggested to be attributed solely to legacy P, because since the 1990’s P export out of the surrounding soil has exceeded P import (Civan *et al.*, 2018). Similarly, in the U.S. lingering legacy P did not allow any substantial improvements in water quality, even after implementing nutrient management practices for 20 years (Knowlton and Ray, 2013a). Therefore, devising strategies to improve PUE in dairy farming systems is important in mitigating environmental P loading from agriculture into waterbodies.

2.2.6 Surface phosphorus runoff

It was previously widely assumed that most P is lost from agricultural soil as surface runoff. Generally, surface runoff is the portion of water that can no longer infiltrate the soil-surface. Indeed, surface runoff from agricultural land is a major source of environmental P loading to accelerate eutrophication in waterbodies (Daniel, 1991). However, the erratic nature of soil-surface runoff results in measured concentrations of P in overland flow not normally equating to the P concentrations found in rivers (Mihailescu, 2013). The form and amount of P transported via surface runoff is largely determined by biochemical processes in the soil (Heathwaite and Dils, 2000). Whereas, the pathway of environmental P loading is further influenced by land slope hydrology, land management practices (*i.e.* mineral fertiliser and organic manure application and soil compaction by grazing livestock), soil moisture status (*i.e.* intervals between precipitation events) and the duration and intensity of precipitation events (Johnston and Dawson, 2005). Therefore, when developing strategies to mitigate environmental P loading via surface runoff from dairy farming systems, a wide range of climate, soil and dairy farming system factors need to be considered.

Surface runoff can transport P into waterbodies by carrying eroded sediment bound P (particulate P) and dissolved reactive P (DRP) in its water solution (<0.45 µm). Environmental P loading from surface runoff is generally low during base flow compared to 'incidental P loss' events. Incidental P losses occur when precipitation directly interacts with the DRP in mineral fertiliser or manure freshly applied to the soil-surface. A dominant faction (50 – 98%) of environmental P loading is reported to be attributed to surface runoff in incidental P loss events (Withers *et al.*, 2003, Johnston and Dawson, 2005). Furthermore, a much larger fraction of DRP entering waterbodies is immediately available for algae to utilise for growth compared to particulate P (Ellison and Brett, 2006, Ballantine *et al.*, 2009). Therefore, strategies to mitigate environmental P loading from dairy farms primarily focus on controlling incidental P losses of DRP by restricting the timing of fertiliser and manure P application to land.

Surface runoff carrying particulate P occurs during precipitation events when precipitation erodes soil particles from the main mass of soil and transports them along with any sediment-bound P to waterbodies. Subsequently, the process of erosion more commonly impacts smaller soil particles (Sharpley *et al.*, 1992). Finer soil particles are associated with higher concentrations of P than coarser materials because of their increase surface area providing more sites for P to bind (Ballantine *et al.*, 2009). Consequently, soils with fine particles poses increased eutrophication risk associated with particulate P loss. Furthermore, since particulate P loss is concerned with transporting sediment-bound P, the amount of P lost as particulate P to waterbodies is largely dependent on the P saturation of the soil exposed to precipitation (Ballantine *et al.*, 2009). Thus particulate P loss can be a greater concern in dairy farming systems that have soils saturated with P. Therefore, strategies need to be devised that tackle P loss by holistically considering all pathways of environmental P loading. For example, sub-surface P runoff (leaching) is also an important environmental P loading pathway (Gentry *et al.*, 2007).

2.2.7 Soil phosphorus leaching

Historically, environmental P loading to waterbodies has been thought to be primarily associated with surface runoff as DRP and eroded particulate P (Knowlton and Herbein, 2002). Consequently, minimal attention was given to the transport of DRP and particulate P in the flow of water through the sub-surface of soil, because such an environmental P loading pathway was deemed negligible (King *et al.*, 2015). However, sub-surface environmental P loading pathways have been more recently reported to be significant in agricultural land where soils are often saturated with P (*i.e.* livestock farms), where soils have a low P sorption capacity (*i.e.* sandy soils and soils with high organic matter) and where soils require artificial drainage (King *et al.*, 2015, Schoumans *et al.*, 2015). Therefore, consideration of soil phosphorus leaching is important when devising strategies to mitigate environmental P loading from dairy farming systems.

The movement of water through the profile of the soil sub-surface occurs as preferential and matrix flow, both of which are important in the transport of P through the soil profile. The matrix flow refers to the uniform flow of water which transports P vertically through the soil profile (Daniel, 1991). Only a minimal amount of environmental P loading from agricultural soils in GB are attributed to the matrix flow, with environmental P loading attributed to the preferential flow being twice more than that of the matrix flow (King *et al.*, 2015). However, the amount of environmental P loading attributed to the matrix flow is dependent on the rate of the flow, which influences the reabsorption of P to soil particles in the deeper sub-surface profile of soil. Consequently, sandy soils (non-calcareous and calcareous) and peat soils can be particularly vulnerable to P leaching through the matrix flow, because they have a low degree of soil P saturation and subsequently P is unlikely to be reabsorbed by soil particles in the deeper soil profile (Schoumans *et al.*, 2015). Therefore, holistically considering all pathways of environmental P loading remain important when developing strategies to mitigate environmental P loading from diverse dairy farming systems.

The preferential flow of water transports DRP and particulate P unevenly through pores and fissures in the soil. More rapid preferential flows of water are associated with heavy-textured clay soils, hence the installation of artificial drainage on arable and grassland that have heavy-textured soils to remove excess water (Johnston and Dawson, 2005). Approximately, 60% of agricultural soils in the UK have artificial drainage installed (Withers *et al.,* 2017). However, such artificial drainage provides a more rapid flow of water, consequently leading to a more rapid transport of P to waterbodies. Furthermore, this flow of water through artificial drainage bypasses the soil profile to reduce the exposure time that P has to bind with soil particles deeper in the soil profile (Heathwaite and Dils, 2000). In the UK, during the wetter months the amount of drain flow is continuous, with a low TP concentration dominated by DRP (65%). Whereas, in the drier months drain flow is more irregular but contains a greater TP concentration dominated by particulate P (60%) (Heathwaite and Dils, 2000). Greater TP concentration of drain flow in the direr months is influenced by soil cracking and the application of fertiliser to land during these months. Consequently, strategies to mitigate environmental P loading from dairy farming systems must also be mindful of P lost in the preferential flow of soils.

A considerable source of P leachate is from livestock manure applied to land. Livestock manure contains a significant fraction of water soluble P, which is vulnerable to transfer to waterbodies as both runoff and leaching and contributes towards the P saturation of soil (Mihailescu, 2013). In a longer-term trend, the proportion of P import into the soil-surface attributed to livestock manure has increased. This is because efforts to reduce mineral fertiliser P import have been successful, whilst P import into the soil-surface from livestock manure has remained largely unchanged (OECD, 2018). Therefore, strategies to improve soil P management to subsequently mitigate environmental P loading from dairy farming systems is closely linked with P feeding practices that farmers adopt in their dairy farming systems.

2.3 PHOSPHORUS CYCLING IN THE DAIRY COW

In dairy cows, P has more known biological functions than any other mineral element, with a primary function in the development of the skeletal system and an involvement in almost all energy transactions as ATP, cell membranes as phospholipids, buffer systems, ruminal cellulose digestion and microbial protein synthesis (NRC, 2001). Since P cannot be synthesised by cows, it is primarily supplied from dietary sources. In most forage and grains, P is found as Po in the form of phytate. This phytate can be utilised by ruminants because of an endogenous supply of the enzyme phytase, which is synthesised by microbes in the rumen. Phytase catalyses the release of phytate groups from the inositol ring of phytate (Hill *et al.*, 2008). However, some studies have reported the lack of effect on the degradation of phytate in ruminants when dairy cows are supplied with exogenous phytase supplementation, likely because of the endogenous supply of phytate in the rumen (Jarrett *et al.*, 2014, Humer and Zebli, 2015, Winter *et al.*, 2015). Conversely, cows have been reported to degrade phytate even when they were fed a high phytate diet (Ray *et al.*, 2013). This work further concluded that it was total concentration rather than form of P in the diet that was the major driver of faecal P excretion in dairy cows (Ray *et al.*, 2013).

Unlike monogastrics, the absorption of P in ruminants is not coupled with Ca and thus P absorption can be increased independent of Ca status (Goselink *et al.*, 2015). Further investigation into the role that the Ca:P ratio plays in regulating bone P throughout lactation is required (Goselink *et al.*, 2015). However, extant feed recommendations for P and models of P metabolism for ruminants generally do not consider Ca metabolism. In dairy cows, the majority of P is absorbed in the small intestine (especially the first part of the small intestine) by passive paracellular transport when P concentration in the digesta is very high compared to cows' P requirement (Goselink *et al.*, 2015). However, P can further be absorbed in the small intestine (especially the jejunum and ileum) by active trancellular transport of P mediated by NaPi co-transporters (Goselink *et al.*, 2015), which is likely simulated by dietary P depletion (Wilkens and Muscher-Banse, 2020). Therefore, lowering the P concentration of dairy cows' diet can increase the amount of P absorbed to improve the efficiency of P digestibility (Wu *et al.*, 2000). Inversely, feeding dairy cows a diet with a high P concentration can reduce the efficiency of P digestibility and consequently lead to increased faecal P excretion.

Dietary P and salivary secretion of Pi are the major sources of Pi into the rumen. Predominantly through rumination, this highly available salivary Pi enters the rumen to be utilised by microbes for growth and metabolism. A considerable part of salivary Pi secretion is then reabsorbed in the digestive tract to create an element of Pi recycling (Puggaard *et al.*, 2011). The salivary Pi concentration *(*4 to 15 mmol/L) is usually high compared to blood plasma Pi concentration (1 to 3 mmol/L) because the salivary glands concentrate Pi obtained from blood in saliva (Goselink *et al.*, 2015). In some dynamic models of P metabolism, the amount of saliva produced and the salivary Pi concentration is assumed to be constant (Hill *et al.*, 2008). However, this can be influenced by various factors, such as the amount of fibre in the diet which influences the duration of rumination or if the regulators of salivary P excretion are influenced by a low Pi concentration in the rumen or blood (Goselink *et al.*, 2015). However, a decrease in dietary P intake is demonstrated to lower the blood plasma Pi concentration but not salivary Pi concentration in lactating dairy cows. This is because in response to low TP dietary intake, lactating dairy cows prioritize the Pi supply from salivary recycling to maximize rumen function in the short-term at the expense of long-term consequences of depletion of bone P (Puggaard *et al.*, 2011). Within the body of a cow, P is predominantly (80 to 85%) found in bones and teeth as insoluble apatite salts and calcium phosphate, whilst the remainder (15 to 20%) forms the pool of readily available P within soft tissue and body fluids (Goselink *et al.*, 2015). Despite essentially no net transfer of P between blood and bone in homeostatic conditions for mature cows, cows in early lactation can mobilize up to 30% of bone P content, equating up to an estimated supply of 1 kg of P in early lactation for a 600 kg cow (Knowlton and Herbein, 2002).

Even though dairy cows are capable of utilising P from phytate and have the unique physiological ability to recycle Pi through saliva, the efficiency of using P in dairy cows is still low and ranges from 20 to 40% of dietary P intake (Bannink *et al.*, 2010, Knowlton and Ray, 2013a). Subsequently, this poor efficiency of P utilisation in dairy cows has led to a large amount of P excretion, primarily via faeces in dairy cows (Knowlton and Ray, 2013a). Since faecal P excretion has been considered a contributor to environmental P loading from dairy farms, several efforts have been made to reduce faecal P excretion in dairy cows by improving PUE. Faecal P in dairy cows consists of

3 fractions (Figure 2.2): dietary P that was unavailable to the cow, inevitable P loss from microbial debris and endogenous P that was absorbed in excess of the cow's P requirement but recycled back into the rumen via saliva (NRC, 2001). Therefore, it is evident that faecal P excretion in dairy cows is influenced by both digestion and metabolism of P. Even though substantial progress has been made to understand P digestion and metabolism in ruminants, further research is needed to identify factors that influence P digestion and homeostasis in dairy cows. In addition, better insight into P digestion and metabolism will allow more accurate prediction of dietary P requirements, which will facilitate development of further strategies to reduce faecal P excretion in dairy cows.

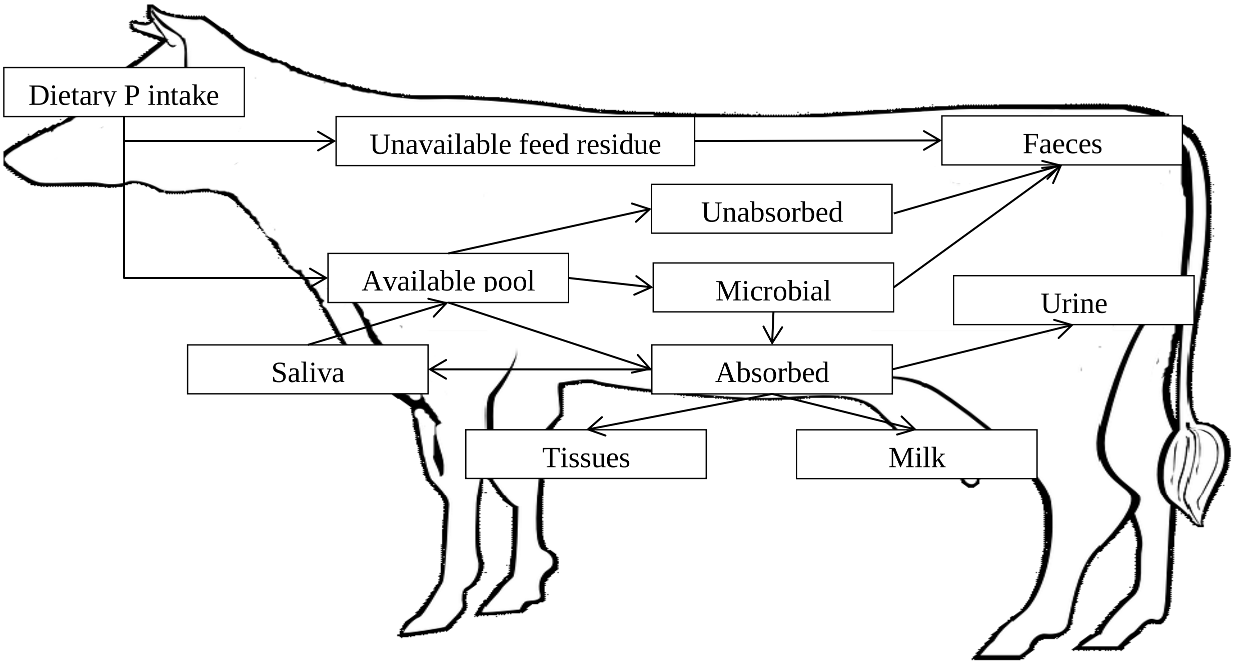

Figure 2.2 Schematic illustration of phosphorus (P) partitioning in a lactating dairy cow linked with faecal P excretion (Dou *et al.*, 2010).

2.3.1 Reducing faecal phosphorus excretion

A high concentration of dietary crude protein (CP) has been associated with a lower faecal P excretion in dairy cows (Kebreab *et al.*, 2005, Klop *et al.*, 2013). However, this may not be a direct effect of dietary CP but rather because high dietary CP increases milk yield (Law *et al.*, 2009), causing more P being channelled into milk as opposed to manure (Bannink *et al.*, 2010). Similarly, high dietary neutral detergent fibre (NDF) reduced faecal P excretion in dairy cows fed a diet with P concentration in excess of cows' P requirement (Klop *et al.*, 2013). Reduced faecal P excretion in dairy cows fed a high fibre high P diet might be due to increased duration of rumination associated with greater levels of NDF and subsequently a greater amount of P absorbed in excess of cows' requirement is recycled through saliva. Alternatively, reduced faecal P excretion in dairy cows fed a high fibre could be because high NDF levels likely coincide with low starch levels. Lower levels of starch in the diet are associated with a lower availability of fermentable substrate for microbes in the rumen, consequently reducing P uptake by ruminal microbes (Klop *et al.*, 2013). Additionally, feeding a high energy diet reduced faecal P excretion in dairy cows but most likely by increasing milk yield and hence increased amount of P secretion in milk (Kebreab *et al.*, 2005, Hill *et al.*, 2008). More specifically, it is a slow release energy source in the diet that can reduce faecal P excretion, because these sources supply nutrients to the microbe at a rate optimal for utilisation, including P (Kebreab *et al.*, 2013b). Since all the strategies proposed above are based on the correlation between dietary factors and faecal P excretion, more research is needed to determine the causation before these strategies could be adopted as sustainable strategies in dairy production systems.

Further research into alternative methods for improving the availability of dietary P in the dairy cow such as mechanical processing, soaking, germination and fermentation of feeds is warranted to improve the PUE in dairy cows (Humer and Zebli, 2015). However, the TP concentration of a diet remains the determining factor of P digestibility and subsequently the TP concentration of a diet has been observed to highly and positively correlate with faecal P excretion in dairy cows (Ray *et al.*, 2013). Moreover, a high P diet increases the amount of the water soluble fraction of faecal P, which is more prone to runoff losses to waterbodies (Dou *et al.*, 2002). Therefore, feeding diets with a P concentration that closely matches P requirement in dairy cows is important in improving PUE and subsequently reducing faecal P excretion.

2.3.2 Dietary phosphorus requirement

In most national feeding recommendations for dairy cows (AFRC, 1991, NRC, 2001), TP requirement for maintenance, growth, milk production and gestation is first calculated (Valk *et al.*, 2000). This is then divided by the ‘absorption coefficient’ of dietary P to determine the dietary P requirement (Valk and Baynen, 2003). Therefore, the recommended dietary P concentration for lactating dairy cows largely varies with milk production. Even though a relatively recent study reported that milk P concentration can vary with the protein and lactose content of the milk and ranges from 0.7 to 1.2 g P/kg milk (Goselink *et al.*, 2015), the concentration of P in milk has been considered relatively constant at 0.9 g P/kg milk (NRC, 2001). Therefore, the amount of net P required by a dairy cow for the same amount of milk production remains relatively constant across national P feeding recommendations of different countries. However, the estimated absorption coefficient of dietary P varies substantially across countries, primarily because of the use of data obtained from studies taking different approaches. Consequently, this has led to differences in dietary P requirement recommended by national feeding systems in different countries.

In the UK, the dietary P requirement for dairy cows is recommended on the basis that DM intake rather than dietary P intake correlates with inevitable faecal P excretion (Scott *et al.*, 1995). This is because the Agriculture and Food Research Council (AFRC) assumes the underlying idea that increased DMI is associated with greater endogenous P flow via saliva (AFRC, 1991). Since only a certain proportion of salivary P will be recycled, the remainder will be lost as faecal P (Valk and Baynen, 2003). However, this assumption that increased DMI is associated with greater endogenous P flow via saliva may not be appropriate for dairy cows because salivary Pi concentration is more closely associated with blood plasma P concentration than with DMI (Valk and Baynen, 2003).

In comparison to the UK feeding system, the US recommends a lower dietary P concentration to dairy cows, which has progressively lowered over the years (NRC, 1978 and 1987 and 1989). This gradual decline in NRC recommended dietary P requirement for dairy cows was a result of a smaller safety margin being added to the recommended dietary P requirement, to compensate for uncertainties in the availability of P because of improved precision in predicting P availability in dairy cows (Ray and Knowlton, 2014). In the current NRC feeding recommendations (NRC, 2001), the availability of P varies between feed sources based on fixed values for forages (64%), concentrates (70%) and minerals (≥ 75%). However, the current NRC (2001) recommended dietary P concentration is suggested to not fully consider the variation in

P availability between feed ingredients within a feed type *i.e.* forages, concentrates and inorganic mineral supplements (Feng *et al.*, 2016). In addition, the current NRC recommendation does not fully consider the supply of P from bones during early lactation (Salazar *et al.*, 2012). However, the dietary P concentration recommended by the NRC (2001) cannot be further reduced until the potential long-term effects on cow health and performance are further understood (Bannink *et al.*, 2010, Salazar *et al.*, 2012). Instead, an important strategy to reduce the faecal P excretion of dairy cows has been to encourage dairy farmers and feed professionals to formulate diets with a P concentration closer to the NRC (2001) recommended level (Knowlton, 2011a). Implementation of this precision P feeding strategy could reduce faecal P excretion and subsequently environmental P loading from GB dairy farms because dairy herds in Central and Northern England were found to use dairy cow diets with high P concentrations that were on average 20% in excess of NRC (2001) recommendations (Sinclair and Atkins, 2015).

Ensuring a sufficient supply of dietary P to dairy cows is essential as a diet deficient in P can lead to poor cow health, productivity and fertility. Severe P deficiency can lead to rickets in the youngstock and osteomalacia in mature cows (Theiler, 1912, Ternouth, 1990). Furthermore, an insufficient supply of dietary P can reduce microbial digestion and protein synthesis in the rumen, which feeds back to the satiety centre in the hypothalamus to negatively influence DM intake (McDowell, 1992, Valk *et al.*, 2000). Reduced DM intake then acts as a catalyst for further metabolic disorders and deterioration of health. A dietary P concentration of 2.3 g P/kg DM is one of the lowest documented P concentration in a diet fed to dairy cows in a modern feeding trial (Puggaard *et al.*, 2014). However, this 2.3 g P/kg DM could not support high milk yield

(9000kg milk/lactation) as milk yield started to decline around week 6 after partition, and this decline was concurrent with a decline in DM intake. A decline in milk yield from cows fed a P deficient diet may not be observed in early lactation because the high P requirement of dairy cows in early lactations could be met by P mobilised from bone. However, a delayed drop in milk yield in later lactation can occur from a cow fed a continued P-deficient diet because of a lack of supply of P from bone as P mobilised from bone earlier in lactation would not have been replenished (Puggaard *et al.*, 2014).

Severe P deficiency was reported to reduce reproductive success in dairy cows (Ternouth, 1990). However, in a meta-analysis of feeding trials conducted between 1920 and 1960, no significant impact on fertility parameters was observed in cattle fed diets with P concentrations between 1.6 to 5.6 g P/kg DM (Ferguson and Sklan, 2005). Furthermore, feeding trials that more carefully controlled influential variables to assess the impact of dietary P on reproductive performance, found no impact on fertility or ovarian activity when dietary P concentration was reduced from 5.7 g P/kg DM to NRC (2001) recommended concentrations (Lopez *et al.*, 2004, Tallam *et al.*, 2005). This limited impact on fertility from low P diets is likely because in a P deficient cow, reproductive performance takes priority over milk production, and thus milk yield is reduced to compensate for reproductive performance (Valk *et al.*, 2000). The consensus of the literature is that it is particularly difficult to feed a diet low enough in P to impair reproductive success (Cerosaletti *et al.*, 2004). Moreover, lowering dietary P concentrations to match NRC (2001) recommended concentrations reduces faecal P excretion without any negative impact on health, productivity and fertility of dairy cows (Wu *et al.*, 2001b, Lopez *et al.*, 2004, Ekelund *et al.*, 2006, Wang *et al.*, 2014) over multiple lactations (Ferris *et al.*, 2009). However, the P concentration in bones was lower in high producing dairy cows (> 11900 kg milk/lactation) fed a diet with P concentration of 3.1 g P/kg DM (Wu *et al.*, 2001b).

2.3.3 Summary of the impact of dietary P concentration on cow performance

A review of the literature on modern P feeding trials suggests that a dietary P concentration of 3 g P/kg DM is borderline deficient for cows producing approximately 9000 kg of milk per lactation (Valk and Sebek, 1999, Puggaard *et al.*, 2011). Whereas, research suggests around 3.5 to 4.2 g P/kg dietary DM is required to sustain production in moderate to high producing dairy cows (7500 to 11,000 kg milk lactation) (O'Rourke *et al.*, 2010b). Therefore, the dietary P concentration recommended by the NRC (2001) varies between 3.1 to 4.1 g P/kg DM (Table 2.5) depending on the milk yield and DMI of dairy cows (Knowlton, 2011a). Reducing dietary P concentration to the level recommended for a certain level of milk yield and DM intake has been shown to have no detrimental effect on cow health, productivity or fertility (Lopez *et al.*, 2004, Ferris *et al.*, 2009, Wang *et al.*, 2014). Therefore, the NRC (2001) recommended dietary P concentration for dairy cows could be considered optimum. However, the NRC provides a moderate safety margin that is progressively being lowered as new information emerges regarding dietary P availability, (Ray and Knowlton, 2014), early and late lactation P requirement (Salazar *et al.*, 2012) and long-term feeding over multiple lactations (Ferris *et al.*, 2009). Consequently, the optimum dietary P concentration for dairy cows may in truth be lower than the NRC recommended level.

Table 2.5 Phosphorus requirements for Holstein lactating cows (600 kg BW) with varying DMI and milk yield (NRC, 2001). Adapted from Knowlton *et al.* (2011a)

	Milk yield (kg/day)						Milk yield (kg/day)					
	30	32	34	36	38	40	30	32	34	36	38	40
DMI (kg/day)	Absorbed P requirement (g/day)						Dietary P requirement (g/kg DM)[1]					
21.8	49	51	52	54	56	58	**3.5**	3.6	3.7	3.9	4.0	4.1
22.5	49	51	53	55	57	58	3.3	**3.4**	3.5	3.7	3.8	3.9
23.2	51	53	54	56	58	60	3.2	3.4	**3.5**	3.6	3.7	3.8
23.9	52	53	55	57	59	61	3.2	3.3	3.4	**3.5**	3.6	3.8
24.6	52	53	55	57	59	61	3.1	3.2	3.4	3.5	**3.6**	3.7
25.3	52	54	56	58	60	61	3.1	3.2	3.3	3.4	3.5	**3.6**

[1] Shaded cells with bold indicate dietary P requirement based on NRC predicted DMI for the specified rate of daily milk yield

2.4 PHOSPHORUS CYLING IN A DAIRY FARM

On a typical dairy farm that uses home-grown forages to feed the dairy herd, the cows receive the majority of their dietary P from forages that extracted P for their growth from the soil P pool. This soil P pool is routinely replenished by the manure generated from the dairy herd (Aarts and Haans, 2013). Therefore, the flow of P through a dairy farming system can be characterised as a cycle of P (Figure 2.3). The P that is lost from a dairy farm’s P cycle as milk, meat and environmental P loading is primarily replenished by purchased feed and mineral fertiliser import. However, the large amount of purchased concentrate feeds in an all-year housed system may increase the proportion of imported P that is unaccounted for in crop and livestock produce leaving the farm. Consequently, increasing the remaining P accumulating in the soil or being lost the environment over time (Adenuga *et al.*, 2018).

The long-term risk of the accumulation of P in dairy farms is widely assessed by farmers, policy-makers and scientists via the calculation of a P balance (Oenema *et al.*, 2003, Thomas *et al.*, 2020). A P balance is defined as a summary table of the annual import of P into and export of P out of the targeted boundary (Oenema *et al.*, 2003). A P surplus (import exceeds export) suggests a long-term risk of P accumulating in soil and subsequently being lost to waterbodies (Mihailescu *et al.*, 2015). However, a P balance should be interpreted carefully because unlike N surplus, which is seen as an unnecessary economic waste and potential environmental problem, in the short-term a P surplus could be required to build up soil P to optimal levels for crop production without environmental risk (Withers *et al.*, 2014, Mihailescu *et al.*, 2015). Similarly, a P deficit in the short-term could be required to draw down soil P to optimal levels for crop production. However, a long-term P deficit is unsustainable because the depletion of soil P reserves can reduce soil fertility (Thomas *et al.*, 2020). The import and export considered in a calculation of P balance depend on whether the P balance is considered at a farm-gate P balance (FPB) or soil-surface P balance (SPB) scale.

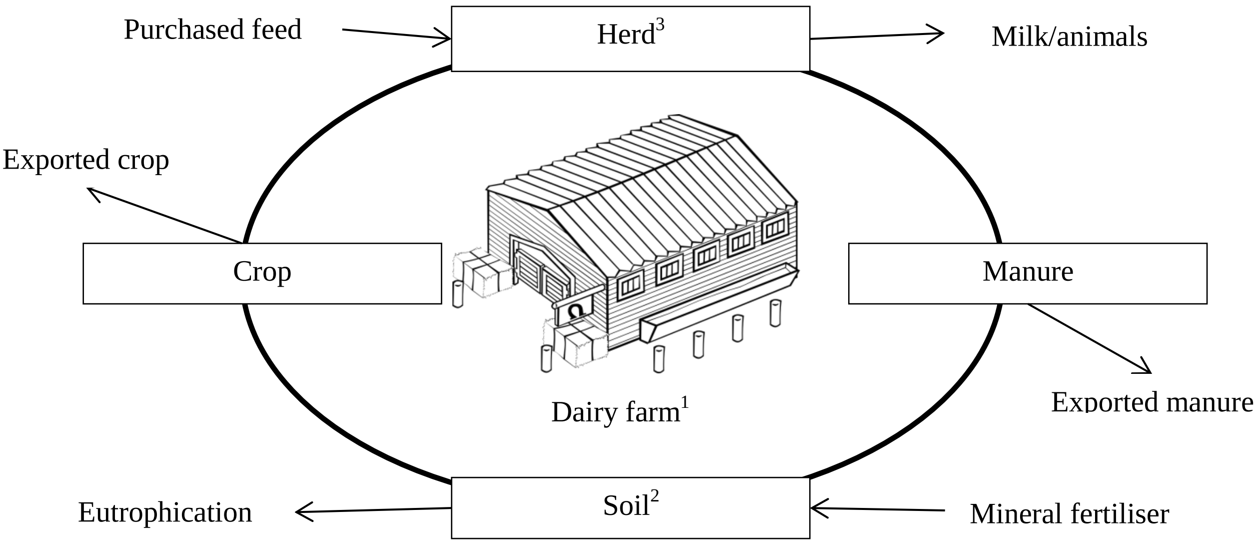

Figure 2.3. The cycle of phosphorus (P) on a typical dairy farm and the position of P balances. Adapted from Aarts *et al.* (2013). [1] A farm-gate P balance, [2] a soil-surface P balance and [3] a herd's P use efficiency,

2.4.1 Farm-gate phosphorus balance

Dairy farmers are required to calculate a FPB as a license to produce milk in some states in the US (Knowlton and Ray, 2013a), in the Netherlands (Aarts *et al.*, 2015) and in Northern Ireland when farmers request a N derogation from the Nitrates Directive (Northern Ireland Environment Agency, 2019). However, GB is similar to Poland, France and other European countries, in that there is no extensive legislation specific to P (*i.e.* limit on feeding or fertiliser application) despite having large soil P reserves (Amery and Schoumans, 2014). Consequently, the information on the current status of FPB in GB dairy farming is limited (Withers *et al.*, 2001, DEFRA, 2005, Raison *et al.*, 2006). However, previously determined FPB may not be relevant to modern GB dairy farming because there is an increased prevalence of housed dairy farming systems

(March *et al.*, 2014), which were modelled to pose greater eutrophic risks compared to pasture-based systems primarily because of greater amount of concentrate feed import into housed dairy farming systems (O'Brien *et al.*, 2012). Therefore, there is a need for re-evaluation of the status of FPB on dairy farms that is reflective of modern GB dairy farming.

A FPB can be calculated using the nutrient management decision support tool ‘Planning for Land Application of Nutrients for Efficiency and environmenT’ (PLANET). PLANET is a widely applicable tool that was developed to integrate into GB dairy farming records, making it well adopted by GB dairy farmers and advisers (Dampney and Sagoo, 2008). Furthermore, FPBs calculated using PLANET have been observed to fit well with the amount of environmental P loading modelled for lakes at a catchment scale (Norton *et al.*, 2012) and PLANET has been effectively used to explore N management strategies for livestock farms in the UK (Gibbons *et al.*, 2014). In addition to calculating a FPB, PLANET also provides benchmarks to users of the tool. Such benchmarks were devised using data from 171 commercial dairy farms between the years 2002 to 2005. The mean FPB of the dairy farms (20.1 kg P/ha) was used as the ‘norm’. The top 25% of dairy farms had a FPB < 14.4 kg P/ha and the bottom 25% had a FPB > 24.9 kg P/ha (DEFRA, 2005), when back-calculating the reported phosphate values to P using a factor of 2.29. However, the FPB benchmarks provided by PLANET are suggested to be limited because they favour dairy farms in South-West England (DEFRA, 2005). Furthermore, these benchmarks were devised using standard book or literature value of P concentrations in the import and export items, which DEFRA suggested may have under-collected fertiliser use. Additionally, the use of standard values for P concentrations in items such as forages increases the likelihood of either under- or over-estimation of P import or export. The P concentration in forages can vary considerably with forage maturity and soil P concentrations (Cerosaletti *et al.*, 2004). Similarly, P concentration in manure can vary to a great extent with changes in the P concentration of diets fed to the cows (Ray *et al.*, 2013). A feasible FPB benchmark of 13 kg P/ha has been determined for dairy farms in New York (Cela *et al.*, 2014) by considering the FPB (kg/ha) that 75% of participating farms could achieve. The same approach has been used to identify a feasible farm-gate N balance for dairy farms in Flanders (Nevens *et al.*, 2006). Furthermore, an optimal zone for milk production and animal density that provides farmers with specific FPB targets they should aim towards operating within based on their milk production and animal density was also determined. This was calculated by further considering FPB on a milk production (1.1 kg P/tonne of milk) and animal density (5 kg P/LU) basis that 50% of participating farms could achieve (Cela *et al.*, 2014). However, such FPB benchmarks have not been determined for modern GB dairy farming. Furthermore, considering national benchmarks that are not system-specific may not be appropriate for GB dairy farming which operates diverse dairy farming systems because these systems may contribute to eutrophication differently from one another (O'Brien *et al.*, 2012). Therefore, there is a need for current FPB benchmarks that are devised from measured P concentrations in P import and export items and reflect current diverse dairy farming systems in GB.

A FPB is easily calculated by subtracting P that enters the farm from P that leaves the farm via the farm-gate. Therefore, the calculation of FPB requires minimal assumption compared to a SPB, meaning the uncertainties associated with the approach of determining FPB are smaller than the approach used to calculate a SPB (Oenema *et al.*, 2003). Additionally, a farm-gate PUE can be determined by expressing the proportion of P import onto a farm recovered in the export of P out of a farm. Both FPB and farm-gate PUE have been used to assess the environmental and economic sustainability of dairy farms in many countries (Raison *et al.*, 2006, Cela *et al.*, 2014, Mihailescu *et al.*, 2015). The mean FPB across these countries ranges between a mean of 5.1 kg P/ha in Ireland (predominantly pasture-based) (Mihailescu *et al.*, 2015) and 16.4 kg P/ha across England, Scotland and Ireland (Raison *et al.*, 2006), with 10.4 kg P/ha for dairy farms in New York (Cela *et al.*, 2014). Compared to the mean FPB, mean PUE information is less available for comparisons to be made but a mean 70% is observed for dairy farms in Ireland (Mihailescu *et al.*, 2015). However, while a FPB can be used to determine P surplus on a farm, it cannot provide information about the fate of surplus P in the soil (Weaver and Wong, 2011).

Principally, FPB and SPB should match, but are not always identical because FPB cannot explicitly represent the build-up, depletion and consumption of internal stock. Whilst, SPB may under-estimate the manure P import into soil, as the extant energy systems that SPB relies on can under-predict the energy requirement of dairy cattle. Therefore, both FPB and SPB are important to provide a meaningful assessment of the risk posed by a dairy farm to the aquatic environment (Adenuga *et al.*, 2018). However, SPBs on dairy farms have been rarely determined, likely because of the difficulty in estimating the amount of P export from soil as grazed grass (Adenuga *et al.*, 2018), the amount of P import onto the soil as manure and the limited tools available to address these limitations. Therefore, the development of an approach to calculate SPB on GB dairy farms is critical to assess the eutrophic risk of modern GB dairy farming.

2.4.2 Soil-surface phosphorus balance

Generally, a SPB has been employed to indicate the environmental performance of agriculture as a whole in the UK (DEFRA, 2018a) and throughout Europe (EUROSTAT., 2007). A SPB is the difference between the amount of P that enters and leaves the soil-surface (Oenema *et al.*, 2003). Although there are minimal differences in P import and export between FPB and SPB in crop production systems, P import and export at farm-gate and soil-surface level can substantially differ in livestock production systems (Oenema *et al.*, 2003). On a dairy farm, P import onto the soil-surface includes land application of mineral fertiliser P and manure P (via both manure application and direct deposition onto soil surface by grazing cows), atmospheric deposition, seed and planting materials and crop residues. However, atmospheric deposition, seed and planting materials and crop residues are not routinely considered in SPB because they contribute minimal (≤ 5%) P towards the total P import onto the soil-surface (EUROSTAT., 2007). Furthermore, atmospheric deposition tends not to be considered when calculating nutrient balances because such an import is out of the farmers control (Cherry *et al.*, 2012). The main export of P from the soil-surface on a dairy farm is attributed to harvested crops and grass (harvested for making silage or grazed). The difficulty in estimating P import onto the soil-surface via manure and P export out of the soil-surface via grazed grass has limited the interest in determining SPB on dairy farms (Adenuga *et al.*, 2018).

To reduce the uncertainty in estimating manure P import and grazed grass P export for the calculation of SPB, the use of well validated simulation models is required (Oenema *et al.*, 2003, Adenuga *et al.*, 2018). Dutch dairy farmers are required to collect data required to use the ‘Annual Nutrient Cycling Assessment’ (ANCA, in Dutch: Kringloopweiser) tool. ANCA calculates a SPB to demonstrate to the Dutch government that the farmer is producing milk sustainably (Aarts and Haans, 2013, Aarts *et al.*, 2015). In ANCA, manure P import into the soil-surface is calculated using the BEX module, which simulates the cycle of P on a farm-scale by subtracting the P deposited in the entire herd for functions such as growth, pregnancy and milk production (estimated using information on herd demographic) from the dietary P intake of the entire herd, with the remaining P assumed to be excreted as manure for land application and direct deposition onto land during grazing (Groor, 2016). The amount of consumed grazed grass from the soil-surface is simulated in ANCA by subtracting the energy supplied to the entire herd by conserved feeds from the herd’s energy requirement (determined using information on herd demographics). The intake of home-grown forages is then adjusted using the remaining energy required by the herd via coefficients that consider factors such as access to pasture and the proportion of silages originally inputted into the tool by the user (Groor, 2016). The grazed grass P export is then determined using the amount of energy consumed attributed to grazed grass using the P concentration of grass silage multiplied by a factor of 1.05. ANCA is a policy tool and is subsequently heavily validated in the Netherlands, but the principles of the ANCA tool have not yet been investigated to develop an approach to calculating SPBs on GB dairy farms. One major limitation has been that ANCA calculates the energy requirement of cows using the Dutch net energy (NE) system *i.e.* the VEM system (feed unit of milk, in Dutch; Voedereenheid Melk), which is different from the UK approach to determining the energy content of feed *i.e.*. metabolisable energy (ME).

However, the ME of feed can be converted to VEM using Eq. 1 (Dijkstra *et al.*, 2008, Wageningen UR, 2016).

$$VEM = 0.6 \times (1 + 0.004 \times (q - 57)) \times 0.9752 \times ME / 6.9\ kJ \times 1000 = (0.0003392 \times q + 0.0654656) \times ME \times 1000.$$

$$q = (ME / GE) \times 100$$

Equation 1. Conversion of a feed metabolisable energy (ME) into VEM using a feeds gross energy (GE)

The constant *0.6* represents that 60% of ME supplied to the cow above maintenance requirement is converted to net energy (NE), when a ration with q = 57 is fed. The second part of the equation, $(1 + 0.004 \times (q - 0.57)$ indicates that diets with a higher q have an improved efficiency of utilization of ME but diets with a lower q have lower efficiency of ME utilisation. The $0.9752 \times ME$ in the equation is a correction factor for a feeding level of 2.38 × maintenance which was derived from feeding experiments, because the ME of a feed decreases with feeding level in ruminants. Lastly, the $ME / 6.9$ in the equation reflects that the arbitrary feed-unit-lactation adopted (VEM) of a feed contains 6900 kJ/kg NE (*i.e.*, 1000 VEM is the mean NE of 1 kg of air-dried barley). Therefore, there is a need to investigate whether the principles of the ANCA tool could be adapted to be used as an approach to calculate SPB on GB dairy farms, which could be implemented as an extension module to the current tools such as PLANET that are widely used in GB dairy farming. Adoption of such a tool could be important in capturing important differences between diverse dairy farming systems that may influence SPB. Such differences may include concentrations of P in milk and manure.

2.4.3 Application of phosphorus balances

Reducing P surplus on a dairy farm can minimise the risk of water pollution and can improve PUE to provide financial savings for farmers (Mihailescu *et al.*, 2015). Therefore, researchers use P balances to identify best management practices to reduce P surpluses. However, the large differences in the approaches used to calculate P balances lead to a level of uncertainty from potential biases and erroneous data (Oenema *et al.*, 2003). Therefore, the approaches to determining P balance should always be validated, which tends to be achieved by comparing the P balance data with direct measures of soil P concentrations (Mihailescu *et al.*, 2015), other published P balance data (Adenuga *et al.*, 2018), modelled environmental P loading into surrounding lakes (Norton *et al.*, 2012) and in ANCA's case, comparison to a multitude of farm data from the 'De Marke' experimental dairy farm (Aarts and Haans, 2013). Therefore, any new P balance that is reflective of current dairy farming will be important in contributing towards validating any future approaches to generating P balance data.

Best management practices recommended for reducing P surpluses on dairy farms have always been identified by investigating the main determinants of P surplus and by comparing P balances between time periods (Mihailescu *et al.*, 2015), regions (Raison *et al.*, 2006) and farms (Adenuga *et al.*, 2018). However, limited research has compared FPB between dairy farming systems (March *et al.*, 2016, Akert *et al.*, 2020). Moreover, no research has compared SPB between GB dairy farming systems, despite dairy farming systems being previously modelled to contribute to eutrophication differently from one another (O'Brien *et al.*, 2012, March *et al.*, 2016). Consequently, strategies to reduce P surpluses on dairy farms are largely based on research from the US (Cela *et al.*, 2014) and Ireland (Mihailescu *et al.*, 2015) where strict housed and pasture-based systems are predominant, respectively. However, GB has a wide assortment of dairy farming systems characterised by diverse calving approaches, varying amounts of annual concentrate feeding and wide range in the number (from none to 365) of grazing days (Garnsworthy *et al.*, 2019). Since the feasibility of implementing management practices (*i.e.* feeding practices) to reduce P surplus on dairy farms may differ between dairy farming systems (March *et al.*, 2014), current strategies to reduce P surplus on dairy farms recommended from countries operating either a strict pasture-based or all-year housed dairy farming system may not be feasible to implement for countries operating diverse dairy farming systems. North-Western and Central European member states produce milk similarly to GB, by operating large specialised dairy farms along with a wide assortment of pasture-based and housed systems (March *et al.*, 2016, Augère-Granier, 2018). Therefore, there is a critical need to investigate the differences in P balances and PUE between GB dairy farming systems, which will contribute towards developing strategies to improve the sustainability of dairy production in countries operating diverse dairy farming systems.

2.4.4 Summary of P balances on dairy farms in the literature

A review of FPBs in the literature suggests that FPB may be different between systems, with systems closer to an all-year housed system having higher P surpluses than more pasture-based systems when using lifecycle assessment and data envelope analysis models (O'Brien *et al.*, 2012, March *et al.*, 2016). However, these studies did not provide FPB information to compare between systems. More recently a study in Switzerland reported a greater FPB (16.5 kg P/ha) in a housed system compared to pasture-based system (2.1 kg P/ha) (Akert *et al.*, 2020). Therefore, it is likely that FPBs will differ between GB dairy farming systems but this has not yet been demonstrated in the literature.

The information on dairy farm FPB that exists in the literature varies greatly between countries (Table 2.6.) because of large differences in many aspects such as farming practice, animal genetics, feeds, regulations and different fixed values when calculating FPBs (Raison *et al.*, 2006). Information existing for FPBs in GB dairy farms suggest a mean P surplus of between 15.4 to 20.1 kg P/ha. However, the optimal FPB surplus to be maintained on farms is estimated to be 5 kg P/ha (Doody *et al.*, 2020). Such a P surplus may due to lack of consideration of the systems operating in GB by the existing literature, with pasture-based systems suggested to operate a lower FPB than a housed-system (O'Brien *et al.*, 2012, March *et al.*, 2016, Akert *et al.*, 2020). Therefore, information is needed to identify the FPB of GB dairy farms across the different systems operating in GB. Additionally, there is need for SPB information across these systems, which currently does not exist for GB dairy farms. The mean SPB of dairy farms in Northern Ireland is suggested to be 11.0 kg P/ha (Adenuga *et al.*, 2018). However, the difference between the more uniform operation of pasture-based systems in Northern Ireland compared to diverse dairy farming systems in GB (Shortall, 2019) means that such values may not be representative of GB dairy farms.

Table 2.6. A comparison of mean farm-gate phosphorus (P) balances (FPB) between countries

Country	FPB (kg P/ha)	No. farms	Reference
Scotland	17.6	10	(Raison *et al.*, 2006)
SW England	15.4	13	(Raison *et al.*, 2006)
South Ireland	5.09	21	(Mihailescu *et al.*, 2015)
England	20 .1	131	(DEFRA, 2005)
Northern Ireland	17.2	83	(Adenuga *et al.*, 2018)
New York, US	10.0	102	(Cela *et al.*, 2014)

2.4.5 Environmental phosphorus loading from dairy farms

Whilst FPB and SPB are important indicators of the long-term risk of P surplus and subsequently P loss to waterbodies, P surplus is not a direct measure of the environmental P loading from a dairy farm. Instead, to overcome the considerable costs in time, labour and money of directly measuring the environmental P loading from a farm, models of agricultural systems have been developed to support the decision making of policy-makers by simulating the environmental P loading from a farm (Lynch *et al.*, 2018). The Farm SCale Optimisation of Pollutant Emission Reductions (FARMSCOPER) is a Microsoft Excel-based decision model developed by ADAS for DEFRA to simulate multiple pollutant losses from farms, including environmental P loading. FARMSCOPER is built on a suite of validated models that have been used in supporting UK policy development (McDowell *et al.*, 2016). The particular model used to simulate environmental P loading is the PSYCHIC model - Phosphorus and Sediment

Yield Characterisation in Catchments (Davison *et al.*, 2008, Strömqvist *et al.*, 2008). FARMSCOPER simulates environmental P loading by using data on a farm's structure *i.e.* livestock and cropping, and physical characteristics, *i.e.* soil type, rainfall and farm boundaries (Gooday and Anthony, 2010). Therefore, P balances remain important in reducing environmental P loading by identifying source management practices that models such as FARMSCOPER cannot capture. However, the use of models such as FARMSCOPER are also important to capture differences in structural and physical characteristics of dairy farms that may influence the amount of, and the types of pathways of environmental P loading that P balances cannot capture.

FARMSCOPER contains a list of mitigation methods that are given a value for their impact on annual loading of each pollutant and their capital and operational costs (Newell-Price *et al.*, 2011). FARMSCOPER can optimize a selection of the mitigation methods for a farm in terms of minimum cost and maximum reductions in pollutant loading based on a minimum target reduction (Zhang *et al.*, 2012). Previous studies have used FARMSCOPER to simulate environmental P loading from dairy farms and to optimise a suite of least-cost mitigation methods. However, such previous studies that used FARMSCOPER tended to use data transformed from existing databases such as the Farmer Business Survey (Lynch *et al.*, 2018), the Agricultural Census (Zhang *et al.*, 2012) and previously published surveys (Micha *et al.*, 2018). These authors advised that data collection using a more tailored approach to specifically collect data directly from farmers that could be readily used as input into FARMSCOPER, would generate a more reliable dataset.

Mitigating environmental P loading from dairy farms is increasingly important because there is an increased prevalence of housed systems in GB dairy farming (March *et al.*, 2014), which were modelled to pose a greater eutrophic risk than pasture-based systems (O'Brien *et al.*, 2012). The concept of increasing yields without adversely impacting the environment and without cultivating more land is considered to be sustainable intensification (Firbank *et al.*, 2013). Pressures for agriculture in temperate regions to sustainably intensify are increasing, and in some cases FARMSCOPER has been previously used to demonstrate that some innovative arable and mixed farming systems in GB have achieved sustainable intensification (Firbank *et al.*, 2013). However, such works did not observe sustainable intensification in dairy farming in regard to nutrient use. On the contrary, the environmental P loading from dairy farms in GB has been reported to positively correlate with production intensity (Lynch *et al.*, 2018). Therefore, the progress towards achieving sustainable intensification in dairy production in regard to P use could be monitored by comparing the environmental P loading of dairy farms on a land use and milk production basis with previous studies (Firbank *et al.*, 2013, Lynch *et al.*, 2018).

Like any other model, FARMSCOPER has certain limitations. For example, it uses a fixed grazing season for the farm type ‘dairy’ (Willows and Whitehead, 2015). Since GB has a wide assortment of dairy farming systems that differ in many characteristics including the number of grazing days (Garnsworthy *et al.*, 2019), there is a need to assess whether FARMSCOPER can consider important differences between housed and pasture-based dairy farming systems when simulating environmental P loading and optimizing least-cost suites of mitigation methods for each system. If not, there will be a scope to improve FARMSCOPER by considering differences between a pasture-based and housed dairy farming system, which would be required if the tool is to continue to support policy-makers and various other stakeholders by providing information that is reflective of the current diversity of GB dairy farming.

2.5 REDUCING ENVIRONMENTAL PHOPSHORUS LOADING FROM DAIRY FARMS

Whilst the amount of environmental P loading to waterbodies attributed to point sources (*i.e.*. sewage treatment works) has reduced over the last several years, the diffuse sources of environmental P loading (*i.e.*. agricultural land) are now considered the most significant pressure to water quality in Europe (EEA, 2018). Subsequently, the environmental P loading from agricultural land across Europe needs to be reduced in order to meet water quality objectives set out in the WFD by the final deadline of 2027 (Schoumans *et al.*, 2015). If the environmental P loading from dairy farms is not appropriately addressed, it may result in more drastic governmental measures that can have a considerable negative impact on the economics of national dairy farming, as seen in the surrounding areas of Lake Okeechobee in the U.S. (Boggess *et al.*, 1997) and more recently in the Netherlands (The Netherlands Environmental Assessment Agency, 2016).

The environmental P loading from dairy farms has been reported to increase as the milk production increases (Lynch *et al.*, 2018). Therefore, minimising environmental P loading from dairy farms is now more important than ever, because the modernization of agriculture sees dairy farming in many world regions intensifying *i.e.* increase milk output and feed import without acquiring additional land, to improve economic efficiency (Clay *et al.*, 2019). The environmental P loading from a dairy farm can be reduced by improving PUE. Additionally, at the farm scale improved PUE can provide dairy farmers with improved net financial profits (Mihailescu *et al.*, 2015). On a national scale, improved PUE in dairy production can strengthen food security and reduce farmer vulnerability to trade prices for many countries where food supply is dependent on imports of mineral fertiliser P to sustain crop yields (March *et al.*, 2016). On a global scale, improved PUE in dairy farming could contribute towards slowing the depletion of limited global P reserves (Cordell *et al.*, 2011). Therefore, it is evident that the development of system-specific strategies to minimise environmental P loading from dairy farms is critical to improve the environmental and economic sustainability of dairy farming in many countries that operate diverse dairy farming systems. The environmental P loading from dairy farms can be mitigated by implementing strategies that manage the sources of P pollution and the mobilisation of P in the soil.

2.5.1 Mobilisation management

Mobilisation management largely focuses on slowing the flow of water and sediment that carry soluble P and particulate P, originally applied to land as mineral fertiliser and manure towards waterbodies (Sharpley *et al.*, 1998). In particular, streambank erosion is a major contributor of sediment to streams and has been reported to contribute up to 90% of the total environmental P loading in streams. However, this contribution varies greatly between streams depending on a number of factors (Zaimes *et al.*, 2008). A major cause of stream bank erosion is riparian land that has reduced vegetation as a result of livestock overgrazing, because less vegetation cover results in greater erosion during precipitation events. To prevent livestock presence on riparian land whilst overcoming the labour and costs (capital and operational) associated with river fencing, the provision of an alternative water source situated away from riparian land can be effective (Sheffield *et al.*, 1997). Preventing livestock access to riparian land provides the opportunity to install a buffer between land and waterbodies to slow the rate of P runoff (Mihailescu, 2013). However, an intermittent flow of P runoff is required across a buffer strip as a concentrated flow is reported to lead to an anaerobic soil condition in which P is not effectively adsorbed by soil (Kim *et al.*, 2016). Furthermore, buffer strips can smooth out acute peaks of P transport to waterbodies but can inadvertently lead to longer term continuous flows of legacy P to waterbodies (Sharpley *et al.*, 2013).

A poor infiltration capacity of soil as a result of soil compaction from dairy cattle trampling and farm machinery is an important pressure factor for the flow of P runoff (Johnston and Dawson, 2005, Mihailescu, 2013). Therefore, it is important to implement rotational grazing (Zaimes *et al.*, 2008), use correctly-inflated low ground pressure tyres on machinery (Newell-Price *et al.*, 2011) and implement topsoil loosening and shallow spiking to break up compacted layers to allow more efficient rainwater and slurry infiltration (Newell-Price *et al.*, 2011). Most mobilisation management strategies focus on ‘rear-end’ approaches such as manure storage, handling and application to land, which is important in precise nutrient management because a proportion of P will always be excreted in manure. However, these ‘rear-end’ approaches neglect the multitude of effects of feeding practice on nutrient management and, therefore, should not be considered as the only solutions to nutrient management problems (Powell *et al.*, 2002). Thus, a careful combination of strategies that considers both source and mobilisation management is required to address nutrient management problems.

2.5.2 Source management

The amount of P import onto a farm that is unaccounted for in P export leads to saturation of soil P reserves, which are responsible for a large proportion of environmental P loading to waterbodies (Ruane *et al.*, 2013). In addition, the success of mobilisation management strategies to mitigate environmental P loading has been found to be less effective when P continues to accumulate in soils saturated with P (Sharpley *et al.*, 2013, Wironen *et al.*, 2018). Therefore, minimising the sources of P import onto the farm and soil-surface, otherwise known as source management, is an important strategy to mitigate environmental P loading in the long-term (Sharpley *et al.*, 1998, Maguire, 2014).

2.5.2.1 Minimising mineral fertiliser phosphorus import

Previous reductions in farm-gate P surpluses on dairy farms across Europe are largely attributed to the reduced use of mineral fertiliser P, which has historically been applied to agricultural land in excess of crops' P requirement (Withers *et al.*, 2006). However, current trends indicate that the reducing use of mineral fertiliser P applied to agricultural land has plateaued (DEFRA, 2019), assumedly because the application rates of mineral fertiliser P more closely match the amount of P annually removed in crops (Withers *et al.*, 2006). Therefore, further reductions in mineral fertiliser P import onto a farm could be achieved primarily by improving the ability of crops to uptake P from the pool of soil Po that is not readily available (Stutter *et al.*, 2012). Crops are typically poor at accessing Po from soil but some crops use strategies to access Po via the exudation of organic anions into the rhizosphere to solubilize P compounds, and enzymes to mineralize Po to orthophosphate for plant uptake (Stutter *et al.*, 2012). In particular, the plant-associated *Flavobacterium* which can be found in crops such as Barley has been observed to express many previously characterised and novel proteins that target Po mineralization (Lidbury *et al.*, 2020). Therefore, the utilisation of soil Po by crops could be increased by niche adaptions in the future via genetic manipulation and selective breeding to promote such strategies in crops in the future (Richardson *et al.*, 2009).

Future efforts to minimise mineral fertiliser P import may also see mineral fertiliser P import being replaced with bio fertilisers that use Pi recovered from waterbodies as secondary resources such as fish sludge and algae biomass (Brod, 2015, Solovchenko *et al.*, 2016). However, further research is required into the dynamics of P metabolism in algae, the engineering of algae strains possessing mechanisms to increase P uptake and the understanding of micro algae biomass as a bio fertiliser (Solovchenko *et al.*, 2016). Consequently, these strategies to minimising mineral fertiliser P import could be considered longer-term goals.

Mineral fertiliser P import may be more readily reduced without agronomical consequence via the consideration of soil P reserves and reducing fertiliser application rates accordingly in soils saturated with P (Stutter *et al.*, 2012, Withers *et al.*, 2014, Liu *et al.*, 2015). Increasing the reliance on soil P reserves in P saturated soils can draw down the P accumulated in soil to reduce the risk of environmental P loading whilst also providing farmers financial savings by the more precise purchasing of mineral fertiliser P (Mihailescu *et al.*, 2015). However, almost no recent information is available on the amount of P surplus in the soils across GB dairy farming systems despite such information being important in determining whether mineral fertiliser P import could be minimised by increasing reliance on soil P reserves. Therefore, the determination of soil P reserves on GB dairy farms is required to contribute towards developing strategies to improve PUE and reduce environmental P loading from GB dairy farms.

Mineral fertiliser P import may be further readily reduced via the accurate crediting of the highly variable concentration of different forms of P in manure and reducing fertiliser application rates accordingly. This is particularly true in cases where cows are fed P in excess of cows' P requirement, which can additionally improve the availability of applied P to crops by reducing the soil acidity (Zewide *et al.*, 2018). However, little attention has been given to testing the P content in manure, despite the amount of P in manure applied to land that is available for uptake by crops (*i.e.* inorganic orthophosphate) is suggested to be similar to that of mineral fertiliser P (Eghball *et al.*, 2005, Withers *et al.*, 2006). Consequently, unlike soil testing, manure is not routinely tested, particularly so for dairy farms managing small herds (Dou et al., 2001, Withers et al., 2006). 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 (Lugo-Ospina *et al.*, 2005). Although such rapid tests cannot replace the accuracy of laboratory methods, they can be useful in improving the accuracy of manure application rates by providing timely information on manure P concentration

In the UK, farms designated within Nitrate Vulnerable Zones are limited to applying 170kg of N per ha of agricultural land as livestock manure (manure deposited by livestock and spreading) (DEFRA, 2018c). However, the losses of N as ammonia during manure spreading and the feeding of dietary P in excess of the cows' P requirement can lead to dairy cattle manure containing up to five times more P than N (Bittman, 2009). Consequently, the imbalanced ratio of N:P content in dairy cow manure can be mismatched to the crops requirement, resulting in P being applied in excess of the crops' P requirement. Housed dairy farming systems tend to have a higher stocking rate and a greater import of concentrate feed compared to pasture-based systems (O'Brien *et al.*, 2012, March *et al.*, 2016). Densely stocked farms generate large quantities of P-rich manure that is repeatedly applied to the same nearby lands, usually in excess of crops P requirement (Svanback *et al.*, 2019). Therefore, manure testing is increasingly important because of the increased prevalence of housed dairy farming systems in GB (March *et al.*, 2014).

Manure testing for P plays an important role in managing manure application. However, in some cases manure testing alone may not be the most cost-effective solution to mitigate environmental P loading from dairy farms. For example, farms generating a large amount of P-rich manure in areas of high P index soils will incur additional costs to transport a large volume of manure to faraway lands (Maguire, 2014, Tayyab and Mclean, 2015). The cost of transporting P-rich manure could be reduced by establishing a system where manure is spread on nearby land of home-grown feeds or to a neighbour's arable land (March *et al.*, 2016). Alternatively, the transport of P-rich manure can be made easier by separating liquid and solid fractions, with the solid fraction being transported to further lands (Bittman, 2009) or the manure can be chemically treated to remove P via struvite crystallisation. However, there is little success in the chemical removal of P from dairy cattle manure because the characteristics of manure are unique to independent management practices implemented by each farm. Consequently, farmers would require understanding of and access to numerous costly procedures (Harris *et al.*, 2008, Zhao *et al.*, 2010). Therefore, although manure testing remains important as it provides farmers with an indication of the relative degree of excess P feeding on their farms (Nordqvist *et al.*, 2013), reducing the P content in manure through dietary manipulation is still the most cost-effective long-term solution (Knowlton, 2011b).

2.5.2.2 Reducing feed phosphorus import

2.5.2.2.1 Increasing P utilisation in the dairy cow

The efficiency of using P in dairy cows is low and ranges from 20 to 40% of dietary P intake (Bannink *et al.*, 2010, Knowlton and Ray, 2013b). Increasing the amount of dietary P available to the dairy cow by as little as 5% could reduce faecal P excretion by 15% if dietary P is fed to match the increased absorption (Knowlton and Herbein, 2002). However, strategies to improve the utilisation of P in dairy cows, such as the supplementation of exogenous phytase to aid hydrolyses of phytate (Hill *et al.*, 2008) and mechanical processing, soaking, germination and fermentation of feeds (Humer and Zebli, 2015) require further investigation as they show varying levels of success. Increasing the annual milk yield of the herd could provide the opportunity to reduce the stocking rate of a farm at no detriment to milk export, thereby increasing the amount of the dietary P intake that is utilized in milk production as opposed to being used in fulfilling the maintenance P requirement of more cows (Knowlton *et al.*, 2004a). However, the effectiveness of this strategy is impaired if farmers do not accurately reduce their stocking rate accordingly to maintain their milk export (Dunlap *et al.*, 2000), which is unlikely because herd size has not decreased in GB (AHDB, 2019) despite the dairy sector making considerable advancements in cow productivity. A cow's annual milk yield can be increased through genetic selection (March *et al.*, 2016) or by implementing various management practices such as increasing milking frequency to thrice daily and extending photoperiod length (Collier *et al.*, 2017). Implementing practices to increase the annual milk yield of a herd has been reported to reduce the environmental N loading from a dairy farm by 16% (Dunlap *et al.*, 2000).

Housed dairy farming systems raising high producing cows are required to import large amounts of concentrate feed (Ruane *et al.*, 2013), because it is difficult to meet the high energy demand of high yielding cows by feeding only forages or high-forage diets (March *et al.*, 2014). Conversely, the degradation of dietary P in higher producing dairy cows may be limited compared to lower producing cows because of a faster passage of dietary P, subsequently reducing the exposure of P molecules to phytase enzymes in the rumen (Humer and Zebli, 2015). Consequently, further research is required to investigate the impacts of increased milk yield on feed P import and P surplus across dairy farming systems because such information is limited, despite this information being important in developing strategies to reduce feed P import to mitigate the risk of environmental P loading. However, since the concentration of total P in a diet remains the main determining factor of dietary P digestibility in dairy cows (Ray *et al.*, 2013), reducing the import of high-P feed remains crucial to mitigate environmental P loading.

2.5.2.2.2 Formulating dietary P concentrations

A trend in dairy farming over time shows that purchased feed has become the greatest import of P entering a farm through the farm-gate, overtaking mineral fertiliser P import (Haygarth *et al.*, 1998, DEFRA, 2005, Raison *et al.*, 2006, Withers and Foy, 2006). The limited recent information available suggests dairy farms in the UK import approximately 19.7 kg P/ha as feed (Adenuga *et al.*, 2018). However, a further increase in feed P import is likely because of the increasing prevalence of housed dairy farming systems, which import greater amounts of concentrates compared to pasture-based systems to support high milk yield (March *et al.*, 2014). Unlike the relatively more accurate application of mineral fertiliser P to crops' P requirement, farmers have little consideration of the P concentration in the diet they offer their cows (Withers *et al.*, 2006) and tend to feed diets with P concentration in excess of the concentration recommended by the NRC (2001) for dairy cows (Dou *et al.*, 2003, Sinclair and Atkins, 2015). Consequently, feeding P in excess of the cow's requirement generates P-rich manure because faecal P excretion in dairy cows highly and positively correlates with dietary P concentration (Ray *et al.*, 2013). However, reducing dietary P concentration to closely match NRC (2001) recommended dietary P requirement can reduce faecal P excretion without any negative impacts on health, productivity or fertility in dairy cows (Ferris *et al.*, 2009, Wang *et al.*, 2014). Subsequently, minimising excess P feeding to dairy cows is important to ensure sustainable dairy production because reducing a dietary P concentration from 5.5 to 3.5g P/kg DM on a 100 cow farm could reduce the land required to spread manure by ~ 80% (Knowlton *et al.*, 2004b). Additionally, eliminating or reducing the use of inorganic P supplements can save farmers' money

(Kebreab *et al.*, 2008) and can minimise the water soluble fraction of manure P that is more prone to runoff loss to waterbodies (Dou *et al.*, 2002).

Water soluble P in manure is more easily dissolved by rainwater than insoluble P, making it more prone to leaching through the soil profile and running off the soil-surface during precipitation. The runoff from a plot that applied manure from cows fed a diet containing 4.9 g P/kg DM was observed to contain a P concentration four to five times greater than the runoff from a plot that applied manure from cows fed a diet with 3.1 g P/kg DM despite both plots received an identical application rate of 17.9 kg P/ha (Powell and Satter, 2008). However, it may not always be feasible to formulate a cost-effective low-P diet because the P concentration in least-expensive protein and energy sources such as by-products of distillers or brewer's industry are always high in P concentration (Bateman *et al.*, 2008, Newell-Price *et al.*, 2011). In particular, formulating a low-P diet is suggested to be difficult in an organic farm because there is limited availability of organic protein feeds, which can result in the use of protein sources with high P concentration such as locally grown rapeseed (Nordqvist, 2012). Additionally, formulating a low-P diet is suggested to be difficult in an all-year housed systems because they tend to manage higher producing dairy cows, which require a greater energy supply (March *et al.*, 2014). Consequently, housed systems import a large amount of high P concentrates that contain greater energy content than grass-based feeds. Reducing P feeding is important to ensure the sustainability of dairy production because feeding P to closely match cows' P requirement provides the opportunity to reduce the amount of land a farmer needs to appropriately recycle their P-rich manure without applying P to land in excess of the crops' P requirement (Powell *et al.*, 2002, Gamroth *et al.*, 2006). Therefore, the question that remains unanswered is ‘why are excess amounts of P being fed to dairy cows?’

2.5.2.2.3 Drivers of excess P feeding

Limited research has investigated why cows are fed P in excess of their P requirement on GB dairy farming systems. However, such information would be important in developing strategies to reduce P feeding in diverse dairy farming systems. A driver of excess P feeding in the US is the addition of a safety margin to a dietary P concentration (Dou *et al.*, 2003). These safety margins are added by farmers and in particular feed professionals to ensure against reduced cow productivity and fertility (Knowlton *et al.*, 2004a), and as a substitute for quantifying forage P concentration, which is highly variable (Kebreab *et al.*, 2013a). However, the inclusion of a safety margin to a dietary P concentration that has been formulated following the national feeding recommendations in the UK (AFRC, 1991) is unnecessary because the AFRC (1991) requires a reappraisal of dietary P requirement in dairy cows to take into account bone P dynamics (Valk *et al.*, 2000) and consider that dietary P intake rather than DMI correlates with faecal P excretion (Scott *et al.*, 1995). Consequently, the AFRC (1991) recommended dietary P requirement could be reduced by at least 10% for high producing dairy cows without any impact on cow health and productivity (Valk *et al.*, 2000). Similarly, the inclusion of a safety margin to a dietary P concentration that has been formulated to the national feeding recommendations in the US (NRC, 2001) is also unnecessary, because the NRC (2001) recommended concentration includes a modest safety margin to compensate for uncertainties associated with the absorption coefficients of P for different types of feed (Knowlton *et al.*, 2004a). Furthermore, dietary P concentration in a diet formulated following the NRC recommendation is also considered to be in excess of the cows' P requirement because although the accuracy of the NRC publications have improved with each reappraisal (Ray and Knowlton, 2014), a further reappraisal is overdue to consider P feeding in a more modern perspective using information that has emerged since the last publication, such as further understanding into the dynamics of bone P metabolism throughout lactation, a more accurate description of feedstuff P availability, a better understanding on the minimal level of dietary P to support milk production and a greater focus on environmental impact in addition to production (Wu *et al.*, 2001a, Salazar *et al.*, 2012, Humer and Zebli, 2015). Therefore, the dietary P requirement recommended by national feeding systems for dairy cattle may be reduced in the future, but in the meantime ensuring that dairy cow diets are formulated as precisely as possible following the most up to date and consistent advice on P feeding is important to reduce feed P import onto dairy farms (Knowlton, 2011a).

2.5.2.2.4 Precision P feeding practices

Formulating diets with P concentrations specific to groups of cows with a similar milk yield and stage of lactation is a recommended practice to precisely feed P to match cows' requirement. This is because P requirement in dairy cows is influenced by milk yield and stage of lactation, due to the relatively constant P concentration in milk (Goselink *et al.*, 2015) and subsequently changes with the accretion and resorption of bone P throughout lactation (Kebreab *et al.*, 2013a, Biagini and Lazoroni, 2018). Bone P resorption can mobilize up to 30% of the cows bone P content, equating up to an estimated 1 kg of P in early lactation for a 600 kg cow (Knowlton and Herbein, 2002). In the future, the natural mechanism of bone P mobilisation may be induced by further lowering a dietary P concentration in early lactation (Knowlton and Herbein, 2002, Ekelund *et al.*, 2006). However, further research is required to investigate the longer-term effects of such P feeding strategies. A group feeding strategy may seem to be relatively easy to implement in a housed dairy farming system because it easier to control (*i.e.* formulate and feed) diets for groups of cows housed separately (March *et al.*, 2014). However, cows could also be carefully grouped in a pasture-based system using a block calving approach. However, information on the implementation rate of a group feeding strategy across different dairy farming systems is limited. Therefore, information on the implementation of a group feeding strategy could be important in developing strategies to minimise the need of excessive feed P import onto dairy farms in countries operating diverse dairy farming systems.

Forage P testing is required for accurate crediting of the P supplied by forages in the formulation of a diet with a target P concentration, which could reduce the need of unnecessary P import via concentrate feed ingredients onto a dairy farm (Cerosaletti *et al.*, 2004). The content of P in forage varies between location, variety, plant maturity, growing conditions, stem to plant ratios and storage conditions (Kertz, 1998, Cerosaletti *et al.*, 2004, Knowlton, 2011a). Previous research in the US suggested that larger herds are more likely to test the P concentration of their forages (Dou *et al.*, 2003) but the housed dairy farming system is predominantly operated in the US. Since countries such as the UK, Ireland and New Zealand have a large presence of pasture-based systems (March *et al.*, 2014), it could be assumed that frequent forage P testing is particularly important in such countries because the majority of the herds’ diet is comprised of home-grown forages in these systems. However, the information on implementation of the practice of forage P testing across diverse GB dairy farming systems is currently limited.

Pasture-based dairy farming systems are suggested to be associated with lower P surpluses than a housed system because of the greater reliance on P supply from home-grown feed (primarily forages) leading to a lower import of high P concentrate feeds in the pasture-based system compared to housed systems (March *et al.*, 2016). Subsequently, extending the grazing season in pasture-based systems to further reduce feed P import, by increasing the reliance on home-grown feeds is a suggested strategy to reduce P surplus (Mihailescu *et al.*, 2015, Adenuga *et al.*, 2018). Conversely, there are concerns that the benefit of lowering P surplus by increasing the reliance on home-grown feeds may be nullified by the potential increase in the amount of mineral fertiliser P import to support increased production of home-grown feed (O'Brien *et al.*, 2012, Adenuga *et al.*, 2018). Furthermore, increasing the amount of home-grown feed may not be feasible for a housed dairy farming system with a limited land capacity. Therefore, the impact on mineral fertiliser P import from extending the grazing season in pasture-based systems and alternative strategies to reduce P feeding in housed dairy farming systems need further investigation in order to mitigate environmental P loading from dairy farms in countries operating diverse dairy farming systems.

Reducing feed P import onto a dairy farm as purchased feed, predominantly in a housed system, largely relies on the availability and price of feed ingredients with a low P content (Mihailescu, 2013). In recent years, increased availability and reduced cost of distillery by-products encouraged dairy farmers to use these by-products as a source of protein, energy and fibre (Yang and Li, 2016). However, the nutrient content of these by-products is highly variable (Waldo and Yu, 2009, Buckner *et al.*, 2011) and these feed ingredients are usually very rich in P (Sihag *et al.*, 2018). Increased use of distillery by-products makes it difficult for farmers and feed professionals to formulate diets with a P concentration that closely matches cows' P requirement. Consequently, a greater P surplus on farms feeding these by-products directly compared to farms that are not feeding these by-products has been reported (Koelsch and Lesoing, 1999). However, encouraging farmers to avoid feeding such by-products as a strategy to reduce feed P import may not be feasible. This is because farmers benefit financially by using these readily available and least-expensive nutrient sources in dairy cow diets (Hazzledine *et al.*, 2011, Kalschuer *et al.*, 2012, Sihag *et al.*, 2018). In the future, the removal of P from such by-products could be a solution to reduce feed P import but there is currently no suitable technology available to achieve this (Knowlton, 2011a).

In many cases, lowering dietary P concentration to closely match the concentration recommended for optimal production (NRC, 2001) could be achieved by reducing or eliminating the unnecessary inclusion of inorganic P supplements into dairy cow diets (Knowlton, 2011c). In the Netherlands, P feeding has been successfully reduced by limiting the P content in feeds. This has largely attributed to an improved SPB from an average 5.1 kg/ha (2010-2013) to -0.8 kg/ha (2014-2017) (Lukács *et al.*, 2019). Limited SPB information is available for GB dairy farms but a recent study calculated a mean SPB of 11.05 kg P/ha on dairy farms in Northern Ireland, with the majority (77%) of the P import into the soil being from the mean 26.1 kg P/ha import from livestock manure (Adenuga *et al.*, 2018). Therefore, minimising excess P feeding to subsequently reduce P import into soil from livestock manure may be a considerably effective measure to mitigate environmental P loading in GB dairy farms. However, up-to-date SPB information that is reflective of current diverse GB dairy farming systems is required to confirm this.

2.5.2.3 Impact of slurry/manure on P losses

Reducing excess P feeding is well documented to be essential in reducing the P concentration in manure (Ray *et al.*, 2013). Reducing dietary P concentration has been observed to reduce the total P content in manure by largely (but not exclusively) reducing the water soluble fraction of P in manure that is more prone to runoff (Dou *et al.*, 2002). Therefore, reducing dietary P concentration has the potential to reduce both manure P bioavailability and susceptibility to runoff (O'Rourke *et al.*, 2010a). However, even with a dietary P concentration fed precisely to the cows requirement there will be inevitable P excretion in manure (Dou *et al.*, 2010). Additionally, increasing the time interval between slurry application and the generation of overland flow has been suggested to have a greater impact on P losses than does varying dietary P content (O'Rourke *et al.*, 2010a). Consequently, farmers are required to adopt a combination of both precision P feeding and various ‘rear-end’ approaches to mitigate environmental P loading (McConnell *et al.*, 2016b).

In regard to ‘rear-end approaches’, the system used to apply slurry to land can influence P losses in surface runoff, with the trailing shoe technique having lower DRP concentrations in runoff than the splash-plate technique (McConnell *et al.*, 2016b). Additionally, the condition of soil can influence P loss from slurry application. For example, greater P concentrations from runoff have been observed in December and March compared to January and April, likely due to these months coinciding with high soil moisture contents (McConnell *et al.*, 2016b). Furthermore, providing time for soil to recover after soil compaction from grazing cattle can be a strategy to reduce P loss (McConnell *et al.*, 2016a). Therefore, in an attempt to address such environmental influences on farms in the UK within a NVZs and participating in Agri-environmental schemes are permitted to only spread manure in January, February and October if required and if the soil is not water-logged, frozen snow-covered or flooded (DEFRA, 2016).

2.5.3 Current governmental strategies to mitigate environmental phosphorus loading from GB dairy farms

The WFD was established to assess, manage, protect, and improve the quality of water across Europe (DEFRA, 2014). The WFD aims to provide 'good' status for all waters throughout Europe, by agreeing on specific management plans that are required to achieve 'good' water quality objectives for each river basin district (McDowell *et al.*, 2016). European countries are required to propose technically and financially feasible mitigation measures which will allow them to achieve 'good' water quality objectives set out by the WFD by the final deadline of 2027. In the UK, a mixture of regulatory, voluntary and advice-led approaches have been adopted (McDowell *et al.*, 2016).

Catchment Sensitive Farming (CSF) is one of the major advice-led approaches to improve water quality by engaging and working with farmers in the UK (Environment Agency, 2019). In a priority area or catchment, Catchment Sensitive Farming Officers (CSFO) provide farmers with free training on topics such as nutrient, manure and soil management to reduce water pollution from agricultural land. Furthermore, CSFO provide advice on meeting the mandatory restrictions on manure storage, handling and application to land when designated within a Nitrate Vulnerable Zone (NVZ). These NVZ's are based on waters containing more than 50mg/l of nitrates and almost 55% of land in England fall within an NVZ. In addition, CSFO help farmers to write grant applications for ‘cross-compliance’ and ‘Countryside stewardship’, both of which are part of the Common Agricultural Policy. Cross-compliance provides payments to farmers complying with statutory management rules to support good health, welfare, and environment. The ‘Countryside Stewardship Scheme’ covers the capital cost for farmers implementing practices that go above the statutory requirement to improve the environment (McDowell *et al.*, 2016). In Ireland, the ‘Common Agricultural Policy’ has been amended to become the ‘Good Agriculture for protection of waters’ (GAP), which further considers P. Comparisons of dairy farms in the South of Ireland before and after the introduction of GAP suggest reduced P surpluses and increased PUE in dairy farming, largely due to reduced stocking densities and more strategic mineral fertiliser import (Ruane *et al.*, 2013, Mihailescu *et al.*, 2015). However, cross-compliance, countryside stewardship scheme and NVZ in the UK have been assessed as only being ‘partially successful’ in improving water quality. This is largely because of the lack of regulations specific to P use (Worrall *et al.*, 2009, MacGregor and Warren, 2016, McDowell *et al.*, 2016, Garske *et al.*, 2020).

Historically, environmental P loading from agricultural land has been overshadowed by the more formidable concerns of N pollution. Consequently, approaches to mitigate environmental nutrient loading from agricultural land has primarily focused on N loss (Matuszeski, 1999, Garske *et al.*, 2020). However, it is not until recently that the ‘Reduction and Prevention of Agricultural Diffuse Pollution Regulations’ has been established in the UK that requires farmers to consider soil test P from the last five years, weather forecasts and pollution risk (ground cover, land drains, and soil type) when planning fertiliser application to land (DEFRA, 2018b). Farm inspections are carried out by the Environmental Agency with initial advice-led support, which could eventually lead to potential prosecution (DEFRA, 2018b). These new regulations begin to address P mobilisation. However, they do not consider the long-term issue of source management, such as excess import of mineral fertiliser P and purchased feed P at the farm level. Conversely, CSF is considered a more successful approach to reducing P pollution of water in GB and has reduced environmental P loading in waterbodies by an average 7% in priority areas between 2006 to 2014 (Environment Agency, 2014). The success of CSF is likely in part due to advice being given that considers effective source management whereas current regulations tend to only consider mobilisation measures. Furthermore, farmers tend to avert responsibility and resist enforced regulations. Subsequently policy-makers are becoming increasingly interested in using voluntary approaches to influence positive environmental change (Collins *et al.*, 2017). However, identification and improved understanding of the determinants of P surplus in diverse dairy farming systems and the cost and feasibility of implementing methods to mitigate environmental P loading across diverse dairy farming systems are required to encourage and support farmers to adopt the voluntary measures to reduce P loss to waterbodies. Therefore, information on the determinants of P surplus and cost and feasibility of implementing P mitigation methods need to be investigated to strategize further mitigation of environmental P loading from dairy farms via regulations and advice-led approaches to ensure the sustainability of dairy production in countries operating diverse dairy farming systems.

2.6 IMPLICATIONS OF THE RESEARCH

In a recent briefing prepared by the European Parliamentary Research Service, it was suggested that the European dairy sector needs to improve its sustainability by more efficiently utilising feedstuffs, including P (Augère-Granier, 2018). It is well established that faecal P excretion increases and P digestibility decreases with increasing dietary P supply in dairy cows at a given DM intake and milk yield and when cows are fed more P than they require to support production and health (Ferris *et al.*, 2009, Ray *et al.*, 2013). However, most research into minimising excess P feeding is based in the US, where strict housed systems are common (Dou *et al.*, 2003, Harrison *et al.*, 2012), which may not be appropriate for many countries operating diverse dairy farming systems. This is because feeding practices, DM intake and annual milk yield will be different between housed and pasture-based systems. In addition, housed-systems are estimated to pose a greater eutrophic risk than pasture-based systems primarily due to the import of relatively large amount of concentrates into housed systems. Even though pasture-based systems use relatively small amount of concentrates, the increased production of home-grown forage required to replace the need of purchasing concentrates was found the major contributor of pasture-based systems to eutrophication (O'Brien *et al.*, 2012). Furthermore, the ease of implementing certain feeding practices may differ between dairy production systems (March *et al.*, 2014). Therefore, the present research will contribute towards currently limited data on how farmers and feed advisers feed P in diverse dairy farming systems and will identify the factors that influence implementation of precision P feeding practices. The findings of this research will support the development of regulatory and advice-led strategies to reduce P feeding in diverse dairy farming systems and subsequently reduce the risk of P loss to waterbodies.

Strategies to improve PUE in dairy farming is largely based on research from the US (Cela *et al.*, 2014) where strict housed dairy farming systems are predominant and

Ireland (Mihailescu *et al.*, 2015) where strict pasture-based systems are predominant. Consequently, such strategies may not be appropriate for many countries operating diverse dairy farming systems because of different contributions to eutrophication (O'Brien *et al.*, 2012), different PUE (March *et al.*, 2016, Akert *et al.*, 2020) and different feasibility of implementing practices between dairy farming systems (March *et al.*, 2014). Therefore, investigation of the differences in P balances and PUE between dairy farming systems will contribute towards developing strategies to improve the sustainability of dairy farming in countries operating diverse dairy farming systems.

The current status of P balance in modern GB dairy farming systems is not well documented. Only limited information is available from Northern Ireland, which suggests mean FPB of 17.2 kg P/ha and SPB of 11.0 kg P/ha (Adenuga *et al.*, 2018). The limited FPB information that is available for dairy farms in England, Scotland and Wales ranges between 16.4 to 20.1 kg P/ha FPB (Withers *et al.*, 2001, Raison *et al.*, 2006). However, no SPB information is available for dairy farms in England, Scotland and Wales. Furthermore, this FPB information was calculated for dairy farms in the early 2000’s. Consequently this data may not be relevant to modern GB dairy farming, because there is an increased prevalence of housed dairy farming systems in GB (March *et al.*, 2014). In addition, most recent studies that calculated FPB for dairy farms outside of GB used standard values of P import and export items (Mihailescu, 2013, March *et al.*, 2016, Akert *et al.*, 2020). Such standard values tend to underestimate or overestimate the actual contributions of P to a surplus (Oenema *et al.*, 2003), particularly for forage (Cerosaletti *et al.*, 2004). Furthermore, there is almost no research on the SPB in GB dairy farming (Adenuga *et al.*, 2018). Therefore, the current research will provide a timely and much-needed accurate assessment of current FPB and SPB on dairy farms representing diverse dairy farming systems and will identify main determinants of P surpluses to recommend practices that should be promoted to reduce environmental P loading.

Lowering P surplus is important to reduce the long-term risk of environmental P loading and to improve PUE and associated financial benefit (Mihailescu *et al.*, 2015). However, previous studies that have investigated the environmental P loading and financial impact of implementing methods to mitigate environmental P loading from dairy farms used data from existing databases (Zhang *et al.*, 2012, Lynch *et al.*, 2018, Micha *et al.*, 2018). However, adapting existing databases to an appropriate format requires a level of assumptions, which could lead to an increased risk of error. Therefore, collecting on-farm data using a tailored approach to specifically collect appropriate data for inputting into a model could generate a richer more reliable environmental P loading dataset. Furthermore, previous studies have simulated environmental P loading and investigated the financial impact of implementing methods to mitigate environmental P loading from dairy farms by considering dairy farming as one representative farm type (*i.e.* arable, mixed and dairy). Consequently, such information may not be reflective of current diverse dairy farming in GB and subsequently, may not effectively be used to advise UK dairy farmers and policy-makers. Therefore, the current thesis will contribute towards consolidating the environmental P loading from diverse dairy farming systems, assess the progress of dairy farming towards achieving sustainable intensification and will identify a least-cost suite of mitigation methods to minimise environmental P loading.

In conclusion, the outcomes of the current thesis will be important in strategizing the mitigation of environmental P loading from dairy farms in countries operating diverse dairy farming systems. This will be achieved by identifying 1) source management strategies, in particular to reduce P feeding, to subsequently lower P surplus and 2) mobilisation management strategies to cost-effectively mitigate environmental P loading. However, the novelty of this project could largely be attributed to the consideration of diversity in dairy farming systems, which is essential in developing system-specific strategies to mitigate environmental P loading from dairy farms in countries operating diverse dairy farming systems.

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3 PHOSPHORUS FEEDING PRACTICES, BARRIERS TO AND MOTIVATORS FOR REDUCING PHOSPHORUS FEEDING IN DIVERSE DAIRY FARMING SYSTEMS

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Publication: Full article published by 'Animal - the international journal of animal biosciences'

Harrison, B., Dorigo, M., Reynolds, C. , Sinclair, L. and Ray, P. (2021) Phosphorus feeding practices, barriers to and motivators for minimising phosphorus feeding to dairy cows in diverse dairy farming systems. Animal. ISSN 1751-7311, DOI https://doi.org/10.1016/j.animal.2021.100248

Conference papers:

Harrison BP, Dorigo M, Reynolds C, Sinclair L and Ray P 2020. Survey of current phosphorus feeding practices on Great British dairy farms. In Proceedings of the British Society of Animal Science, 30th March - 1st April, Nottingham, UK, p. 22.

Harrison BP, Dorigo M, Reynolds C, Sinclair L and Ray P 2020. Assessing the attitudes of feed and land advisers towards reducing phosphorus losses from Great Britain dairy farms. In Proceedings of the British Society of Animal Science,30th March - 1st April Nottingham, UK, p. 21.

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Harrison BP, Dorigo M, Reynolds C, Sinclair L and Ray P 2020. Identification of barriers to and facilitators for reducing phosphorus losses from Great Britain dairy farms. In AHDB Livestock PhD Conference,27th - 28th January Nottingham, UK,

SUMMARY

Reducing phosphorus (**P**) feeding to dairy cows can reduce feed costs and minimise water pollution without impairing animal performance. This study aimed to determine current P feeding practices and identify the barriers to and motivators for reducing P feeding in diverse dairy farming systems in Great Britain. Farmers (n=139) and feed advisers (n=31) were involved simultaneously in independent questionnaire surveys on P feeding in dairy farms. Data on the herd size, milk yield and concentrate fed were analysed using ANOVA to investigate the effect of farm classification, region, and feed professional advice. Chi-square tests were used to investigate associations between farm characteristics and implemented P feeding and management practices. Most farmers (72%) did not know the P concentration in their lactating cow's diet and did not commonly adopt precision P feeding practices, indicating cows may be offered excess dietary P. Farmers' tendency to feed P in excess of recommendations increased with herd size, but so did their awareness of P pollution issues and likeliness of testing manure P. However, 68% of farmers did not analyse manure P, indicating that synthetic fertilizer application rates were not adjusted accordingly; highlighting the risk of P being applied beyond crops' requirement. Almost all farmers (96%) were willing to lower dietary P concentration but the uncertainty of P availability in feed ingredients (30%) and concerns over reduced cow fertility (22%) were primary barriers. The willingness to reduce dietary P concentrations was driven by the prospect of reducing environmental damage (28%) and feed costs (27%) and advice from their feed professionals (25%). Most farmers (70%) relied on a feed professional, and these farmers had a higher tendency to analyse their forage P. However, farmers of pasture-based systems relied less on feed professionals. Both farmers (73%) and feed advisers (68%) were unsatisfied with the amount of training on P management available. Results emphasise that training on P management needs to be more available and the influence that feed professionals have over P feeding should be better utilized. Study findings demonstrate the importance of considering type of dairy production systems when developing precision P feeding strategies and highlight the increasing importance of feed professionals in reducing P feeding.

Keywords: Dairy farm, feeding practice, phosphorus, nutrient management, survey

Implications: Study findings highlight to policy-makers and knowledge exchange bodies the need for training on effective phosphorus management in dairy production systems to be more available to both farmers and feed professionals. The results further demonstrate the importance of considering type of dairy production systems when developing precision P feeding strategies.

3.1 INTRODUCTION

Globally, there has been increasing public concern about environmental pollution from livestock farming (Kebreab *et al.*, 2013). In particular, eutrophication degrades water quality and reduces aquatic biodiversity, annually costing the UK an estimated minimum of £229 million (Moxey, 2012). Eutrophication is accelerated when waterbodies are enriched with phosphorus (**P**) and a major source of P enrichment is agricultural land that has received P above the crops' requirement. In the UK and in many European Union **(EU)** member states, land application of P is indirectly regulated by limits on the application of nitrogen via livestock manure (European Commission, 1991). However, dairy cows excrete 60 to 80% of consumed P in faeces, and this faecal P excretion is positively correlated with dietary P intake (Knowlton and Ray, 2013). Therefore, feeding more P than required to dairy cows results in P-rich manure that contains an imbalanced N:P ratio, which makes it almost impossible to apply to land based on crop N requirement without applying P beyond crops' P requirement (Knowlton and Ray, 2013). As the P content can vary, handling manure can be improved via analysing manure P to adapt synthetic fertiliser application rates by crediting the accurate amount of P present in manure (Svanback *et al.*, 2019). However, reducing P feeding remains the optimal cost-effective approach to reduce the over-application of P to land. This is especially important in areas with a high soil P index where farmers need to transport P-rich manure to further lands which will incur costs (Knowlton, 2011).

Dairy herds in England have been identified as feeding a dietary P concentration higher than what is recommended by the National Research Council (NRC, 2001) for dairy cows (Sinclair and Atkins, 2015a). Reducing dietary P concentrations to closely match NRC (2001) recommended concentrations reduces faecal P excretion without any negative impacts on health, productivity or fertility in dairy cows (Ferris *et al.*, 2009, Wang *et al.*, 2014). Additionally, eliminating or reducing the use of inorganic P supplements can save farmers' money (Kebreab *et al.*, 2008) and can minimise the water soluble fraction of manure P that is more prone to runoff (Dou *et al.*, 2002). Therefore, the question that remains unanswered is 'why are excess amounts of P being fed in dairy farms?'

A driver of excess P feeding in the US is the addition of a safety margin to dietary P concentrations (Dou *et al.*, 2003). These safety margins are added by farmers and feed professionals to ensure against reduced cow productivity and fertility (Knowlton *et al.*, 2004), and as a substitute for quantifying forage P concentration, which is highly variable (Kebreab *et al.*, 2013). Testing forages for P is critical to adopt precision P feeding in all dairy farming systems because the variable contribution of P from forages can then be accurately considered when formulating diets (Cerosaletti *et al.*, 2004). However, frequent testing of forages for P is particularly important in countries such as the UK, Ireland and New Zealand where pasture-based systems feeding a diet comprised largely of home-grown forages are present (March *et al.*, 2014). This is because of the greater reliance on the dietary P supplied by forages, than in an all year-housed system. Formulating diets with P concentrations specific to groups of cows with a similar milk yield and stage of lactation is also recommended to precisely feed P, because a cow's P requirement changes during the stage of growth, lactation and gestation (Kebreab *et al.*, 2013). Furthermore, an opportunity exists to lower dietary P concentration by accounting for the accretion and resorption of bone P that occurs throughout lactation to compensate for changes in P requirement during lactation. However, a group feeding strategy is more likely to be adopted in housed systems because these systems make it easier to control diets for groups separately (March *et al.*, 2014). Little is known about the adoption of such 'precision P feeding practices' by dairy farmers in countries operating diverse dairy farming systems.

The EU dairy sector needs to improve its sustainability by improving the utilisation efficiency of feed nutrients, including P management (Augère-Granier, 2018). However, dairy farming systems in North-western and central EU member states are similar to Great Britain **(GB)**, which operates large specialised dairy farms of high yielding cows along with a wide assortment of pasture-based and housed systems (March *et al.*, 2014, Augère-Granier, 2018). Consequently, the majority of the research into reducing P feeding, which is based in the US where housed systems are common (Dou *et al.*, 2003, Harrison *et al.*, 2012), may not be appropriate for many countries operating diverse dairy production systems. This is because housed-systems are estimated to be a greater eutrophic risk for a given level of milk and per farmland area than pasture-based systems due to the large amounts of concentrates fed in these systems. Whereas, total eutrophication of a housed and pasture-based system are more similar on a total farmland basis, with the main contributor to total eutrophication on pasture-based systems being P loss following the application of manure and synthetic fertilisers to home-grown forages (O'Brien *et al.*, 2012). Furthermore, the ease of implementing certain feeding practices may differ between dairy production systems (March *et al.*, 2014). Therefore, the current survey aims to fill the knowledge gap by assessing how farmers and feed advisers feed P to dairy cows in diverse dairy farming systems and identify factors that influence adoption of precision P feeding practices. The objectives of this study were to assess the current P feeding practices used in dairy farms and to identify barriers to and motivators for achieving precision P feeding. The GB dairy farming system was used as an example of diverse dairy farming systems.

3.2 MATERIALS AND METHODS

3.2.1 Questionnaire survey: Great Britain dairy farmers

An anonymised list of all (6780) dairy farms registered with Agriculture and Horticulture Development Board (AHDB) was obtained from the 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 (Table 7.1). 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 (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.

3.2.2 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.

3.2.3 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.

3.3 RESULTS

3.3.1 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 ($P < 0.05$)

3.3.2 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 they fed to their cows relied on a feed professional. However, the remaining 33% of farmers that did not know the dietary P concentration were presumably formulating diets with no consideration of dietary 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.

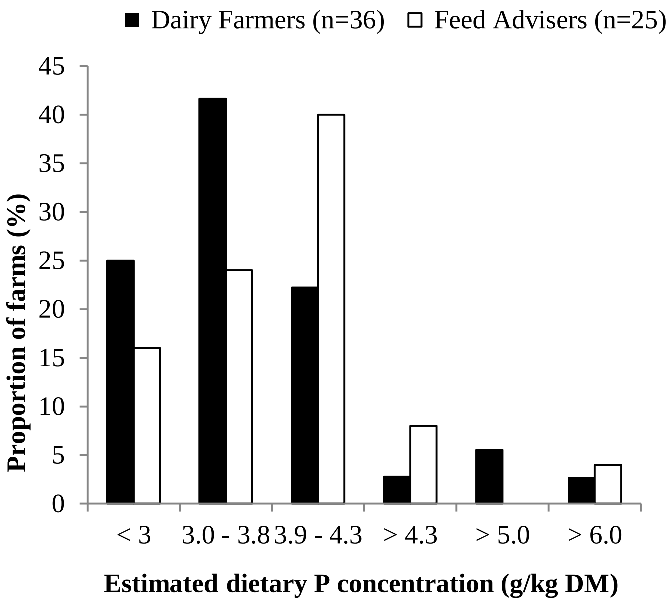

Figure 3.1 Dietary phosphorus (P) concentrations (g/kg DM) estimated by dairy farmers and feed advisers in Great Britain. Recommended average P concentration in dairy cow diet: 3.5 g/kg DM (NRC, 2001) or 4.1 g/kg DM (AFRC, 1991), based on a cow annually producing 7956 kg milk (average for participating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

3.3.3 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, management practices and opinions about 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

Table 3.2 Continued. Responses of Great Britain dairy farmers *(n* = 139*)* and feed advisers *(n* = 31*)* involved in a survey of phosphorus (P) feeding, management practices and opinions about P feeding.

Characteristics	No. of Farmers (%)	No. of Advisers (%)
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.

3.3.4 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 the 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 3.3 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 3.4 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 3.5 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

3.3.5 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).

3.4 DISCUSSION

3.4.1 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, 2019a) 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. This 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).

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

Most 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 reducing P feeding on dairy farms (Dou *et al.*, 2003). The 36 farmers in the current study that were able to estimate 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, 2015b). 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.

3.4.3 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 for specific groups of cows 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). Therefore, the farms using book values of forage P concentration may have underestimated forage P concentrations and consequently could feed excess P in the form of supplements. Thus, indicating an opportunity for these farms to minimise P overfeeding to cows and reduce the purchasing of excess inorganic P supplements by regularly testing forage P (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 reducing P feeding.

3.4.4 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 (classifications 1 to 4) compared to an all-year housed system 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). Reducing P feeding in pasture-based systems 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 reducing 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 reduce 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 accurately quantifying total P in manure. However, a number of colorimetric test kits for manure P are commercially available. Currently, such rapid tests cannot match the accuracy of laboratory methods. However, they are 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 excess 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 reducing 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 are estimated to 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

3.4.5 Barriers to and motivators for dairy farmers to reduce excess phosphorus feeding

The current survey highlighted that emphasising the potential benefit of reduced feed costs (when reducing inorganic P supplements is an option) and water pollution associated with reducing P feeding (Kebreab *et al.*, 2008), would motivate farmers to lower dietary P concentrations. However, in order to reduce 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 P concentrations, fertiliser P application rate, 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 excess 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 reducing 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 reduce 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.

3.4.6 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 reducing P feeding and address their barriers to minimising excess P feeding, which were similar to the dairy farmers.

3.5 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 reduce 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, policy-makers 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 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. However, this may partly be facilitated by updating national P feeding recommendations which would require undertaking further research into the availability and concentrations of P in individual feed ingredients.

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4 DETERMINANTS OF PHOSPHORUS BALANCE AND USE EFFICIENCY IN DIVERSE DAIRY FARMING SYSTEMS

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Publication: Full article under review by the ‘Journal of Agricultural Systems’ - major revisions

Conference papers

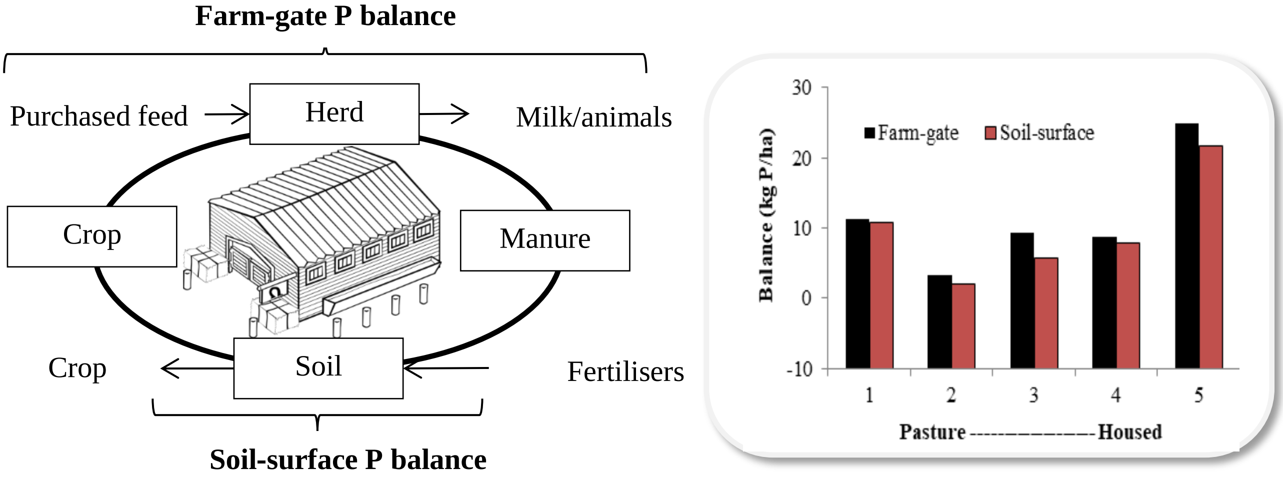
Harrison BP, Dorigo M, Reynolds C, Sinclair L and Ray P 2021. Determinants of phosphorus balance and use efficiency between diverse dairy farming systems. In Proceedings of the British Society of Animal Science, 13th - 15th April Virtual,

SUMMARY

Identifying the determinants of phosphorus (P) balance and use efficiency (PUE) is critical to improving the sustainability of dairy production in countries operating diverse dairy farming systems, because each system contributes to eutrophication through different pathways and utilisations. However, information about the determinants of P balance and PUE across diverse dairy farming systems is scarce. Therefore, the current study aimed to identify the determinants of P balance and PUE in a range of dairy farming systems in Great Britain. Data from 29 dairy farms in Great Britain representing dairy farming systems with differing feeding systems and levels of production 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) was used to calculate farm-gate P balance (FPB) and the principles of ‘Annual Nutrient Cycling Assessment’ (ANCA) were used to calculate soil-surface P balance (SPB). Differences in P import, export, balance, and PUE between dairy farming systems were investigated using ANOVA. Determinants of P balance and PUE were identified using multiple stepwise linear regressions. Large P surpluses and consequently large soil P reserves were observed across all dairy farming systems. However, P surpluses were higher and PUE was lower in housed compared to pasture-based systems (except for a Spring-calving system with ≥ 274 days grazing/year), primarily because of greater import of concentrate feed. Farms that had a greater percentage of their herds' diet from home-grown feed (primarily forages) had an improved PUE and lower P surplus but farms applying greater amounts of mineral fertiliser P to their land had a greater FPB. It is therefore recommended that most dairy farming systems lower the risk of P loss and improve PUE by reducing fertiliser P import through accurate crediting of P in soil and manure. Furthermore, the high P surplus and poor PUE in housed systems could be mitigated by improved diet formulation to use concentrates more efficiently and import less P with concentrates, whereas increasing the percentage of a herd's diet from home-grown feeds and maintaining a stocking rate to match the feed demand of the herd to the availability of home-grown feeds would 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.

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

Graphical summary:



Highlights:

- Housed systems had greater surpluses of P per hectare than some pasture-based systems.
- Reducing fertiliser import by crediting soil and manure P lowers P surpluses.
- Increasing the reliance on home-grown feeds reduces P surpluses.
- Reducing unnecessary feed P import in housed systems can improve P use efficiency.
- Strategies to improve P use efficiency should be system-specific.

4.1 INTRODUCTION

Dairy farming in many world regions is intensifying by increasing milk output and feed import without acquiring more 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 proportion of concentrate feed is imported into the region with the P-rich manure subsequently being produced applied on nearby land, in addition to imported fertiliser (Svanback *et al.*, 2019). Land application of this manure often leads to application of P in excess of the crops' ability to utilise it, which then accumulates in the soil and is gradually lost from agricultural land to waterbodies, consequently contributing to eutrophication (Adenuga *et al.*, 2018). Improving P use efficiency (PUE) is important for sustainable dairy production 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). Nationally, improved PUE in dairy farming can strengthen food security for many countries where food supply is dependent on the import of mineral fertiliser P to sustain crop yields (March *et al.*, 2016). Globally, improved PUE in dairy farming contribute towards slowing the depletion of limited global P reserves (Cordell *et al.*, 2011).

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, but are not always identical (Adenuga *et al.*, 2018) because FPB cannot explicitly represent the build-up, depletion and consumption of internal stock. Whilst, SPB may under-estimate 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). Therefore, both FPB and SPB are important to provide a meaningful assessment of the risk posed by a dairy farm to the aquatic environment.

Great Britain (GB) and multiple North-European countries have large soil P reserves but no specific P legislation (Amery and Schoumans, 2014). Strategies to improve PUE in dairy farming are largely based on countries where housed dairy farming systems are prominent (Knowlton and Ray, 2013, Cela *et al.*, 2014), pasture-based systems are prominent (Gourley and Weaver, 2012, Mihailescu *et al.*, 2015) or where direct legislation are in place (The Netherlands Environmental Assessment Agency, 2016). However, GB has a wide assortment of dairy farming systems characterised by diverse calving patterns, varying amounts of concentrate feeding and grazing days

(Garnsworthy *et al.*, 2019). Many North-European countries produce milk similarly to GB, by operating large specialised dairy farms along with a range of housed and pasture-based systems (March *et al.*, 2016, Augère-Granier, 2018). However, such systems contribute to eutrophication differently from one another (O'Brien *et al.*, 2012) and have different nutrient use efficiencies (March *et al.*, 2016, Akert *et al.*, 2020) and feasibilities of implementing practices (March *et al.*, 2014). Consequently, current strategies to improve PUE in dairy farming based on production systems in other countries may not be appropriate for countries operating more diverse dairy farming systems. However, there is limited P balance information relevant to modern GB dairy farming (Withers *et al.*, 2001, Raison *et al.*, 2006) because there is an increased prevalence of housed dairy farming systems (March *et al.*, 2014). Therefore, there is a need for P balance information that is reflective of modern GB and North-European dairy farming systems in order to develop strategies to improve the sustainability of GB and North-European dairy farming. The objectives of the present study were to (1) determine FPB, SPB and PUE and (2) identify the key determinants of FPB, SPB and PUE across a range of dairy farming systems in GB.

4.2 MATERIALS AND METHODS

4.2.1 Study farms and data collection

Dairy farms from across GB were recruited through advertisements by various stakeholders. After the responding farms provided further information on their calving plan, grazing days and concentrate feeding approach, thirty dairy farms with no other livestock enterprises were selected (geographical spread in Figure 4.1) 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 2.1). 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.

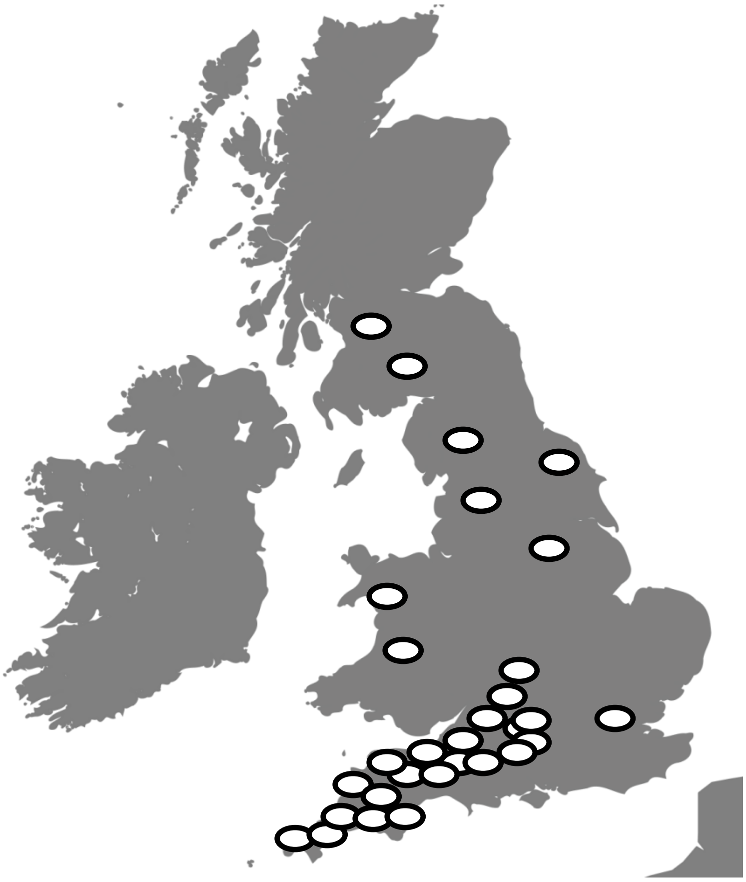


Figure 4.1. Map of the geographic spread of participating dairy farms in Great Britain

Participating farms completed a form (Table 7.2) 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 and stocks at the start and end of the year 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 entire herd (including young stock), 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 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.

4.2.2 Sample Collection

Two to five representative bulked 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 for grassland, ≥10 soil cores were collected. For arable land ≥10 soil cores were taken in a ‘W’ pattern, and an additional five soil cores were taken 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 if the P concentration of feed ingredients was not available from recent farm records or product labels. Samples were not collected if P concentration of a feed was available and instead used the P concentration from recent farm records or product labels. 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 in a ‘W’ pattern from the face (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.

4.2.3 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 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).

4.2.4 Calculation of phosphorus balances, benchmarks and use efficiencies

The current study calculated FPB by employing the methodology of 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 previously used to explore nutrient balance benchmarks for dairy farms in other countries (Nevens *et al.*, 2006, Cela *et al.*, 2014). In the current study, this benchmark approach was not used to propose benchmarks for GB dairy farming because of the limited sample size but rather used to investigate potential differences in the feasibility of GB dairy classification operating below benchmarks, as to provide insight to policy-makers.

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). Since ANCA was designed for Dutch dairy farming systems, the use of ANCA for GB dairy farms without any modifications may bring limitations and could lead to biased estimation of P balance. Therefore, the principles of the ANCA tool were used to create a spreadsheet model and to identify the type of data that should be collected from participating farms. 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):

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

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]
Milk P content (g/kg)	0.24 + (0.0220 × milk crude protein (g/kg))[1] (Klop *et al.*, 2014)
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 (land application and deposition during grazing) + 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)

[1] Concentrations of P from product label, farmer 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

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

Terms	Calculation
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 diet's proportions of silages VEM (%)
VEM supplied to entire herd by grazed grass	VEM supplied by grass silage adjusted using ANCA's coefficients of grazing[5] (Groor, 2016)(Groor, 2016)(Groor, 2016)(Groor, 2016)(Groor, 2016)(Groor, 2016)

[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

4.2.5 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).

4.3 RESULTS

4.3.1 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 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 P concentration of the entire 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. Mean P concentrations of each type of sampled feed ingredient can be found in Table 7.3. 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]	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, collected from farmer, [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, $^{a\text{-}b}$ Means in a row without a common superscript letter differ ($P \leq 0.05$)

4.3.2 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 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 4.3 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 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, $^{a\text{-}b}$ Means in a row without a common superscript letter differ ($P \leq 0.05$), * Significantly different means was not found in the Tukey's test because of too wide of a confidence interval for farms in this system, likely a result of a small sample size

4.3.3 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 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 4.4 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); * $P \le 0.05$, ** $P \le 0.01$.

[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).

4.3.4 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).

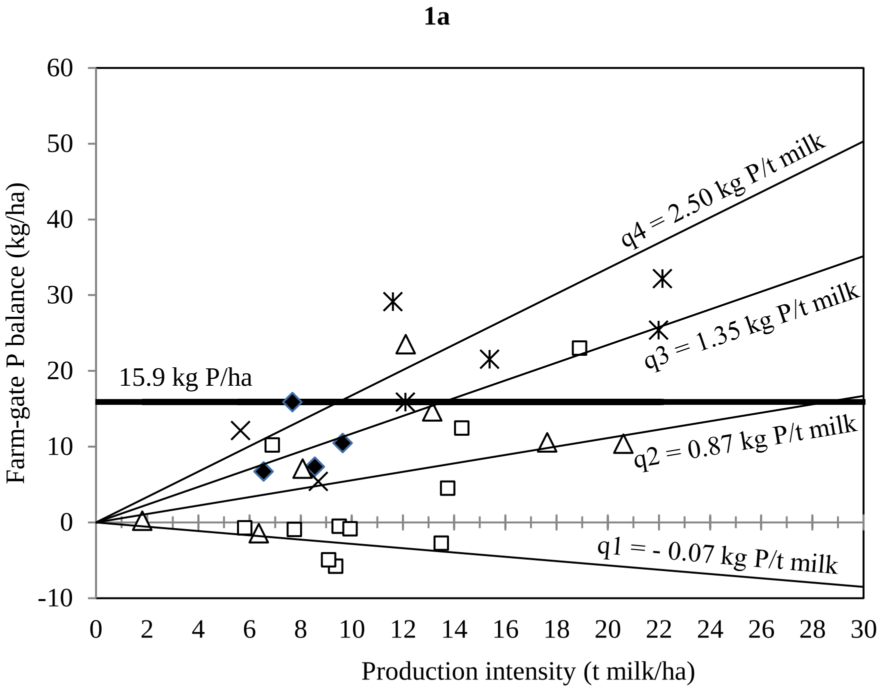


Figure 4.2 The Farm-gate phosphorus (P) balance per hectare (ha) as a function of (1a) production intensity (tons [t] of milk/ha) and (1b) animal density (livestock unit [LU]/ha) for 29 dairy farms across dairy farming systems (Garnsworthy *et al.*, 2019). Dairy farming system 1 (black diamonds), 2 (white 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. Quartile lines are trend lines of farm-gate P balances for farms operating below each quartile.

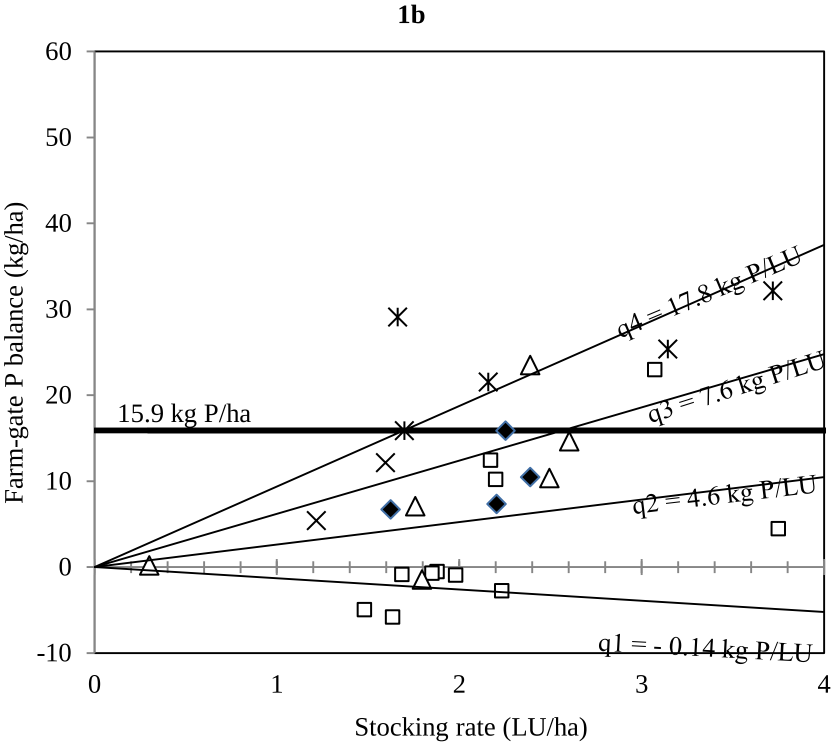


Figure 4.2. Continued. The Farm-gate phosphorus (P) balance per hectare (ha) as a function of (1a) production intensity (tons [t] of milk/ha) and (1b) animal density (livestock unit [LU]/ha) for 29 dairy farms across dairy farming systems (Garnsworthy *et al.*, 2019). Dairy farming system 1 (black diamonds), 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. Quartile lines are trend lines of farm-gate P balances for farms operating below each quartile.

4.3.5 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%). However, 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, $^{a\text{-}b}$ means in a row without a common superscript letter differ ($P \leq 0.05$)

4.3.6 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 4.6 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}

4.4 DISCUSSION

4.4.1 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, 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 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. 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).

The milk P content can vary between 0.7 and 1.3 g/kg (Pfeffer *et al.*, 2005). The novel estimation of milk P provides improved accuracy of P balances than previous studies assuming a constant P concentration in milk export. The finding that greater milk P content was estimated in the longest grazing pasture-based system compared to the housed system, suggests that important differences in P flows between dairy farming systems need to be considered when calculating P balances in diverse dairy farming systems.

4.4.2 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 to 20.1 kg P/ha range previously reported for dairy farms in South-West England (Raison *et al.*, 2006), the 17.6 kg P/ha for Scotland (Raison *et al*, 2006), the 17.2 kg P/ha for Northern Ireland (Adenuga *et al.*, 2018) and the 10.0 kg P/ha for New York (Cela *et al.*, 2014). However, the mean FPB in the current study remains to indicate that on average the environmental sustainability of participant farms could be improved, with the optimal target for a FPB proposed to be 5kg P/ha (Doody *et al.*, 2020). This difference was 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 in the current study are likely attributed to the increased number of housed systems observed in GB dairy farming (March *et al.*, 2014). Therefore, the current study provides much needed FPB information that can contribute towards determining the current P status of modern GB dairy farming. In particular, the current study raises the question ‘has reductions in mineral fertiliser P simply been replaced by increased feed P import?’ 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). Therefore, this first time comparison of P balances in the 5 GB dairy classifications allowed the current study to provide results that suggest that pasture-based systems with minimal imports of P were not more efficient in P use than housed systems because of the subsequent lower export of P as milk in the minimal import pasture-based system.

In the current study, mean FPB across most pasture-based systems was within the 5.1 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.

4.4.3 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 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 as a consequence, 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.

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 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 a simplified approach to maximising a farm's milk P export by increasing SR, 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 or housed systems.

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, cows in the housed system in the current study were offered 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. This could be achieved the adoption of a number of precision P feeding practices (*i.e.* group or phase feeding, analysing forage P and reducing formulated safety margins) not commonly adopted by modern GB dairy farming systems (Harrison *et al.*, 2020).

4.4.4 Optimal zone for milk production and animal density

The feasible FPB 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 demonstrated that system-specific benchmarks may be required for countries operating diverse dairy farming systems. However, this raises the question on whether poorer water quality should be accepted because a region has higher input systems than another. The benchmarking exercise further showed that the pasture-based system (classification 3) annually producing 21 t of milk/ha operated within the optimal zone for milk production in the current study which illustrated that a high producing dairy farm can be highly eco-efficient with P.

4.4.5 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 from farms in the current study. Therefore, this supports that accurately applying mineral P fertiliser based on crop requirements and increased crop production may be viable 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 a financial saving to farmers (Withers *et al.*, 2017). The current study is the first to provide SPB values for GB dairy farms using quantified P concentrations of feed and manure and an approach that can calculate SPB across diverse dairy farming systems because it does not use fixed standard coefficients for milk and manure P.

4.4.6 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 the increased amount of grazed grass P export increased with the Olsen P concentration (utilisable by forages) in the soil. This was likely because of greater P cycling and direct deposition of faecal P onto the soil by grazing cows in a system with more intensive grazing (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.

4.5 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 some other studies calculating P balances (Adenuga et al 2018), which may have contributed to an imbalance in the number of farms in each classification. However, 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 FPB and SPB approach that captured important differences in internal flows of P (*i.e.* feeding and milk P) between GB dairy farming systems. Since the participating farms in the current study were self-selected, 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. In the current study, soil test P did not significantly correlate with SPB, likely because of the limited number of soil samples taken per farm. Therefore, the results presented here may reflect a better than actual representation of the national situation.

4.6 CONCLUSIONS

The current study provides much needed up to date information on P flows on dairy farms that is reflective of modern GB dairy farming systems, which is important to contribute toward developing management strategies to meet the need for more sustainable dairy production systems. The results indicate large P surpluses and consequently large soil P reserves across all systems. Therefore, the current study suggests 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 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. The current study demonstrated that precision P feeding to closely match cow's P requirement could allow housed systems to achieve a P balance similar to that of pasture-based systems. 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 that should be promoted more amongst pasture-based systems to improve PUE. Therefore, countries operating dairy production which is more diverse than strict pasture-based and houses systems may achieve relatively higher PUE in systems that are in between two extreme systems *i.e.* strict pasture-based and housed systems. The current study demonstrated a new approach to calculate SPB that can be easily implemented by farmers and can capture important differences in the flow of P between GB dairy farming systems, which in the current study highlighted that not all pasture-based systems were more efficient with their P than housed systems. Farmers could employ this new SPB to identify strategies to improve their P management to provide their farms with the benefits to financial and environmental sustainability associated with improved PUE.

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5 ASSESSING THE ENVIRONMENTAL PHOSPHORUS LOADING FROM, AND IDENTIFYING LEAST-COST SUITES OF MITIGATION METHODS FOR, A PASTURE-BASED AND HOUSED DAIRY FARMING SYSTEM

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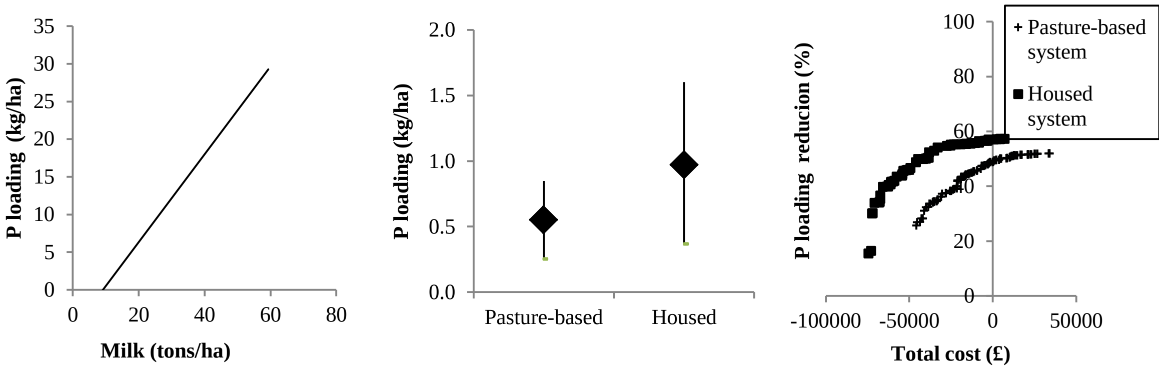
Publication: Being submitted to ‘PlosOne’.

5.1 SUMMARY

Mitigating environmental phosphorus (**P**) loading from dairy farms is important to reduce water pollution and improve the sustainability of dairy production. Studies generally simulate environmental P loading from dairy farms using a representative farm type generated from existing databases. However, housed and pasture-based dairy farming systems are suggested to contribute to eutrophication differently and have a varied feasibility of implementing mitigation methods. The current study is the first to: (1) quantify environmental P loading from dairy farms using FARMSCOPER specific data collected directly from farmers and (2) compare environmental P loading and identify a least-cost suite of methods to mitigate environmental P loading from farms using pasture-based or housed systems. The structure and physical characteristics of 27 British dairy farms (pasture-based = 20, housed = 7) were collected through farm visits. Annual environmental P loading from each farm was simulated in FARMSCOPER under 3 scenarios: 'baseline' (no mitigation methods implemented), 'current' (estimated implementation rate of mitigation methods) and 'maximum' (all mitigation methods in the FARMSCOPER library implemented). Mean environmental P loading of the 2 production systems were compared using ANOVA with Tukey's test and a linear regression was used to investigate any relationship between environmental P loading and average 305 day adjusted milk yield of cows on each farm in Minitab. A least-cost suite of methods to mitigate environmental P loading was optimised for two model farms generated to represent either a housed or pasture-based system. Across both systems, 'current' implementation of mitigation methods was simulated to have minimally reduced environmental P loading from 0.63 to 0.56 kg P/ha (11%). The 'current' environmental P loading positively correlated with milk production on a kg and kg/ha basis. Furthermore, farms operating a housed system had a mean 'current'

environmental P loading 59% greater than the pasture-based system but this numerical difference was not significant (*P* = 0.316). This lack of statistical significance was partly because of a small sample size and because FARMSCOPER's estimates exclude variations in important farm practices (*i.e.* feeding). Environmental P loading was reduced by ~50% and ~60% without incurring annual financial losses by implementing existing mitigation methods for pasture-based and housed systems, respectively. The current study highlights the importance of mitigating environmental P loading from GB dairy farming especially considering the increasing prevalence of high yielding herds and housed production systems. Furthermore, emphasis should be put on increasing the system-specific implementation of existing mitigation methods to reduce environmental P loading (*i.e.* knowledge transfer).

Graphical abstract



Keywords: Dairy farm, environmental phosphorus loading, mitigation methods, diverse dairy farming, sustainable intensification

Highlights

- Environmental phosphorus loading increased with milk production intensification

- Mitigating environmental phosphorus loading provides financial saving for farmers
- Research into environmental and cost impacts of reducing phosphorus feeding is needed.
- FARMSCOPER should consider both pasture-based and housed dairy farming systems.

5.2 INTRODUCTION

The enrichment of P in waterbodies accelerates eutrophication (degradation of water quality and reduction in aquatic biodiversity) which was previously estimated to incur a minimum annual loss of £229 million to the UK economy (Moxey, 2012). Since the amount of P loading to waterbodies from point sources (*i.e.* sewage treatment works) has reduced over the last several years, subsequently the diffuse sources of environmental P loading (*i.e.* agricultural land) are now considered the most significant contributors to degrading water quality in Europe (EEA, 2018). Therefore, the environmental P loading from agriculture across Europe needs to be reduced in order to meet water quality objectives set out in the WFD by 2027 (Schoumans *et al.*, 2015).

Mitigating environmental P loading from Great Britain (GB) dairy farming in particular, is increasingly important because there is an increased prevalence of farms using year-round housing in GB dairy farming (March *et al.*, 2014). A year-round housed dairy farming system is modelled to pose a relatively higher eutrophic risk compared to a pasture-based system, primarily due to the import of a large amount of P in concentrate feeds (O'Brien *et al.*, 2012, Akert *et al.*, 2020). The concept of increasing yields without causing environmental harm and without acquiring more land is considered to be sustainable intensification (Firbank *et al.*, 2013). Pressures on agricultural production in temperate regions to intensify sustainably are increasing due to the need for greater food production to satisfy a growing global population whilst being constrained to a limited land capacity. Previous research has reported that some innovative arable and mixed farms in GB have demonstrated sustainable intensification (Firbank *et al.*, 2013). However, achievement of sustainable intensification in regard to P use in dairy farming was not observed (Firbank *et al.*, 2013). On the contrary, the environmental P loading from dairy farms in England has been reported to positively correlate with production intensity (Lynch *et al.*, 2018). However, these previous studies use data from before 2012, and consequently may not be reflective of current diverse dairy farming systems in GB. Therefore, there is a need to monitor the progress towards achieving sustainable intensification in GB dairy farming, by comparing the environmental P loading from dairy farms with previous studies (Firbank *et al.*, 2013, Lynch *et al.*, 2018). Any changes in environmental P loading values could help indicate whether dairy farms are intensifying sustainably or not, in regard to environmental P loading.

Nitrate Vulnerable Zones (NVZ) are designated in GB based on waterbodies containing more than 50 mg/l of nitrates and farms within these NVZs have mandatory restrictions on manure management and fertilizer application. However, the effectiveness of NVZs in reducing environmental P loading is uncertain because of the limited consideration for the long-term accumulation of legacy P in the soil (Worrall *et al.*, 2009, MacGregor and Warren, 2016). Additionally, farmers tend to avert responsibility and resist enforced regulations and consequently policy-makers are becoming increasingly interested in using voluntary approaches to influence positive environmental change (Collins *et al.*, 2017). For example, agri-environmental schemes such as the Countryside Stewardship Scheme in England, offer grants to farmers in GB to cover the capital costs of implementing practices that will improve the environment (McDowell *et al.*, 2016). In particular, farmers in England and Ireland are reported to have the most positive attitude towards changing practices that are associated with lower costs, such as practices that will reduce inputs (Collins *et al.*, 2017, Micha *et al.*, 2018). Subsequently, the cost-effectiveness of individual mitigation methods relevant to UK agriculture have been explored using cost-curve analysis (Haygarth, 2003). However, limited research has investigated the cost-effectiveness of suites of mitigation methods for GB dairy farming using a genetic algorithm approach. (*i.e.* search and optimisation technique inspired by natural evolution (McCall, 2005)). Such an approach is able to overcome the short falling of a cost-curve approach, in regard to recognising a situation where it may be preferable to select one financially costly method over selecting a number of smaller methods with higher cost effectiveness (Gooday and Anthony, 2010). Consequently, there is a need to investigate cost-effective suites of methods to mitigate environmental P loading from dairy farming using a genetic algorithm approach.

Previous studies using cost-curves have recommended that further work is needed that investigates cost-effective mitigation options on a system-level (Haygarth, 2003). Despite this, limited research has investigated suites of cost-effective methods to mitigate environmental P loading from dairy farming on a system-level (*i.e.* pasture-based and housed). Dairy farming in GB operates a wide assortment of systems characterised by diverse calving approaches, varying amounts of concentrate feeding and number of grazing days (Garnsworthy *et al.*, 2019) and the feasibility of implementing practices may differ between dairy farming systems due to factors such as land availability and control over the diet (March *et al.*, 2014). Therefore, there is a need to identify suites of least-cost methods to mitigate environmental P loading from dairy farms on a system-level, to contribute towards developing strategies to reduce environmental P loading from modern diverse GB dairy farming.

The ‘FARM Scale Optimisation of Pollutant Emission Reductions’ (FARMSCOPER) model has been developed to simulate the diffuse agricultural pollution from representative farm types (Gooday and Anthony, 2010). FARMSCOPER is a Microsoft Excel-based decision support tool developed by the Department of Environment, Food and Rural Affairs (DEFRA), that uses data on a farm’s structure (*i.e.* livestock and cropping) and physical characteristics (*i.e.* soil type and rainfall) to simulate environmental loading of nutrients (Gooday and Anthony, 2010). Additionally, FARMSCOPER can be used to optimize a least-cost suite of methods to mitigate pollutant loading by a targeted amount (Zhang *et al.*, 2012) using a library of mitigation methods and their impact on annual pollutant loading and their capital and operational cost (Newell-Price *et al.*, 2011). Such functionalities allow FARMSCOPER to support the decision making of policy-makers, whilst reducing the considerable costs in time, labour and money of directly measuring environmental P loading (Gooday and Anthony, 2010). Therefore, it is important to ensure that FARMSCOPER produces accurate and reliable information on the environmental P loading and least-cost methods to mitigate environmental P loading in modern diverse dairy farming systems. It is especially critical if FARMSCOPER is to continue to support the strategizing of mitigating environmental P loading from dairy farms.

Previous studies have used FARMSCOPER to investigate the environmental P loading from broader representative farm types (*i.e.* dairy, arable and mixed). However, previous studies tend to use existing datasets such as the Agricultural Census (Zhang *et al.*, 2012), the Farmer Business Survey (Lynch *et al.*, 2018) and previously published surveys (Micha *et al.*, 2018) to gather data to be inputted into FARMSCOPER. Consequently, the use of existing datasets can provide less accurate and reliable input data into FARMSCOPER compared to using a tailored approach (*i.e.* targeted surveys or a focus group) to directly collect the appropriate data (Firbank *et al.*, 2013). This is because the mismatch of existing datasets can require the transformation of data into an appropriate format, which involves a level of assumption. Limited research has collected data directly from farmers, using a tailored approach to specifically collect data readily appropriate for input into FARMSCOPER and such research used only 4 dairy farms (Firbank *et al.*, 2013). Therefore, there is need for information of environmental P loading and least-cost mitigation methods for dairy farms, using FARMSCOPER input data collected directly from farmers using a tailored approach.

Datasets such as the Farmer Business Surveys do not explicitly represent independent systems within the broader representative ‘dairy farm’ type (*i.e.* pasture-based and housed). Consequently, no research has used FARMSCOPER to investigate the environmental P loading and identify least-cost suites of methods to mitigate environmental P loading from pasture-based and housed system independently. However, such information will be critical in recommending least-cost strategies to mitigate environmental P loading from modern GB dairy farming. Therefore, there is a need to quantify the environmental P loading and identify least-cost suites of methods to mitigate environmental P loading from both pasture-based and housed dairy farming systems. The objectives of this study were to (1) quantify environmental P loading from dairy farms using FARMSCOPER specific input data collected directly from dairy farmers using a tailored approach, (2) compare environmental P loading data simulated from FARMSCOPER for housed and pasture-based dairy farming systems and (3) identify a least-cost suite of mitigation methods to reduce environmental P loading from both housed and pasture-based dairy farming systems.

5.3 MATERIALS AND METHODS

5.3.1 Participating dairy farms

Dairy farms from across GB were recruited through advertisements by various stakeholders (listed in acknowledgements). Of the responding farms, twenty-seven dairy farms with no other livestock enterprises 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 concentrate feed supplements. Classification two, three and four farms adopt block or all year calving with increasing use of concentrate feed supplementation 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 mixed ration. For the current study, classifications one (n = 4 farms), two (n = 9 farms), three (n = 7 farms) were deemed pasture-based (a total of 20 farms) whereas classification four (n = 2 farms) and five (n = 5 farms) were deemed housed (a total of 7 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, 2019). 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.

5.3.2 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. Subsequently, 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).

5.3.3 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 baseline environmental P loading 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 farm practices that are important in determining environmental P loading (*i.e.* dietary P concentration) were fixed in FARMSCOPER. Environmental P loading for each farm was simulated under three scenarios (1) 'baseline scenario' –this is the baseline environmental P loading annually lost determined by farm structure and environmental characteristics and is essentially a counterfactual and thus assumes that no mitigation methods are implemented, (2) 'current scenario' – This is the environmental P loading estimated to be lost annually after considering reductions in environmental P loading associated mitigation methods implemented at 'the current rate'; this current rate can be user-specified but by default is internally estimated 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' – This is the environmental P loading annually lost after considering reductions in environmental P loading achieved when all mitigation methods in the DEFRA user guide (*i.e.* regarding nutrient, livestock soil, delivery and pesticide management) are hypothetically implemented (Newell-Price *et al.*, 2011).

The 'maximum scenario' expresses the maximum potential mitigation of environmental P loading 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 environmental P loading 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), which is an optimisation technique inspired by natural selection (McCall, 2005). In FARMSCOPER, the algorithm is used to select the best solutions for achieving a user-specified minimum target of specified pollutant reduction at minimum cost to the farmer. Essentially, this genetic algorithm approach operates on a population of artificial chromosomes, which represent a solution to a problem and has a fitness which measures how good a solution is to a particular problem. The genetic algorithm conducts fitness-based selection to produce a successor generation. 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). This process continues for a specified number of generations, (in this case 50 generations, in which the most evolved solution is the optimal solution to the particular problem (McCall, 2005).

5.3.4 Generation of model farms to 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 5.1 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 numbers			
	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

5.3.5 Statistical Analysis

The environmental P loading 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, environmental P loading was calculated on a total basis (kg) but also relative to UAA (kg/ha) and milk yield (kg/ton milk). To compare environmental P loading from previous studies, the environmental P loading 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 environmental P loading 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 environmental P loading 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).

5.4 RESULTS

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

The mean annual environmental P loading 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 environmental P loading by only ~ 11% from the 'baseline', equating to a 'current' environmental P loading of 0.56 kg P/ha UAA. However, the simulation under the 'maximum' scenario suggested the potential for a reduction in environmental P loading of ~ 54% of the 'baseline', equating to a potential annual environmental P loading 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).

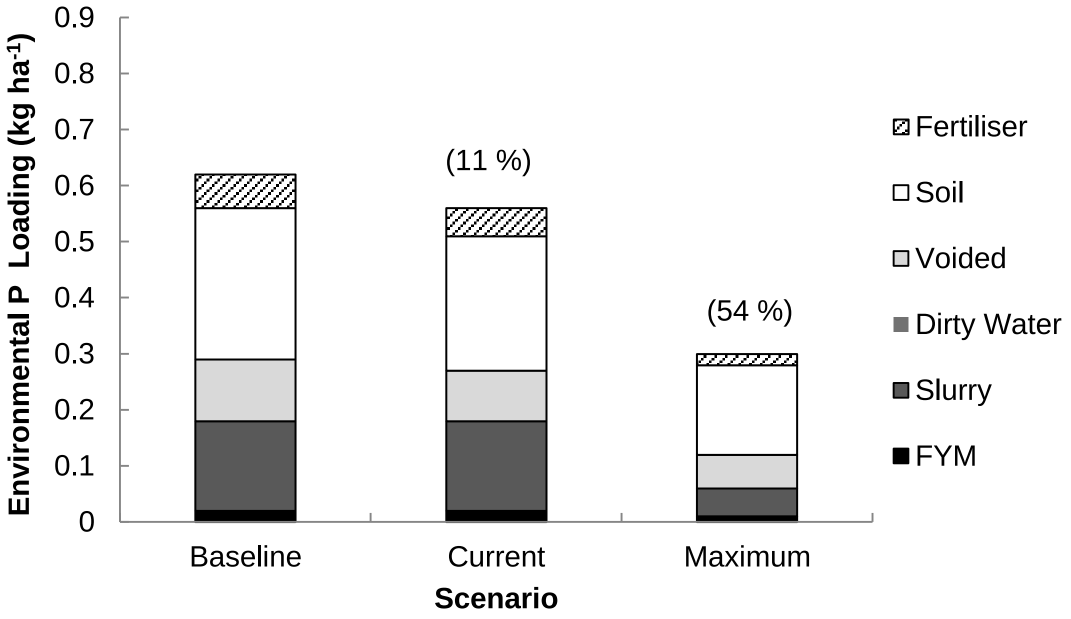


Figure 5.1 Mean source apportionment of the annual environmental phosphorus (P) loading simulated in FARMSCOPER for 27 dairy farms in Great Britain across all systems. 'Baseline' scenario - no mitigation methods implemented, 'Current' scenario – mitigation methods implemented at an estimated rate and '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 environmental P loadings under the 'baseline' scenario, per unit of milk produced and per unit of energy from milk produced 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 environmental P loadings 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 environmental P loading 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).

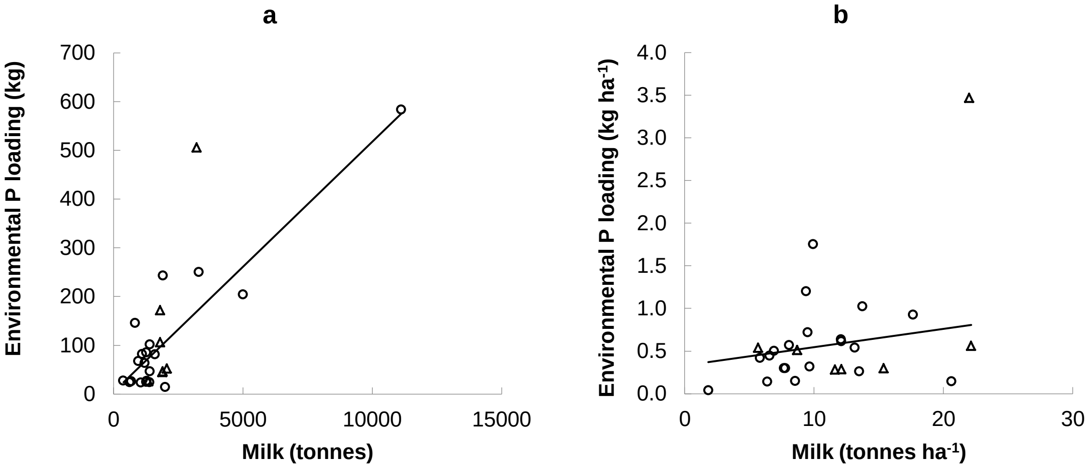


Figure 5.2 Relationships between annual milk production and the annual environmental phosphorus (P) loading simulated using FARMSCOPER under the ‘baseline’ scenario ((a) total milk production/year (P ≤ 0.001; R^2 = 64.3 %) and (b) milk production/year relative to land use basis (P = 0.026, R^2 = 18.1%)) and under the ‘current’ scenario ((c) total milk production/year (P ≤ 0.001; R^2 = 49.39%) and (d) milk production/year 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).

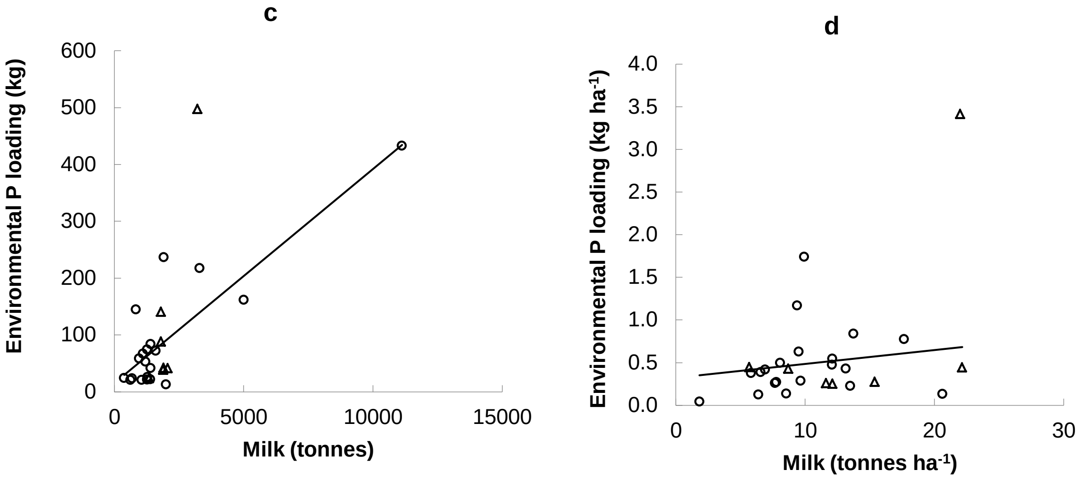


Figure 5.2. Continued. Relationships between annual milk production and the annual environmental phosphorus (P) loading simulated using FARMSCOPER under the 'baseline' scenario ((a) total milk production/year ($P \leq 0.001$; $R^2 = 64.3$ %) and (b) milk production/year relative to land use basis ($P = 0.026$, $R^2 = 18.1\%$)) and under the 'current' scenario ((c) total milk production/year ($P \leq 0.001$; $R^2 = 49.39\%$) and (d) milk production/year 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).

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

A numerically lower (*P* = 0.32) mean environmental P loading 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% numerically higher mean environmental P loading from farms using the housed compared to pasture-based system under the ‘baseline’, ‘current’ and ‘maximum’ scenarios, respectively.

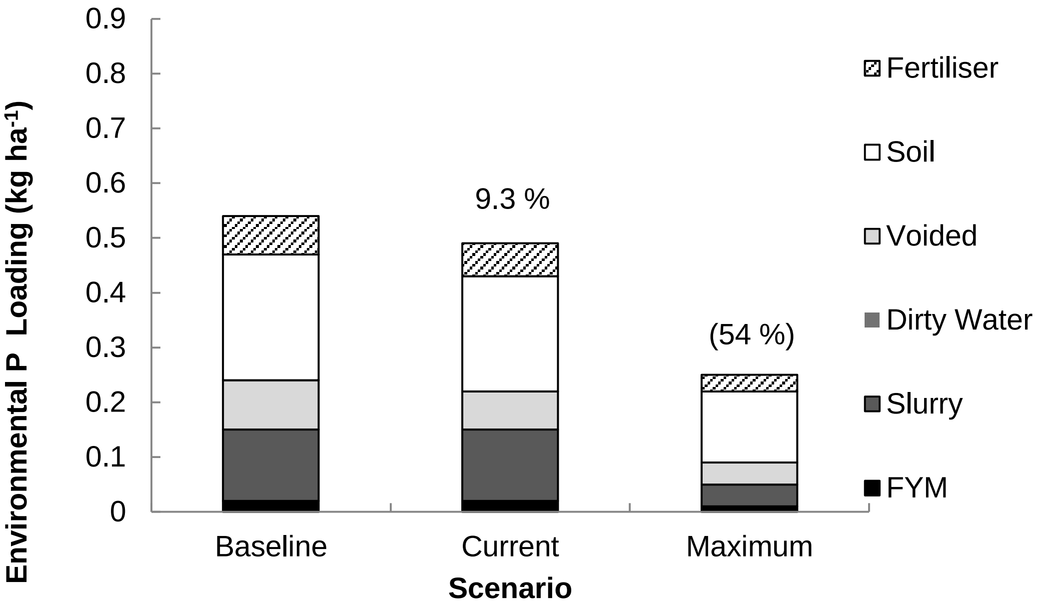


Figure 5.3 Mean source apportionment of the annual environmental phosphorus (P) loading simulated in FARMSCOPER for farms operating a pasture-based system (n = 20). ‘Baseline’ scenario - no mitigation methods implemented, ‘Current’ scenario – mitigation methods implemented at an estimated rate and ‘Maximum’ scenario - all mitigation methods in FARMSCOPER’s library are implemented. Percentages (in parentheses) are the reductions in environmental P loading from the baseline scenario.

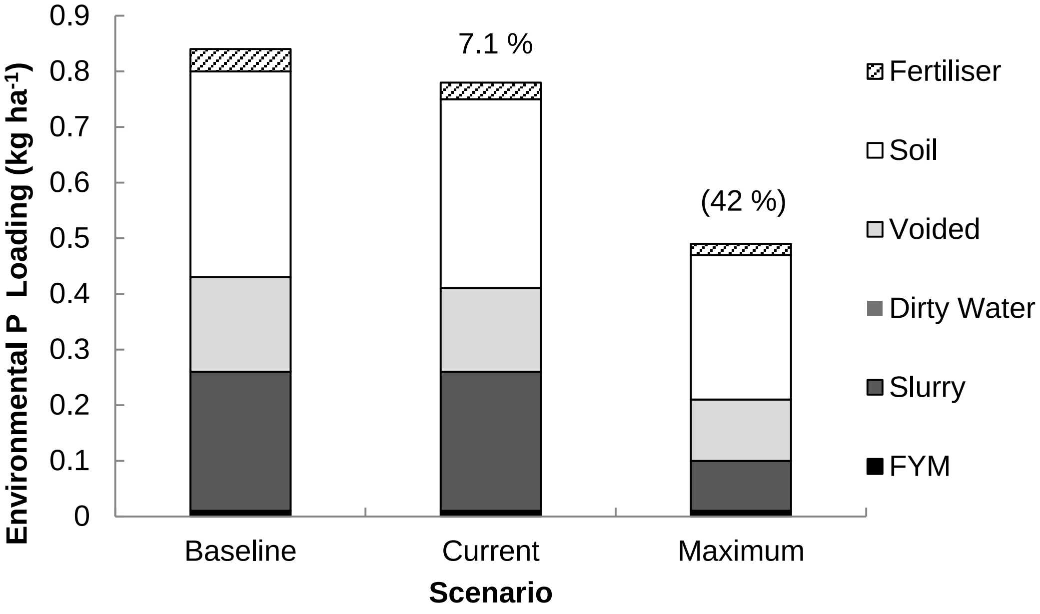


Figure 5.4 Mean source apportionment of the annual environmental phosphorus (P) loading simulated in FARMSCOPER for farms operating a housed dairy farming system (n = 7) in Great Britain. ‘Baseline’ scenario - no mitigation methods implemented, ‘Current’ scenario –mitigation methods implemented at an 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

5.4.3 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 environmental P loading from both the pasture-based and housed dairy farming system (Fig. 5.5). The pasture-based system could potentially reduce environmental P loading by ~ 50% of the ‘baseline’ without incurring annual financial losses, whereas the housed system could reduce environmental P loading by ~ 60% without annual financial losses.

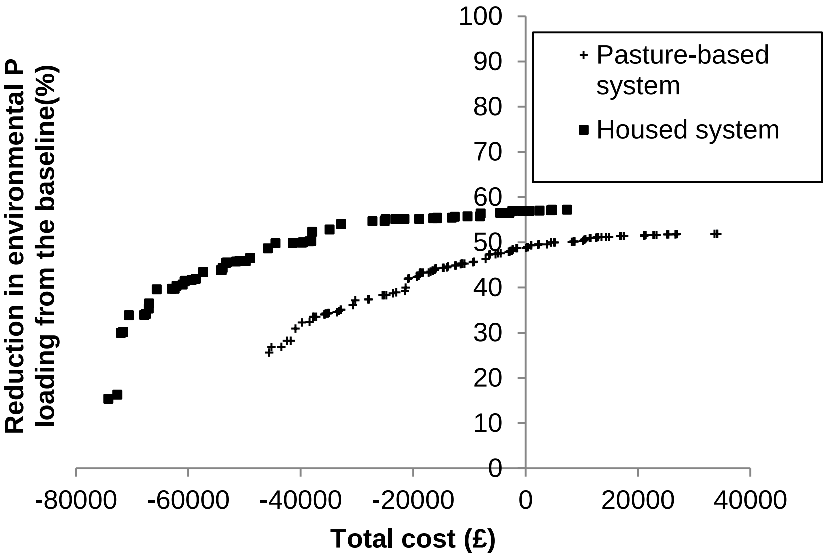


Figure 5.5 Suites of cost-effective mitigation methods following optimisation on environmental phosphorus loading for a minimum target reduction of five percent, for two model farms generated to closely represent either a pasture-based[1] or housed[2] dairy farming system. [1]Generated using average 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 7.4) to achieve the user-inputted minimum target of 5% reduction in environmental P loading in the pasture-based system provided a potential annual saving of £45,578 and annual reduction of environmental P loading by 25.6% (Table 5.2). In contrast, a potential annual financial saving of £74, 176 and a reduction of 15.4% in environmental P loading when implementing the least-cost suite of 14 mitigation methods (Table 7.5) to achieve the minimum target of at least a 5% reduction in environmental P loading from baseline 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 5.2 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 (%)[4]	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 , [4] User specified minimum target of reduction (%) in environmental P loading from the baseline environmental P loading

Table 5.3 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.

	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

[1] Total cost = capital cost - operational cost

5.5 DISCUSSION

5.5.1 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 environmental P loadings 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 environmental P loading 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 environmental P loading. However, the variation in the simulated environmental P loading in the current study that used a farm visit approach to collect specific data for model input could not be compared to prior studies that transformed data from existing datasets because such studies did not provide information on the variation of simulated environmental P loading from dairy farms (Zhang *et al.*, 2012, Lynch *et al.*, 2018). However, the mean annual environmental P loading across all participating farms simulated for the ‘baseline’, ‘current’ and ‘maximum’ scenarios (0.63, 0.56 and 0.29 kg P/ha, respectively) in the current study were all similar to the environmental P loading simulated from dairy farms in the South of England using geo-referenced data, *i.e.* rainfall, soils and farm types specific for the Hampshire Avon test catchment (Zhang *et al.*, 2012) using the same scenarios (0.5, 0.44

and 0.19 kg P/ha). Conversely, environmental P loading values in the current study were lower than the mean 0.94 kg P/ha simulated from South-Western England dairy farms using data adapted from the Farm business survey (Lynch *et al.*, 2018). Therefore, findings in the current study demonstrated the uncertainty associated with larger transformations of less relevant existing datasets into an appropriate format for inputting into models to simulate environmental P loading. However, the implementation rate of mitigation methods in the 'current' scenario was not collected in the current study and was assumed by FARMSCOPER by simulating 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). However, annual assessments of schemes such a Catchment Sensitive Farming report that there is an increase in the uptake of mitigation methods amongst farmers they advise (Environment Agency, 2019). Consequently, the reliability of simulated environmental P loading 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 wider variation in environmental P loading 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 environmental P loading. Therefore, farms with a higher environmental P loading should aim towards operating with environmental P loading values closer to the more environmental sustainable dairy farms of a similar milk production. The mean 0.021 kg P/GJ milk produced per year of environmental P loading 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 environmental P loading 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 findings of the current study indicate that progress may have been made towards reducing P loss from dairy farms between 2012 and 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 environmental P loading from dairy farms is positively correlated with the amount of milk produced, emphasises the importance of mitigating environmental P loading from dairy farms, as the average milk yield in GB continues to increase (March *et al.*, 2014, AHDB, 2019).

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

Housed dairy farming systems are associated with increased imports of purchased concentrates, which usually contain 50% more P than grass herbage 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 environmental P loading. Furthermore, more highly stocked farms have a greater soil compaction than less densely stocked farms, and subsequently a greater amount of environmental P loading 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 environmental P loading 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 environmental P loading from the farms using the housed system compared to the pasture-based system under the ‘current’ scenario, because of differences in livestock and land management and geographic condition (soil and rainfall), this numerical difference was not statistically significant ($P = 0.316$).. The chances of finding significant differences in environmental P loading between the housed and pasture-based dairy farming systems 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 an all-year housed system amongst GB dairy farming has increased (March *et al.*, 2014). Therefore, the current study highlights the need for

FARMSCOPER and other models of farm P flows 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 farmers in making decisions about P management on their individual farms and policy-makers in decision making by simulating regional and national information that is reflective of modern diverse dairy farming systems.

5.5.3 Least-cost phosphorus mitigation methods

In the current study, the optimization feature of FARMSCOPER suggested that there is considerable scope to reduce environmental P loading 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 environmental P loading 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 to reduce environmental P loading, 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 financial 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 (*i.e.* loosening compacted soils) was important in reducing environmental P loading in the pasture-based system but this was associated with an operational cost. Consequently, less annual financial savings occurred in the pasture-based scenario. Therefore, the current study suggests that the approaches used to increase the implementation rate of existing methods to mitigate environmental P loading in GB dairy farming would benefit from a system-specific approach.

5.5.4 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 environmental P loading 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. This is 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 environmental P loading 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 environmental P loading. 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 reduced 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). Conversely, In Northern Ireland, a field trial has observed that a reduction in the P concentration of diets fed to dairy cows from 5.4 to 3.0 g P/kg DM and applying the subsequently less P-rich manure from cows fed the lower dietary P concentration to land, significantly reduced the P concentration measured in overland flow. However, the observed large drop in P concentration of overland flow between simulated rainfall events suggested that increasing the time between manure application and the generation of overland flow has a greater impact on P loss than does varying dietary P concentration (O'Rourke *et al.*, 2010). Therefore, the most optimal solution would be a combination of strategies to improve resource use efficiency (*i.e.* precision P feeding) and ‘rear-end’ strategies.

Extending the grazing season was a selected method in the least-cost suite of methods to mitigate environmental P loading for both the pasture-based and housed dairy farming system. This was largely because it provided an estimated saving in operational costs for farmers in regard to reduced cost of silage production and manure management (Newell-Price *et al.*, 2011). However, extending the grazing season in an all-year housed system could reduce milk yield and have financial cost not necessarily considered by FARMSCOPER. Inversely, FARMSCOPER also estimated that an extended grazing season would increase environmental P loading because of increased soil poaching from grazing livestock (Newell-Price *et al.*, 2011). Conversely, environmental P loading 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 farmers and 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).

5.6 CONCLUSIONS

The lower environmental P loading simulated from dairy farms using appropriate data collected directly from farmers in the current study compared to previous studies that simulated environmental P loading from dairy farms using largely transformed data from existing datasets demonstrated the importance of considering the trade-off between a large sample size and uncertainty associated with larger data transformation. Furthermore, housed dairy farming systems in the current study had a mean ‘current’ potential environmental P loading ~ 59% numerically greater than farms using the pasture-based system. Additionally, despite the current study indicating progress has been made towards improving the sustainability of dairy farming in the aspect of environmental P loading, the current study indicates environmental P loading from dairy farms will continue 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 environmental P loading as the prevalence of housed systems in GB dairy farming and milk yield has increased. The current study demonstrates that there is considerable scope to reduce environmental P loading 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 findings of the current study suggests that more emphasis should be put on approaches to increase the implementation rate of existing methods to mitigate environmental P loading, such as increasing knowledge transfer between farmers, advisers and researchers. However, such approaches would benefit from a more system-specific approach based on farm typologies. Further consideration of the environmental and financial impacts from reducing P feeding and the increased customizability of parameters in FARMSCOPER and other P flow models 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 environmental P loading.

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6 GENERAL DISCUSSION

In Experiment 1 (Chapter 3), a key finding was that most (72%) participating dairy farmers reported that they did not know the amount of P they feed to their cows. Consequently, this also meant that it was not possible to generate quantitative information about the amount of P fed to dairy cows on GB dairy farms. However, based on the limited information available it was evident that a third (33%) farmers that provided a dietary P concentration fed more P to their cows than the dietary P requirement recommended for dairy cows (NRC, 2011). Furthermore, some of the farms that provided a dietary P concentration likely underestimated the contribution of P supplied from all dietary sources because the average P concentrations of the total diet provided by the farmers (≤ 3 g P/kg DM), which was less than the average 3.5 g P/kg DM P concentration measured in forage mixes (excluding concentrate and inorganic P supplements) across 50 dairy herds in England (Sinclair and Atkins, 2015). The average range in dietary P concentration of 3.9 to 4.3 g/kg DM in dairy cow diets reported by feed professionals, who are expected to be more aware of dietary P concentration, was greater than that reported by the farmers, which suggested that underestimation of dietary P concentration by the farmers was highly likely. The lack of awareness on P feeding amongst GB dairy farmers has been speculated in previous literature (Withers *et al.*, 2006) but has not been documented prior to this thesis. Therefore, Experiment 1 provided new and much needed information that demonstrated many dairy farmers in GB may not be aware of how much P they feed to their cows. Subsequently, this information recommends to Agri-environmental stakeholders for dairy farms that whilst attention should be given to improving the accuracy of official feeding recommendations, an important strategy to reduce P feeding in GB dairy farming would be to raise awareness and increase the implementation rate of existing precision P feeding strategies in GB dairy farming.

A second key outcome of Experiment 1 (Chapter 3) was that over two thirds (70%) of responding farmers relied on feed professionals, who were more aware of the P concentration in the diets they formulated for their client dairy farms than the farmer respondent (83 *vs* 28%). However, the presence of a feed adviser had minimal impact on P feeding practice, tended to increase the likeliness of a farm to feed inorganic P supplements and furthermore almost two thirds (68%) of feed advisers were unsatisfied with the amount of training on P management available to them. Therefore, findings from Experiment 1 suggest that feed professionals could be better utilized than they currently are and that a strategy to address the issue of diffuse P pollution from dairy farms could be supported by providing more training on P management to farmers and feed advisers. Furthermore, the use of a novel approach to consider results across five GB dairy classifications (Garnsworthy *et al.*, 2019) provided new information that suggested housed dairy farming systems tended to rely more on feed professionals compared to pasture-based systems. Therefore, findings from Experiment 1 further demonstrated the particular importance of utilising feed professionals in the housed system. Inversely, this finding indicated that forage P testing should be promoted in pasture-based systems through alternative methods (*i.e.* farm advisory services and subsidiary’s) because farms receiving advice from feed advisers were more likely to analyse forage P concentrations. Consequently, Experiment 1 provided an important indication that going forward strategies to reduce P feeding will benefit from a more system-specific approach.

The findings from Experiment 1 could be even more important to the GB dairy industry when considering the P feeding situation reported in Experiment 1 could be ‘better than actual’ for the national situation. This is because both Experiment 1 and previous research in the US (Dou *et al.*, 2003) have reported that larger herds were associated with being more interested in P feeding ($P < 0.01$). Consequently, the lower than optimal response rate and the larger herds and UAAs of survey respondents compared to the typical 165 lactating cows and 154 ha for UK dairy farms (DEFRA, 2020) suggest that the respondents were representative of farmers more conscientious of their P feeding than the average farmer. Therefore, results from Experiment 1 (Chapter 3) are likely reflective of a ‘best than actual’ national scenario and consequently, the national situation regarding P feeding in dairy farms is likely more concerning than indicated here.

Experiment 2 (Chapter 4) provided much needed information showing large mean P surpluses (FPB: 9.58 kg/ha, SPB: 7.47 kg/ha) and consequently high mean Olsen P concentrations (43.2 mg P/kg) in soil on participant dairy farms across all farming systems. Therefore, a key finding from experiment 2 suggested that there is opportunity to improve the sustainability of GB dairy farming systems in regard to P use. Furthermore, Experiment 2 was the first to consider differences in GB dairy farming systems when calculating P balances and subsequently was the first to suggest that blended pasture-based systems (classifications 2 and 3) had significantly lower P balances and improved PUE than strict pasture-based and housed dairy farming systems. A caveat of caution is that Experiment 2 assessed P balances and PUE using data from 29 dairy farms across GB, which could be considered smaller than desirable to represent the proposed five GB dairy classifications (Garnsworthy *et al.*, 2019).

However, a similar sample size has been used in previous studies that determined PUE on 21 dairy farms (Mihailescu *et al.*, 2015). Furthermore, cows on the farms participating in Experiment 2 had average annual milk yield similar to the UK national average and farms represented each of the proposed five different GB dairy farming systems

The use of five GB dairy farming classifications was justified because it provided the opportunity to recommend strategies to improve PUE that are more system-specific rather than the usual strict pasture -based and housed dairy farming system (*i.e.* multiple classifications of pasture-based system). For example, Experiment 2 observed a negative relationship between farm-gate feed P import and PUE. Consequently, Experiment 2 demonstrated that the higher mean SPB (22.1 kg/ha) in the housed system compared to some pasture-based systems classification 2 and 3) could be reduced to 9.2 kg/ha, a similar SPB observed in the pasture-based system, by reducing dietary P concentration to within NRC (2001) recommended levels. Whereas, the significant positive relationship between the inclusion rate of home-grown forages and PUE indicated that the pasture-based systems could increase PUE by increasing the inclusion rate of home-grown feed. This could be achieved by extending the grazing season (Mihailescu *et al.*, 2015) and maintaining a moderate stocking rate adjusted according to the availability of home-grown feed.

Experiment 2 provides much needed SPB information across diverse GB dairy farming systems that has not been documented before this thesis. Lack of documentation is partly because of the difficulty in quantifying P import onto the soil-surface via manure and the export of P out of the soil-surface via grazed grass (Oenema *et al.*, 2003). Some SPB information for dairy farms is available outside of GB (Adenuga *et al.*, 2018). However, these studies tend to use fixed coefficients for P concentrations in manure and milk, which would miss important differences in diverse dairy farming systems. Therefore, a key outcome of Experiment 2 was the demonstration of a novel approach to calculate SPB in diverse dairy farming systems. This approach was an adaptation of the principles of ANCA, which is a validated tool used widely in the Netherlands to assess nutrient management on dairy farms (Aarts *et al.*, 2015). Since ANCA was designed for Dutch dairy farming systems, the use of ANCA for GB dairy farms without any modifications may bring limitations and could lead to biased estimation of P balance. Therefore, the principles of the ANCA tool were used to create a spreadsheet model and to identify the type of data that should be collected from participating farms. However, to utilise the principles of ANCA, the ME of feed ingredients were required to be converted into VEM using equations derived by Wageningen, UR (2016). Despite being carefully constructed from controlled feeding trials, this conversion equation may have some level of uncertainty associated with it as the feeding level used in the trials was fixed at 2.38 × maintenance energy, which is the feeding level used in the experiments that the VEM system is based on. However, a level of acceptability in the approach used to calculate the SPB on GB dairy farms was evidenced by the agreement between the SPB values calculated in this project and the limited data available in the literature (Adenuga *et al.*, 2018). Therefore, a key outcome of Experiment 2 is the foundations of an approach that could change the way GB dairy farmers and advisers calculate P balances in diverse systems. Going forward, this approach could be further developed, and easily adopted by GB dairy farmers and feed advisers to promote precise P management and subsequently improve the sustainability of GB dairy farming in regard to P.

Experiment 3 (Chapter 5) demonstrated a significant positive relationship between annual milk production and simulated environmental P loading on a total and per ha basis. A similar positive association between milk production and simulated environmental P loading from dairy farms has been reported previously (Firbank *et al.*, 2013). However, the novelty of Experiment 3 is that it is the first to report this relationship using data collected directly from farmers to simulate environmental P loading as opposed to transforming data from existing databases. Therefore, a key outcome of Experiment 3 was a promotion of the importance of mitigating environmental P loading from GB dairy farming as annual milk yield in dairy cows (AHDB, 2021) and the number of housed dairy farming systems are increasing (March *et al.*, 2014).

Through the use of scenario modelling (regarding implementation rate of existing mitigation methods), Experiment 3 simulated that irrespective of farming system there is opportunity to further reduce environmental P loading from dairy farms at a financial saving by adopting the least-cost suite of mitigation methods optimised in Experiment 3. A caveat to the findings in Experiment 3 is that the ‘current’ implementation rate of mitigation methods was not collected from farmers but rather simulated in FARMSCOPER. A more tailored approach to determine the implementation rate of different mitigation methods would improve FARMSCOPER’s accuracy in the prediction of potential reduction of P loss from dairy farms. However, this decision on data collection approach in Experiment 3 was a conscious one to strike a careful balance between simplicity and accuracy. Therefore, a key outcome from Experiment 3 is a suite of existing mitigation methods for each a housed and pasture-based dairy farming system to reduce environmental P loading at a financial saving.

In experiment 3, the lack of captured significant difference in environmental P loading between dairy farming systems was partly due to the relatively limited sample size but also suggested that FARMSCOPER's current approach to defining representative farm types may not capture important differences between dairy farming systems that may influence environmental P loading (Willows and Whitehead, 2015). Therefore, a further key outcome of experiment 3 was recommendations on parameters (such as grazing season length) that need to be more customizable in P flow models such as FARMSCOPER. Implementing such recommendations could improve the accuracy of environmental P loading predictions and the optimization of mitigation methods in P flow models. Subsequently, information from Experiment 3 contributes towards ensuring P flow models such as FARMSCOPER can effectively support the decision making of farmers, advisers, stakeholders and policy-makers.

6.1 Summary of key findings and outcomes

Experiment 1 (Chapter 3) provided information on how the majority of participating dairy farms from a range of GB systems did not know the P concentration in their lactating cow's diet, did not commonly adopt precision P feeding practices, did not analyse manure for its P concentration and were not satisfied with the amount of training on P management available to them. Additionally, these findings were likely representative of a ‘better than actual’ national situation when considering that the relative low response rate of the survey may indicate participation from farmers more interested in their P feeding than the average farmer. Therefore, a key outcome of Experiment 1 was that there is need for P management training to be more available to farmers. Furthermore, the novel aspect of this study investigating diverse dairy systems allowed the study to provide new information on how better utilising feed professionals will be important in promoting precision P feeding in housed systems. The findings of experiment 1 have been widely presented (international conferences and industry seminars) and widely published (in academic journals. industry reports for farmers and various media). They will be important in promoting the awareness and devising strategies to promote precision P feeding in GB dairy farming.

Experiment 2 (Chapter 4) demonstrated a new approach to calculate P balances (SPB and FPB) that is able to capture important differences between diverse dairy farming systems as opposed to using fixed standard coefficients (*i.e.* manure P concentration and milk P concentration were calculated using an adapted version of the principles of ANCA). This demonstrated approach can be easily implemented by farmers, advisers and stakeholder organizations and may be more applicable to diverse dairy farming systems than using fixed standard coefficients. Experiment 2 used this novel approach to calculate P balances, for the first time, to compare P balances across diverse GB dairy farming systems. Therefore, a key outcome of experiment 2 was the provision of new information demonstrating how a blended dairy farming system (*i.e.* classification 2 and 3) were significantly more efficient with P than a strict pasture-based or housed dairy farming system. Further analysis into the determinants of the difference in P balance between systems found various relationships between management practices and PUE which provided a number of system-specific recommendations to improve PUE in diverse GB dairy farming systems. For example, feeding P more precisely to the cow's requirement particularly in the housed system and increasing the inclusion rate of home-grown feed in the diet and matching SR accordingly can increase PUE pasture-based systems. The key outcomes of experiment 2 are (1) the foundations of a new approach to calculate P balance in diverse dairy farming systems that can be further developed and adopted by various stakeholders of GB dairy farming to promote precision P management and (2) various practical, easily implementable and system-specific strategies recommended to improve the sustainability of GB dairy farming in regard to P. These findings have been widely presented widely (at industry seminars and international conferences) and are in the process of being published in industry reports and an academic journal.

Experiment 3 provided, for the first time, new information on simulated environmental P loading and least cost suites of mitigation methods for both a pasture-based and housed dairy farming system scenario. The novel aspect of Experiment 3 was that appropriate data was collected directly from farmers as opposed to transformed from existing data sets. Experiment 3 reported a positive relationship between annual milk production and estimated greater annual financial savings in a housed dairy farming system when implementing a least cost suite of methods to mitigate environmental P loading compared to a pasture-based system. Therefore, the findings highlighted the importance of mitigating environmental P loading from housed dairy farming systems. The key outcomes of Experiment were (1) a least cost suite of existing methods farmers could implement to mitigate environmental P loading with an estimated annual financial saving for each a pasture-based and housed dairy farming system, (2) recommendations of important considerations in P flow models such as FARMSCOPER that could improve simulations for diverse dairy farming systems, (3) baseline data for simulated environmental P loading from dairy farms using an approach that collects data directly from farmers. These findings have been presented at an industry seminar and will be published in industry reports and an academic journal.

In view of the big picture, the current thesis provided new and much needed information on the flow of P throughout a range of GB dairy farming systems and demonstrates novel approaches to calculate these P flows in diverse dairy farming systems. The outcomes of the current thesis is the provision of practical and easily implementable recommendations for GB dairy farmers, advisers and other stakeholders (*i.e.* CSF) to improve the financial and environmental sustainability of GB dairy farming in regard to P use.

6.2 Summary of limitations

The nature of a PhD being a learning process with time and monetary constraints associated with it, leads to some limitations to the data. Therefore, a caveat of caution must be provided and considered when interpreting the findings. The main limitation of experiment 1 (Chapter 3) was the limited number of survey responses. Consequently, it was difficult to be reflective of GB dairy farming. Additionally, the limited response rate was indicative that participating farmers were more interesting in P feeding than the average farm. Consequently results may be reflective of a better situation than the national situation. In future, a shorter survey would likely increase the response rate. Additionally, some information provided by the farmers (*i.e.* dietary P concentration, motivators and barriers for reducing P feeding levels) was likely influenced by options provided in the survey in an attempt to aid analysis. However, in future the greater use of open-ended questions in surveys is recommended, particularly for quantitative answers. However, despite the limitations this experiment was important in highlighting the lack of awareness of P feeding amongst GB dairy farmers.

In experiment 2 (Chapter 4), the main weakness was the ambitious scope of the experiment. In particular, the adaption of SPB approach used in ANCA to be used in GB dairy farms required a large amount of time (including a 3 month fellowship at Wageningen University). Consequently, time constraints led to a smaller sample size of dairy farms than potentially possible. The smaller sample size led to an imbalanced number of farms across dairy farm classifications. A more even spread may have resulted in further significant findings. Similarly, time constraints led to a one day sampling approach per farm, less rigorous than potentially possible. This may have led to likely significant relationships being unobserved in the current study, for example an inverse relationship between mineral fertiliser P application to land and soil Olsen P was expected (Mihailescu *et al.*, 2015). Additionally, these time constrains meant that the principles of SPB could have been further improved to produce more accurate outputs (*i.e.* replace VEM with ME calculations as to remove the uncertainty associated with the VEM to ME conversion equation used). In future, a narrower scope would be recommended. Additionally, future studies should be extended over multiple years to capture changes in P in stocks over time and provide more rigorous sample collection.

In experiment 3 (Chapter 5), the same time constraints as in experiment 2 (Chapter 4) led to various limitations. In particular, the integrated approach used to collect data for experiment 2 (Chapter 4) and experiment 3 (Chapter 5) at the same time whilst visiting farms meant that a large amount of data and samples was being collected from farmers. Consequently, to avoid lack of engagement from participating farmers certain data needed to be prioritised and other ‘desirable’ data had to instead be collected from other sources. For example, the rate at which farmers implemented each mitigation method could have improved the accuracy of the simulated environmental P loading in FARMSCOPER but rather this information needed to be simulated in FARMSCOPER. In future, where time is less limited it would be ideal to maintain a narrower scope for each experiment than what was used in the current thesis. With more time, further investigation could have been conducted into alternative models such as SIMSdairy, a similar farm-scale model that simulates pollutant losses of a dairy farm and associate financial consequences (Prado *et al.*, 2009, Del Prado *et al.*, 2011).

In summary, the key lesson learnt from the current thesis was that particular attention should be made to ensure that the scope of experiments are narrow enough to achieve the highest level of data collection and investigation to produce the most accurate data. In some cases, this may require independent data collection for each experiment. Clearly, a careful balance in the trade-off between a simple protocol and accurate data must be struck with careful consideration of the time and money constraints of a project.

6.3 Future research perspective

i. Will reducing dietary P concentration reduce FPB and SPB of dairy farms? Some previous research began to provide information towards answering this question by reported lower FPB for dairy farms not feeding inorganic P supplements compared to farms feeding inorganic P supplements (Koelsch and Lesoing, 1999). However, no research has compared SPB between farms feeding controlled diets. This could be achieved by calculating the FPB and SPB of the same dairy farms over multiple years or comparing across similar farms whilst making changes to the diet to improve precision P feeding (*i.e.* feeding a lower dietary P concentration, feeding lower P alternative feeds such as maize, removing inorganic P supplements). Differences in P balances over years or between farms could be compared using ANOVA to assess the impact on environmental P loading from various precision P feeding strategies. A financial aspect could also be included in this research to investigate the financial impact of precision P feeding practices.

ii. Promoting the adoption of SPB amongst GB dairy farms. This could be achieved via further work and collaboration with Wageingen University Research to further adapt the principles of ANCA for GB dairy farms. In particular, this would involve changing the feed energy system from VEM to ME to reduce uncertainty associated with conversions. Further investigation (systematic literature review and potentially field trials along with expert advice) would be required to identify further required changes. However, the approach used in the current thesis provides a strong foundation for such an adaptation.

iii. Further investigate strategies to implement the improvements to FARMSCOPER recommended from this project to ensure output is reflective of modern GB dairy farming systems. In particular, increasing the customizability of farm parameters to create a model farm more closely representing a farming system will improve the accuracy of outputs. Furthermore, a survey or use of existing data (*i.e.* Catchment Sensitive Farming's annual assessment) could be used to update FARMSCOPER's simulation of the 'current' scenario for pollutant losses.

6.4 Conclusion

In conclusion, mitigating environmental P loading from 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 cost-effective opportunities to mitigate environmental P loading at a financial benefit for farmers exist and largely involve reducing mineral fertiliser and purchased feed P and employing mobilisation management practices. However, strategies to cost-effectively reduce environmental P loading from dairy farms in countries operating diverse dairy farming systems should be system-specific. A further reduction in environmental P loading from dairy farms in the future largely relies on reducing P feeding.

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7 APPENDIX

Table 7.1 Questions involved in the questionnaire on phosphorus feeding distributed to Great Britain dairy farmers and feed advisers

No.	Question	Response options
1	What are the first 3 digits of your postcode?	Open ended
2	On average how many lactating cows are milked annually?	Open ended
3	What is your rolling annual average milk yield per cow?	Open ended
4	How many days do you allow for lactating cows grazing?	Open ended
4.1	What percentage of your whole herd is grazed?	Open ended
5	Which calving system do you use?	1. All-year, 2. Block
5.1	If block calving, please circle which months cover the block	Months of the year listed
6	Is your farm organic?	1. Yes, 2. No
7	Who is responsible for the nutrition of your herd?	1. Farmer/self, 2. Vet, 3. Feed supplier, 4. Nutritionist, 5. No one, 6. Other (Open ended)
8	What is your annual amount of concentrates per cow (kg)?	Open ended
8.1	When do you feed these concentrates? (Can selected multiple options)	1. In parlour, 2. Total mixed ration, 3. Partial mixed ration, 4. Along fence feeding, 5. Out of parlour feeders, 6. Other (Open ended)
9	How do you feed your lactating cows with inorganic phosphorus (Phosphate) supplements?	1. Drench, 2. Lick, 3. In-water supplements, 4. Boluses, 5. In concentrates, 6. Do not feed, 7. Free access minerals, 8. In partial mixed ration
9.1	Is your current supplement practice different from that followed 5 years ago?	1. Yes, started feeding inorganic P supplements, 2. Yes, stopped using inorganic P supplements, 3. Yes, increased inorganic P supplement use, 4. Yes, reduced inorganic P supplement use, 5. No, 6. Don’t know

Table 7.1. Continued. Questions involved in the questionnaire on phosphorus feeding distributed to Great Britain dairy farmers and feed advisers

No.	Question	Response options
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?	1. None, 2. AFRC, 3. NRC, 4. Don't know, 5. Other (Open ended)
10.1	If you do not follow any recommendation, why is this?	1. Not aware of recommendations, 2. Not advised to, 3. Recommended level is too high, 4. Recommendations not available, 5. Recommendations too dated, 6. Don't understand them, 7. Other, 8. Recommended level is too low, 9. Don't know
11	Do you consider dietary phosphorus concentration when deciding on which feed ingredient to buy?	1. Not at all, 2. Slightly, 3. Moderately, 4. Completely, 5. Don't know
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')	Scale of 0 - 10
13	Please tick the most appropriate option for your feeding strategy	1. Early and late lactation cows diets have different dietary P concentrations, 2. High and low yielder diets have different dietary P concentration, 3.All milking cows are fed the same dietary P concentration in the diet
13.1	If all milking cows are fed the same dietary phosphorus concentration, why have you chosen this option?	1. Advised to, 2. Don't know, 3. Easier to formulate, 4. Other (Open ended), 5. Unaware of why to vary dietary phosphorus concentration
14	How confident are you in the accuracy of your diet mixing? (training and accuracy of people responsible for feeding and scale accuracy)	1. Not at all, 2. Slightly, 3. Moderately, 4. Completely, 5. Don't know

Table 7.1. Continued. Questions involved in the questionnaire on phosphorus feeding distributed to Great Britain dairy farmers and feed advisers

No.	Question	Response options
15	Do you have any systems in place to monitor the accuracy of adding feed ingredients to a mix?	1. Manual recording, 2. None, 3. Feed wagon manufacturer system, 4. Other (Open ended)
16	How regularly do you analyse forage phosphorus content?	1. Never, 2. At least once a month, 3. Quarterly, 4. Every 6 months, 5. Annually, 6. Biannually, 7. Don’t know, 8. Other (Open ended)
16.1	Do you use this forage phosphorus content when you formulate rations?	1. Yes, 2. No, 3. Don’t know
16.2	If you do not analyse your forage phosphorus content, what is the reason for this?	1. Cost, 2. Time availability, 3. Unaware that you could, 4. Do not consider it necessary, 5. Don’t know, 6. Other (Open ended)
17	What do you think phosphorus is required for in the diet?	1. Bone, 2. Fertility, 3. Rumen function, 4. Milk yield, 5. Don’t know
18	Which level of dietary phosphorus [as % diet Dry Matter] do you think will over-feed phosphorus?	1. > 3 g.kg DM, 2. > 4g/kg DM, 3. > 5 g/kg M, 4. > 6 g/kg DM, 5. Don’t know
19	How important is it to you to make sure your cows are eating enough phosphorus?	1. Not at all, 2. Slightly, 3. Moderately, 4. Completely, 5. Don’t know
20	What level of dietary phosphorus [as % diet Dry Matter] are your cows offered in total?	1. < 3 g/kg DM, 2. 3 to 3.8 g/kg DM, 3. 3.9 to 4.3 g/kg DM, 4. > 4.3 g/kg DM, 5. > 5 g/kg DM, 6. > 6 g/kg DM, 7. Don’t know, 7. Phase fed
21	If you were found to be overfeeding phosphorus, would you be willing to reduce dietary phosphorus concentration?	1. Yes, 2. No

Table 7.1. Continued. Questions involved in the questionnaire on phosphorus feeding distributed to Great Britain dairy farmers and feed advisers

No.	Question	Response options
21.1	What would prevent you from reducing phosphorus overfeeding?	1. Uncertainty of or lack of information on phosphorus availability in different feed ingredients, 2. Lack of confidence in phosphorus content of feed ingredients (highly variable phosphorus content) 3. Lack of time, 4. Potential increased feed costs, 5. Reduced productivity concerns, 6. Reduced fertility concerns, 7. Don't know, 8. Other (Open ended)
22	What would be your reasons for reducing phosphorus content if you were overfeeding?	1. Reduced environmental impact, 2. Meeting regulations, 3. Incentive programme, 4. Advised to by adviser, 5. Reduce supplement costs, 6. Other (Open ended)
23	Are you aware of the environmental impact of diffuse phosphorus loss from dairy farms in the UK?	1. Unaware, 2. Partially, 3. Moderately, 4. Completely
24	Are you aware of any UK environmental legislation relating to phosphorus use in animal agriculture?	1. No, 2. Yes (Open ended)
24.1	If yes, where did you hear about this information?	1. Adviser, 2. Media, 3. Consultant, 4. Environment Agency, 5. Vet, 6. Other farmer, 7. Other (Open ended)
25	Are you aware of how phosphorus has impacted dairy farm management in other countries (such as the Netherlands)?	1. Unaware, 2. Partially, 3. Moderately, 4. Completely
26	Are you aware of the close link between phosphorus overfeeding and diffuse phosphorus loss to the environment	1. Unaware, 2. Partially, 3. Moderately, 4. Completely
26.1	If yes, have you changed your practice to reduce phosphorus overfeeding?	1. Yes, 2. No
26.2	If yes, what have you done?	1. Lower dietary P concentration, 2. Lower supplementary levels, 3. Analyse forage, 4. Other (Open ended)

Table 7.1. Continued. Questions involved in the questionnaire on phosphorus feeding distributed to Great Britain dairy farmers and feed advisers

No.	Question	Response options
27	How regularly do you have your manure/ slurry analysed for phosphorus?	1. Annually, 2. Six monthly, 3. Never, 4. Other (Open ended)
27.1	If yes, what do you do with this information?	Open ended
28	Do you feel there is enough training and education on phosphorus pollution management available to you	1. Yes, 2. No, 3. Don’t know
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 ended

Table 7.2. Information collected during farm visits to calculate farm-gate P balance, soil-surface P balance and simulate environmental P loading using FARMSCOPER.

No.	Question	Response type	Response options
1.	Farm reference number	Closed	Provided before visit
2.	Postcode	Open-ended	-
3.	Number of cows present, imported, exported and % managed as slurry	Open-ended	Quantitative for each animal category: Dairy cows - lactating and dry, Heifers over a year, Calves under a year and Calves up to 3 months
4.	Size of herd's prominent breed	Closed	Small (400 kg), Medium (500 kg) and Large (over 600 kg)
5.	Total annual milk sold (kg)	Open-ended	-
6.	Milk fat (%) and protein (%)	Open-ended	-
7.	Herd replacement rate (%)	Open-ended	-
8.	Surface area of each land type (ha)	Open-ended	Quantitative for each land type: Productive grassland, Extensive grassland, Arable maize and Arable crop.
9.	Olsen P of each land type if known (mg/kg)	Open-ended	Quantitative for each land type: Productive grassland, Extensive grassland, Arable maize and Arable crop.
10.	Each type of farm boundary (%)	Open-ended	Quantitative for each farm boundary type: Hedge, Wall, Fence and Other (to total 100%)
11.	Days/year and hours/day grazing outside	Open-ended	Quantitative for each livestock type: Dairy cows, Heifers and Calves
12.	How many ha of land used for rotational grazing (ha)	Open-ended	-
13.	Your livestock… (tick options)	Closed	Can access watercourses while grazing, Can cross water between fields and yards
14	Yard and parlour washings are sent to…(tick options)	Closed	Dirty water store, Slurry store, Minimal dirty water stored

Table 7.2. Continued. Information collected during farm visits to calculate farm-gate P balance, soil-surface P balance and simulate environmental P loading using FARMSCOPER.

No.	Question	Response type	Response options
15.	Calving approach	Closed	All-year round calving or Block calving (select which months cover the block)
16.	Other ruminant livestock imported or exported?	Closed	Yes, No
16.1.	Ruminant type, age (months), weight (kg), number of import, export and present	Open ended	Quantitative for each ruminant type provided by farmer
17	Arable crop production?	Closed	Yes, No
17.1	Arable crop type, surface area (ha), the destination of the main crop and the destination of the by-product (tonnes)	Open-ended	Tonnes of main product used as: Fed on farm, Export sold and Other/bedding Tonnes of by-products used as: Fed on farm, Export sold and Other bedding
18.	Type of feed and information on each feed for 'Grassland products', 'Other roughages and by-products', 'Concentrates, straights and minerals' and 'Milk powder for calves'	Closed	Harvest or import? - for each feed
		Open-ended	Tonnes of initial stock, Import/harvest, Export and Closing stock - for each feed DM (%), ME (MJ/kg), GE (MJ/kg) and P (g/kg DM) - for each feed
19.	Bedding material and tonnes of initial stock, import, export and closing	Open-ended	Quantitative for each bedding material provided by the farmer
20.	Mineral fertiliser type and information on each mineral fertiliser	Open-ended	Tonnes of Initial stock, Import, Export and Closing stock - for each fertiliser P content (%) = for each fertiliser
		Closed	Granule or liquid? For - each fertiliser

Table 7.2.Continued. Information collected during farm visits to calculate farm-gate P balance, soil-surface P balance and simulate environmental P loading using FARMSCOPER.

No.	Question	Response type	Response options
21.	Tonnes and P205 content (kg/tonne) of each organic manure import and export	Open-ended	Quantitative for each: Ruminant slurry, Ruminant farmyard manure, Non-ruminant slurry and Non-ruminant farm yard manure
22.	Mineral fertiliser applied (kg P205/ha) for each land type	Open-ended	Dependant on the land types provided in Q8.
23.	% of Ruminant slurry, Ruminant farmyard manure, Non-ruminant slurry, Non-ruminant farmyard manure and dirty water applied to each land type	Open-ended	Dependant on the land types provided in Q8.
24.	Participant’s signature to accept a farm visit	Closed	Yes, No

Table 7.3. Summary of P concentrations in feed ingredients fed on 29 visited participant dairy farms

Feed type	Mean P concentration (g/kg DM)	Range	S.D.
Grass silage	2.9	1.0 - 3.9	0.6
Maize silage	2.0	1.1 - 2.7	0.5
Whole crop silage	2.7	2.4 - 3.0	0.3
Parlour concentrates	5.4	2.9 - 7.0	1.2
Basal ration	3.6	1.9 - 6.0	0.8

Table 7.4 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 high 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 manufactured fertiliser placement technology	0.0	-143
Integrate fertilise and manure nutrient supply	0.0	-13928

[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 7.4. Continued. 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 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-field 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 7.5 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 farm