Three keys to unlock legacy phosphorus for sustainable crop production: models, budgets, and expert elicitation

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An account of why the legacy P challenge cannot be easily overcome:

“Our 1000 cows poop, we’ve discussed it with them but they won’t stop”
Anonymous

Declaration

This thesis has not been submitted in support of an application for another degree at this or any other university. It is the result of my own work and includes nothing that is the outcome of work done in collaboration except where specifically indicated. Many of the ideas in this thesis were the product of discussion with my supervisors Professor Phil Haygarth, Professor Jess Davies, Dr Martin Blackwell, and Dr Victoria Janes-Bassett.

Excerpts of this thesis have been published in the following conference manuscripts and academic publications.

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Abstract

The term “legacy phosphorus (P)” is used to refer to the accumulated P in soils and wider catchments resulting from past anthropogenic inputs and its subsequent impact in the environment. To explore how the potential of soil legacy P can be “unlocked” for sustainable crop production this thesis used three “keys”: process-based models, substance flow analysis (SFA) models and expert elicitation.

Using the process-based model N14CP, the study demonstrates that legacy P has the potential sustain crop yields for 50-83 years and 155-217 years on a cereal and permanent grassland plot, respectively with no applications of P fertiliser. However, addressing key "blind spots" in our empirical understanding of P cycling may help explain the sustained yields and soil P stocks in some long-term, no-input systems that N14CP cannot capture.

Utilising an SFA model, P balances and internal flows were estimated for an organic mixed farming estate in the UK. This work showed that SFA models can help farmers to track P flows and identify inefficiencies, especially in systems reliant on manure recycling. However, their effectiveness depends on accurate data and application over multiple cropping seasons.

Finally, this thesis identifies significant gaps between scientific perspectives on legacy P and farmers' practices. It highlights that many farmers view legacy P as inaccessible to crops and that socio-economic barriers greatly influence P management practices on farms. The development of tools and strategies that align with farmers' needs, supported by farmer engagement could help to address this.

As data availability and processing capacity continue to grow, so does the opportunity for integrated P research to address the gaps in our understanding of P cycling in the environment. However, legacy P challenges will persist unless there is widespread adoption of strategies that prevent further P accumulation and effectively manage existing legacy P stocks.

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1 Three keys to unlock legacy phosphorus for sustainable crop production: models, budgets, and expert elicitation

1.1 Introduction

1.1.1 The importance of phosphorus in agricultural systems

Phosphorus (P) is essential to life on earth, with P compounds forming: phospholipids (for cellular organisation / cell membranes), adenosine triphosphate (for metabolic energy), nucleic acids (for genetic material) and intracellular signalling molecules (Turner et al., 2005). Plant growth can be limited by soil P availability and with no substitute for P in crop growth, it is critical to our food production systems. Many crop systems are now dependent on regular inputs to meet global yield demands and increasing demand for P fertilisers poses challenges to supply sustainability (Cordell et al., 2009).

Fossil fuels and non-renewable (mined) fertiliser resources, particularly P fertilisers, have been fundamental in increasing productivity of agricultural ecosystems since World War II. While renewable alternatives to fossil fuels are available, there is still no renewable alternative to phosphate rock mining for P fertiliser production (Cordell et al., 2009). A combination of finite resources and geopolitical instability has contributed to rock phosphate supply volatility and its associated price oscillations for fertiliser products, such as the 800% phosphate rock price spike that occurred in 2008. This impacted global food prices and tiggered a sharp increase in interest in long-term P security (Cordell & White, 2011) and its relationship with local, national and global food systems.

As with other key plant nutrients (particularly nitrogen (N), potassium, and sulphur), P must be applied to soils to minimise the risk of deficiency and maintain crop yields. However, compared to other plant nutrients, P has limited bioavailability in soils, with typically less than 10% of total

P readily available for plant uptake (Darch et al., 2014); this can be measured using methods such as the Olsen P extraction method (Olsen et al., 1954). The remaining soil P is contained within primary materials, precipitated (typically complexed with calcium, iron or aluminium), adsorbed, or in organically-complexed forms (Darch et al., 2014).

Historically, agricultural strategies to manage P fixation in soils and crop productivity have focused on applying P fertiliser in excess of crop requirement to maintain plant-optimum P concentrations in soil solution (Syers et al., 2008). Some of the consequences of this approach and long term regular high P inputs has been widespread diffuse pollution of watercourses (Withers et al., 2001).

1.1.2 The evolution of the term “legacy” phosphorus

Scores of researchers across multiple disciplines have spent their careers attempting to address these P challenges and improve our understanding of the processes that govern the role of P in both food and water challenges. However, to understand our current situation and manage P into the future, it is important to understand how the modern P cycle has been impacted by anthropogenic inputs and agricultural practices. Elser and Haygarth (2020) describe a simplified evolution of P use in agricultural systems and its effect on the P cycle, from the pre-farming hunter gatherer practices to early (pre-industrial) agriculture and into the intensive (post-green revolution) era of crop production.

1.1.2.1 Pre-agricultural systems (natural and semi-natural states)

Starting with pre-agricultural systems (natural and semi-natural states), P levels in soil are generally low, with P (and N) limiting plant growth. Natural variations of apatite in parent rock material, in addition to some concentrated areas of P enrichment from animal excretions, are reflected in localised soil P availability for plant uptake. In this state, P cycling is in a largely closed system where P is recycled and slowly replenished by the chemical weathering of the parent material of the soil (Filippelli, 2008).

1.1.2.2 Early agricultural systems

In early, pre-intensive, agricultural systems, specific plants were grown and harvested in localised areas of mixed crop and animal production where crop residues, animal manures, and “night soil”[1] were recycled to the land, and from the mid-1800s sometimes imported from other areas e.g. guano to support production (Smil, 2000). These systems were largely in a P “balance” with increased localised P inputs closely matching the increased P outputs of the harvested plants (Ashley et al., 2011).

1.1.2.3 Intensive agricultural systems

The apparent balance of early agricultural systems remained in place until the so called “green revolution” in the mid-1900s and the development of phosphate rock fertilisers. This, alongside the mass production of N-based fertilisers, increased human population, and increased urbanisation (Ashley et al., 2011), has contributed greatly to the industrialisation of agriculture. Phosphorus applications to crops were commonly in excess of crop requirement, and in some cases, this is still regular practice (Defra, 2022; Panagos et al., 2022; Smil, 2002; Withers et al., 2014). Stocks of soil P in these intensive systems have consequently increased which has increased the risk of P pollution to watercourses (Condron, 2004; Kleinman et al., 2011). The long-term impacts of excess P inputs and P pollution to watercourses now persists far beyond the field-scale from where the P was originally applied, impacting whole catchments and marine systems (Sharpley et al., 2013) potentially long after the original P source has ceased (Haygarth et al., 2014).

The term “legacy phosphorus” has arisen during the last 15 years to refer to the accumulated P in soils and wider catchments resulting from past anthropogenic inputs and its subsequent impact in the environment (Sharpley et al., 2013). However, this concept was initially used to explain the prolonged release of dissolved P in water columns following the deposition of particulate P in

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[1] A Victorian term for human faeces and urine (Ferguson, D. T. (2014). Nightsoil and the ‘Great Divergence’: human waste, the urban economy, and economic productivity, 1500–1900. *Journal of Global History*, *9*(3), 379-402. https://doi.org/10.1017/s1740022814000175)

estuarine sediments (Boynton & Kemp, 1985). It was later referred to as the "P memory effect" by Correll et al. (2000) and then “legacy P” in the 2013 paper of Sharpley et al. (2013). Initially framed in an environmental context, Legacy P now represents a key focus in understanding long-term nutrient cycling and its implications for agricultural sustainability, as a resource to reduce inputs of P fertilisers (Menezes-Blackburn et al., 2018; Rowe et al., 2016; Stutter et al., 2012).

1.2 The three keys to unlock legacy phosphorus

Stores of legacy P in agricultural soils have the potential to be re-mobilised and support crop production. This could then offset new fertiliser or manure P inputs to land (Rowe et al., 2016; Sattari et al., 2012; Stutter et al., 2012). However, concerns over medium to long-term impacts to yield can prevent adoption of reduced or no P input practices. To explore how the potential of legacy P can be “unlocked” for sustainable crop production this research thesis will use three “keys”: process-based models, system budgets and expert elicitation.

1.2.1 Process-based models

Our contemporary understanding of P processes in crops, soil and water has been largely developed through controlled experimental testing and replication, through a range of spatial and temporal scales (Vadas et al., 2013). Guided by questions and hypotheses, researchers design methods and gather data that aims to improve our understanding of legacy P behaviour and mobility in soil and water systems under various treatments. However, baring a handful of long-term experiments in the world, these experiments often capture a “snapshot” of the impacts of different treatments over a few years or cropping cycles and rely on measurable outcomes to infer unmeasurable processes (Johnston & Poulton, 2018; Knapp et al., 2012).

Models are therefore being increasingly used to explore P behaviour in complex systems and to apply our understanding of P behaviour in crop, soil, and water systems. Whether shaping national agricultural policies or used by farmers to plan annual fertiliser applications, these models can have tangible environmental, crop yield, and economic effects. Ensuring that models are thoroughly tested, validated, and regularly updated to incorporate ongoing empirical advancements, will be crucial for informing and evaluating legacy P management strategies (Vadas et al., 2013).

1.2.2 System budgets

The concept of “feed the crop not he soil” involves balancing nutrient inputs with the nutrients removed through harvest and livestock production (Withers et al., 2014). This underpins many sustainable nutrient management practices. Farm-scale nutrient / P budgets are tools / models that quantify the inputs, outputs, losses, and internal flows nutrients within the farming system (Watson et al., 2002). The balances between these flows of helps in assessing nutrient use efficiency, identifying potential deficits or surpluses within the system. Evaluation of the budgets can then be used to facilitate targeted action (Brunner, 2010) to ensure sustainable nutrient use and minimise potential environmental impacts (Watson et al., 2002).

1.2.3 Expert elicitation

Expert elicitation is a third tool in understanding how scientific literature aligns with global perspectives and wider subject thinking surrounding legacy P. As global interest in legacy P grows it is important to understand farmers' perspectives to ensure effective communication and foster interdisciplinary collaboration. A deeper understanding of P management practices and the motivations/barriers on farms can also be a valuable tool to improve research, education, and legislation aimed at maximising P sustainability and reducing agricultural P pollution (Daxini et al., 2018; Gao & Arbuckle, 2022).

1.3 Objectives and thesis outline

The principal aim of this research thesis is to explore how different techniques, specifically process-based models, P budgeting models and expert elicitation, can be used to understand the potential of legacy P to support agricultural production, offsetting new P fertiliser and/or manure inputs. However, I hypothesise that the social and economic motivations and barriers faced by farmers and land managers surrounding P management on their land will limit the adoption of low / no P input systems. Specific objectives are:

- To explore the two contrasting views of legacy P within the scientific literature and how models can be used to address the blind spots in our understanding of legacy P.
- To model soil P stocks, flows, and crop yields under different P management scenarios and explore how the drawdown of legacy P stores can be used to support crop production over extended timescales.
- To explore how perceptions in the wider agricultural industry influence P management on farms and how this influences strategies to manage legacy P.

The following chapters are used to address these objectives.

Chapter 2: A review of legacy phosphorus and exploring how models may be used to balance the agronomic potential for legacy P with the environmental concerns – Literature study

The aim of this chapter is to evaluate the two main views of legacy P in the scientific literature, legacy P as an environmental challenge and as an opportunity for P sustainability in agricultural systems. It will also explore how models can be used to help balance the opportunities for legacy P with the environmental concerns.

Chapter 3: Simulating the capacity of legacy soil phosphorus to maintain long-term crop productivity under reduced phosphorus fertiliser inputs – Process-based model study

This chapter investigates the long-term capacity of legacy P to provide agronomically sufficient P to a grassland and cereal cropping system in response to reduced and eliminated P fertiliser inputs under various historical fertiliser regimes.

This research uses the biogeochemical model N14CP (Davies et al., 2016a; Janes-Bassett et al., 2020; Tipping et al., 2012) to simulate the long-term P changes in agricultural soils using the Broadbalk and Park Grass long term experiments based at Rothamsted Research, UK (Macdonald et al., 2018) as the basis for testing and validating model performance in temperate agricultural systems.

It is hypothesised that the legacy P effect will mean that modelled productivity, simulated by N14CP, will be sustained for a finite period post-reduction of P fertiliser inputs. Soils that have a history of high P fertiliser use, in excess of crop offtake, will be able to sustain productivity for longer post-reduction of P fertiliser. The results of these simulations will be tested against observational yield data from two Broadbalk and Park Grass long term experimental plots.

Chapter 4: Exploring phosphorus sources and use to assess long-term persistent yields in low-phosphorus input agricultural systems through N14CP modelling – Process-based model study

It is hypothesised that the biogeochemical model N14CP should simulate long-term soil P pools and yield well for grassland plots receiving annual inputs of fertiliser, however, baseline model runs will underestimate soil P stocks where there are no fertiliser inputs to the system.

The aim of this research is to explore the sensitivity of modelled grassland systems to different sources of P to investigate the disparity between model outputs and the observed persistent soil P stocks and the yields in agricultural sites with long-term no-P inputs.

Chapter 5: Long term organic production relies on intensive livestock production for the supply of phosphorus for crop production – a Substance Flow Analysis for an organically farmed estate in the UK – System budget study

This chapter aims to highlight the benefit of P system budgets for managing legacy P on a farm-level scale and provide an evidence base promote a more sustainable P future. A system budget that describes the P balances and internal P cycling for an organic farming Estate in the UK will be used to test two hypotheses:

1. Long-term organic crop and forage production on this Estate relies on the recycling of manures from intensive livestock production.
2. In a system where there are multiple stakeholders there is a P imbalance on some intensively managed parcels.

Chapter 6: Understanding the main drivers and motivations for phosphorus management on farms in the UK and farmers' awareness of the term "legacy phosphorus" – a farmer questionnaire – Expert elicitation study

This study aims to explore the motivations and barriers that farmers and land managers in the UK face to manging P on their land as well as to explore their insights surrounding legacy P. UK farmers were asked to complete and online questionnaire, responses to those questions will be used to address five main research questions:

1. To what extent do UK farmers follow best practice guidance and seek professional advice for P management on their farms?
2. How will the motivations for P management differ between different farming enterprises?
3. To what extent do farmers consider whole-farm P management rather than individual field management?
4. What are the main barriers to reducing P application rates to land?
5. How aware are farmers / land managers of the term "Legacy P" and what is their understanding of this term?

Chapter 7: Final Discussion - Bridging science and practice: legacy phosphorus management utilising models and farmer engagement – Overall discussion

This chapter aims to bring together the findings from this thesis to address the three main objectives set out above and to highlight some future directions for legacy P research.

2 A review of legacy phosphorus and exploring how models may be used to balance the agronomic potential of legacy phosphorus with the environmental concerns

2.1 Introduction

Phosphorus (P) is essential and irreplaceable to life on Earth and plays a critical role in cellular organisation, metabolic energy storage, cell replication, protein synthesis and the formation of bones and teeth (Turner et al., 2005). Agronomically, maintaining sufficient soil P concentrations to meet crop demand is critical to crop production and many agricultural systems are now dependent on regular (high) inputs to meet global yield demands. However, there are three key challenges surrounding P use in agricultural systems:

a) phosphorus is a finite resource mined from geographically-limited reserves of phosphate rock, influenced heavily by geopolitical challenges resulting in P supply and price volatility, creating knock-on effects for the global food supply chain (Cordell et al., 2009);
b) compared to other plant nutrients, P has limited bioavailability in soils, with typically 1.5-11% of total soil P readily available for plant uptake and the rest “locked up” in other inorganic and organically-complexed forms (Darch et al., 2014); and
c) intensive agricultural management practices have been linked to widespread diffuse P pollution of watercourses (Schindler, 1974; Withers et al., 2001).

Since Schindler (1974) “awakened” the world to the role of P as a major pollutant of freshwater systems, and Cordell et al. (2009) called for P to be included on global food security agendas; scientific research and agricultural policy has been focused on finding and implementing measures of minimising P pollution, reducing P fertiliser demand and increasing P recovery (including increased crop P use efficiency, and P recovery from a variety of waste products). There is now little doubt, sustainable management of the long-term P cycle in global agricultural systems will be critical in meeting many of the United Nations Sustainable Development Goals (Kanter & Brownlie, 2019).

Since the introduction of phosphate fertilisers, “new” P has been added to many agricultural soils to meet and even exceed crop demand, disrupting and “opening up” the indigenous biogeochemical storage and cycling of P (Childers et al., 2011). The term “legacy P” has evolved in recent years to refer to the stores of P resulting from the build-up of excess anthropogenic inputs into agricultural and other systems, from field scale to whole catchments. Arising from this, researchers across many fields, such as: agriculture, soil chemistry, nutrient management, water quality, limnology and many others have tried to understand how P contributions from past land management practices can influence the storage and cycling of contemporary P stocks in soils and water.

Early references to this concept were indirectly made by Boynton and Kemp (1985) to explain the extended release of dissolved P in water columns following the inputs and subsequent accumulation of particulate P in estuarine sediments, this was then termed the “P memory effect” by Correll et al (2000). Now known as “legacy P” (Haygarth et al., 2014; Jarvie, Sharpley, Spears, et al., 2013; Sharpley et al., 2013; Turner & Kim, 2024), the term has come to also encompass P in terrestrial and agronomic systems. The term “legacy P” has since appeared in more than 2,700 published articles, with approximately half of these published since 2022 (Google Scholar search April 2024[2]) each looking to address one or more of the three key P challenges. Its increasing adoption in the wider industry and policy applications further underscores its interdisciplinary significance.

Global interest in legacy P is growing, yet despite its near-universal links to anthropogenic agricultural nutrient management practices (Turner & Kim, 2024), two views for the term have

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[2] Google Scholar search for the exact term “legacy phosphorus” in all fields. Date of search: 12/04/2024. Number of search results: 2,760 (1,240 since 2022)

emerged. The first view of legacy P is one of an environmental challenge, where legacy P represents the P that is stored and re-mobilised within soils and aquatic sediments that has the potential to impair water quality over extended spatial and temporal scales. On the other hand, legacy P could also be viewed as an opportunity, where legacy P represents the pools of P in soils that persist as a legacy of anthropogenic inputs, which if re-mobilised has the potential to offset fertiliser P inputs and could be used to improve global P sustainability (Rowe et al., 2016; Sattari et al., 2012; Stutter et al., 2012).

Scientific research and agricultural policy (e.g. the European Union Water Framework Directive (2000/60/EC)) has focused on finding and implementing measures of reducing the risk of P entering watercourses. Key strategies have principally addressed surface run-off and erosion P losses such as: cover cropping, in-field or riparian buffer strips, minimum- or no-till systems, constructed wetlands, contour farming[3], precision application of P inputs, and timing of P inputs around rainfall events (Sharpley et al., 2009). However, these strategies do not typically address internal soil P cycling that controls the amount of P available for plant uptake. This necessitates a deeper understanding of P processes within the soil to improve crop P use efficiency; promote legacy P cycling; and overcoming production concerns surrounding reduced or no P inputs to agricultural land.

Our contemporary understanding of P processes in crops, soil and water has been largely driven by controlled experimental testing, from the laboratory to the catchment scale (Vadas et al., 2013). Empirical / inductive research cannot evaluate all P interactions and is often limited by the availability of measurable data; however, it remains crucial for testing hypotheses and understanding key P processes (Beven, 1989; Haygarth et al., 2005). To apply our understanding of P behaviour in soil and water to processes that cannot be physically measured, or in changing/complex systems, experimentally derived data is being increasingly used in tandem with modelling approaches (Krueger et al., 2007).

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[3] The practice of tilling or planting across a slope following its elevation contour lines.

The aim of this review is to describe and compare the two main views of legacy P in the scientific literature. This review will also explore how models may be used to help balance the agronomic opportunities for legacy P with the environmental concerns.

2.2 Alternative views of legacy phosphorus

The term legacy P has become widely used across scientific disciplines, yet the lack of a unified definition may have implications for the identification, quantification, and management of legacy P stores. Zhou and Margenot (2023) noted that "residual P" and "legacy P" have been interchangeably used in literature. They recommended that "legacy P" be used to describe P transfers across landscapes, while "residual P" should be used to describe the accumulation of soil P from past agricultural inputs. Conversely, Turner and Kim (2024) rejected the term "residual P" due to its specific analytical meaning in soil science[4] and conceptually define legacy P as the P accumulated from anthropogenic activity and can be calculated as the sum of the inputs minus the sum of the outputs over a given period of time. This is based on the definition of “legacy” as “something received from the past or through past actions or carried over from an earlier time”.

However, this definition does not consider geogenic P (largely mineral apatite) which it conceptually much older in age than the P fertilisers introduced to systems since the mid-1900s (Elser & Haygarth, 2020). Geogenic P plays an important role in some ecosystems (Anderson, 1988; Walker & Syers, 1976) but it is proposed that it should not be considered legacy P because it lacks an anthropogenic source. This differentiation is vital when setting nutrient and water quality targets, as regions with naturally high P levels must account for geogenic P in their baseline conditions (Smith et al., 2003). While distinguishing between geogenic and anthropogenic P remains a challenge, it is essential for developing effective management strategies.

As such it is proposed that legacy P could be defined as total P inputs represented in a system minus P offtakes (such as P uptake and removal by plants), P losses from the system (such as

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[4] the P forms that remain insoluble after extraction or digestion with strong acids.

runoff, erosion, leaching, or remobilisation); and geogenic P (i.e. the P that would be in the system in the absence of anthropogenic activity) (Shober et al. (2024), **Figure 2-1**). This simple conceptual equation forms the basis for the alternative views discussed in the following sections.

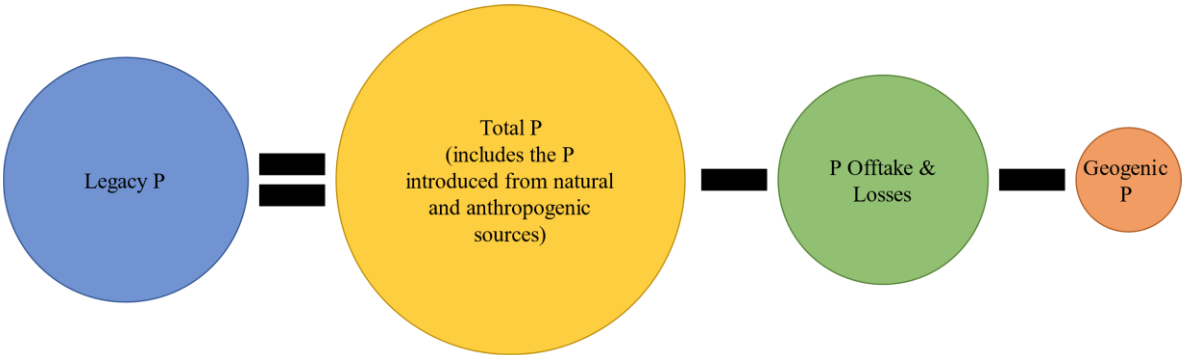

Figure 2-1: A simple conceptual equation for defining legacy phosphorus (P) in a system over time. The size of the circles is loosely representative of the amount of P that they represent in the system. Adapted from Shober et al. (2024)

2.2.1 Legacy phosphorus as an environmental challenge

Past land management has been linked to the accumulation of soil P and the build-up of P within terrestrial and aquatic environments. The subsequent mobilisation and storage of these legacy P pools act as sustained, long-term sources of P throughout the catchment, leading to a lagged response in soil or water quality over various spatial and temporal scales (Sharpley et al., 2013). Legacy P can have an influence on water quality impairment for extensive periods, ranging from years to decades, potentially persisting long after the original P input source (such as fertiliser or manure) has ceased (Haygarth et al., 2014). This highlights the complexity between P sources, sinks and transformations within a catchment as well as the temporal and spatial scale of the legacy P challenge.

Soils are the primary sink for anthropogenic P inputs in a catchment involving intensive agricultural production. As discussed, intensive agricultural practices have previously promoted the application of P fertilisers and manures in excess of crop requirement, resulting in a build-up of soil P. As a result of this build-up, many intensively managed agricultural soils can now be considered a primary source of legacy P, that once mobilised, transfers P to other terrestrial or aquatic areas within a catchment (Kleinman et al., 2011; Sharpley et al., 2013). Soils with greater soil P stocks are more likely to undergo P losses to surface and groundwaters compared to soils with low P stocks, but all soils have the potential to contribute to P mobilisation and delivery given points of hydrological connectivity (such as drainage) between P sources and P sinks (Blake et al., 2002; Heckrath et al., 1995).

Phosphorus losses from intensively managed land can accumulate in areas such as hill slopes, riparian zones, lakes, wetlands, rivers, reservoirs and groundwater (Sharpley et al., 2013). These environments are typically N and P limiting and even small increases in P loading from diffuse legacy P sources can create large impacts on the production of biomass (Farmer, 2018). In aquatic environments, legacy P can accumulate in the water or within sediments in organic and inorganic forms. The specific form it takes greatly influences its storage, mobilisation and bioavailability (Darch et al., 2014). Legacy P stores can contribute to P loads downstream in a catchment either via diffuse buffering of sediment P (Simpson et al., 2021) or during distinct hydrological events such as seasonal snowmelt (Long et al., 2014; Shrestha et al., 2020). Again the routing of legacy P from the source to impact is complex, taking into account: connectivity, P transformations and temporal variations in P resident times and hydrological events (Haygarth et al., 2005).

A key factor in addressing the environmental challenge of legacy P is the timescales necessary for the build-up and release of P in both terrestrial and aquatic systems. Relatively speaking the build-up of legacy P in intensively managed agricultural soils has taken a short amount of time. However, the drawdown and release of legacy P stores could span much longer timescales, encompassing the inherent complex nature of P cycling (Jarvie, Sharpley, Spears, et al., 2013). The slow dissolution of legacy P from aquatic sediments can impede water quality over time, hampering efforts made to minimise P pollution from terrestrial sources. Within many agri-environmental management strategies farmers and land managers employ measures that are designed to reduce diffuse water pollution from their farms (Sharpley et al., 2009). Yet, the positive impact of these measures (improved water quality) is not always seen in the short-term and may even be delaying, rather than preventing the nutrient problem (Meals et al., 2010; Sharpley et al., 2009; Stackpoole et al., 2021).

Overall, the fluctuations and lag times in the amounts of P entering and leaving a catchment, including the slow leakage of legacy P that can impede the impact of water quality improvement strategies, and the biogeochemical processes involved with the uptake, storage, and transformations of P throughout the catchment, are critical concepts for recognising the inherent challenges associated with managing legacy P.

2.2.2 Legacy phosphorus as an opportunity for phosphorus sustainability

Although newly discovered reserves of rock phosphate will help to meet future global supply demand for phosphate fertilisers (IBU-tec, 2022), long-term P sustainability remains a key concern for global food production. However, for some, legacy P provides an opportunity to address some of these concerns. Legacy P can be seen as a yet un-tapped source of P in agricultural soils that as the potential to be exploited by crops to offset agronomic P inputs (such as manures and P fertilisers).

Phosphorus in soil is either: dissolved in solution; contained within plant/microbial cells/plant residues; in particulate form i.e. sorbed to soil particles or colloids; or contained within the parent material of the soil (Darch et al., 2014). Inorganic P accounts for up to 70% of total P in soils; of this, water-soluble orthophosphates account for the majority of the inorganic P pool (Darch et al., 2014). Although not readily available for crop utilisation, soils also contain 30-90% organic P, much of which will be contained within plant residues or microbial cells (Bardgett, 2005; Stutter et al., 2012). Organic P must be mineralised to inorganic P by extracellular phosphatase enzymes. The enzyme type, availability, activity and environmental conditions are important for determining how quickly organic P will become available for crop or microbial uptake (Hayes et al., 1999) and can take from several days (e.g. labile monoesters) to months (e.g. organic polyphosphates) (Darch et al., 2014).

Tests such as Olsen-P, Morgan’s-P, Mehlich-3 measure the “available” P and are commonly used in agricultural systems to assess P stocks in the soil. The results of these tests are used by farmers and land managers alongside specified agronomic thresholds to determine the likelihood of a crop response to additional P inputs (i.e. soils above a given threshold e.g. 25-45 mg P l^{-1} (Olsen-P) are not likely to exhibit a positive crop response with additional P inputs) (AHDB, 2020a). However, this "available" P may account for <10% of the total P in the soil (Stutter et al., 2015). DeLuca et al. (2015) proposed a biologically-based P extraction method, which characterised P pools accessible through plant and microbial acquisition mechanisms. This approach incorporated four P extraction methods: 1) soluble or solution P; 2) enzyme extractable organic P; 3) citrate extractable P; 4) proton extractable inorganic P to offer a more functional and comprehensive approach to assessing plant-available P. This reinforces the need to fully explore the potential opportunity for legacy P to contribute to P sustainability consideration is needed for forms of P that are not as easily solubilised (such as: organic, strongly sorbed, precipitated, or occluded P).

Various strategies and technologies have been proposed to "unlock" soil legacy P stores including 1) cropping with no P inputs to promote soil P drawdown; 2) planting crops, including cover crops or genetically engineered crops to improve P use efficiency; 3) promoting soil microbial communities or applying soil amendments to solubilise stable P forms; 4) the recycling of legacy P from P-rich sediments or wetland soils; and 5) gypsum amendments to manage legacy P.

2.2.2.1 Legacy phosphorus drawdown through cropping

Soils with a history of intensive P inputs often exhibit high concentrations of "available" legacy P, as measured by agronomic P tests. Strategies to draw down these legacy P stores through reduced or no P inputs can sustain crops without yield penalty for multiple cropping seasons, depending on the degree of soil accumulation (Dodd et al., 2012; Johnston et al., 2016; Schulte et al., 2010). Thus, offsetting future P inputs in the short- to medium-term. However, economic concerns of yield loss and farm management factors that determine where, when, and how much P is applied, may limit the adoption of these practices (Chapter 6 of this thesis explores the motivations of UK farmers and land managers towards the planning and application of P to their land). Legacy P drawdown strategies in agricultural systems may require many decades of no P inputs to achieve lower P stocks in soil and water. This in part may be slowed down by the preferential plant uptake of mode labile P forms compared to more recalcitrant forms of legacy P

(Basílio et al., 2022); contributing to an increased risk to long-term crop production. The potential of legacy P to support crop production over extended timescales under no fertiliser or manure P input is explored further in Chapter 3 of this thesis.

2.2.2.2 Crop breeding and cover crops to improve phosphorus use efficiency

Plants vary in their capability to access, mobilise, and utilise P in soils with low P availability (White & Hammond, 2008). Plants can extend their root systems to "explore more of the soil"; they can release exudates to mobilise more stable forms of P (either directly or indirectly through the stimulation of microbial activity) (Lynch & Brown, 2008); and/or they can alter the stoichiometry of their biomass to alter the demand for P within the tissues (Güsewell, 2004). Arguably modern crop varieties have a low P use efficiency and have become reliant on the readily-available water-soluble P supplied by P fertiliser inputs, also known as "Fast Growing Lazy Crops" (Elser & Haygarth, 2020). Breeding more P-efficient plants that are able to access legacy P stores over an extended period will be an important step in achieving P sustainability (Manschadi et al., 2014).

There also is evidence to suggest that cover crops can be used to help main crops take advantage of legacy P, particularly in soils with low P availability. This is achieved through the accumulation of P in the cover crop biomass, from less-available P pools, and the subsequent mineralisation of the cover crop litter that provides available P for the main crop (Hallama et al., 2019).

2.2.2.3 Promoting soil microbial communities and the use of bio-inoculants

Microbial communities in the soil, particularly mycorrhizal fungi, are known to support and greatly enhance P mobilisation and plant uptake of P. This is achieved through the "extension" of the plant root system and the exudation of enzymes and organic acids that can mineralise organic P forms or breakdown mineral complexes to make the P available for plant uptake (Richardson et al., 2009). The adoption of no-till practices or the use of cover crops mixes can further promote diverse soil microbial communities (Hallama et al., 2019), while also having a positive influence on soil structure and soil cover, which can help to minimise soil and P losses to water (Sharpley et al., 2009). The application of soil amendments (also known as bio-stimulants or bio-inoculants) to agricultural land, including microbes, organic acids, and enzymes, has been explored as a means of increasing the mineralisation and solubilisation of legacy P for plant uptake (Owen et al., 2015; Stutter et al., 2012). While these methods have demonstrated promising results for the reduction of P fertiliser requirements, inconsistency in their efficacy remains a key limiting factor to widespread uptake (Mitter et al., 2021). This is likely due to the inherent complexity in the rhizosphere and interactions within soil microbial communities (Jones & Oburger, 2011).

As soil conditions evolve under varying land management practices, the composition of microbial communities also changes, affecting the acquisition of organic P in the soil (George et al., 2018). Despite decades of research into the agronomic and ecological importance of organic P and the influence of microbial communities for P utilisation, accurately quantifying its contribution remains a persistent challenge. Addressing this challenge will necessitate ongoing integrated and cross-disciplinary research efforts (George et al., 2018; Haygarth et al., 2018).

2.2.2.4 Recycling legacy phosphorus

At the farm-scale, ponds or lagoons can be efficient at trapping P from run-off and many contain large amounts of legacy P (Sharpley et al., 1989) which could ultimately become a source of legacy P to the wider catchment area if not managed. The accumulation of legacy P in wetland soils or aquatic sediments could therefore present a cost-effective opportunity for recycling legacy P to agricultural land; whereby P-rich sediments are extracted and applied to land in place of other P inputs, a concept of "Put the Land Back on the Land" (Canfield Jr et al., 2024). The recycling of legacy P in this way not only provides opportunity to offset P fertiliser inputs but may prevent future downstream negative impacts on water quality (Hille et al., 2019).

2.2.2.5 Gypsum amendments to manage legacy phosphorus

Gypsum amendments to soils have been shown to help manage legacy P in soils by reducing P losses (including particulate P and dissolved P) from agricultural fields and improving P uptake by plants. Gypsum has been shown to reduce P losses by promoting P adsorption, and calcium (Ca)-P precipitation, while also improving soil structure and ionic strength, without negatively impacting crop production (Ekholm et al., 2024; Ekholm et al., 2012). Field trials in Europe demonstrate significant reductions in P fluxes (up to 56%) but biogeochemical and management factors can influence its effectiveness (Murphy & Stevens, 2010). Gypsum can also support plant P uptake, likely by enhancing root growth through increased Ca availability (Cox & Jacinthe, 2023; Stout et al., 2003). Its ability to reduce P loss, and improve P availability to plants suggests that gypsum could be a promising amendment for managing legacy P in agricultural systems although its effects may be limited to fewer than three growing seasons, requiring repeat applications (Uusitalo et al., 2012).

2.2.3 Aligning the legacy phosphorus challenge and opportunity

Ultimately legacy P presents a long-lasting challenge to water quality in many catchments but also a potential opportunity for P sustainability. Although differing in their conceptualisation of how legacy P influences the surrounding environment, both views recognise the inherent lag between the P source-mobilisation-delivery-impact continuum and the extended timescales required to manage legacy P stocks (Haygarth et al., 2005). The development of models alongside empirical and inductive research could help to bridge this conceptual legacy P gap and make decisions that consider both plant productivity and water quality.

2.3 Modelling approaches for legacy phosphorus

2.3.1 Concepts of phosphorus modelling

From simple perceptual models to highly parameterised global-scale simulations, since the agronomic value of P fertilisers and manures were tested as part of the Classical Experiments started in 1843 at Rothamsted (Macdonald et al., 2018), models have been used to describe and predict P behaviour in crop, soil, and water systems. During this time the number and complexity of models simulating P processes has rapidly increased (Robson, 2014).

Rosbjerg & Madsen (2005) define a model as “a simplified description of nature developed or adjusted for a specific goal”. These models have helped to formalise our understanding of P processes and will be vital in identifying key knowledge or data gaps in empirical legacy P research (**Figure 2-2**). Research goals and data availability guide the selection and development

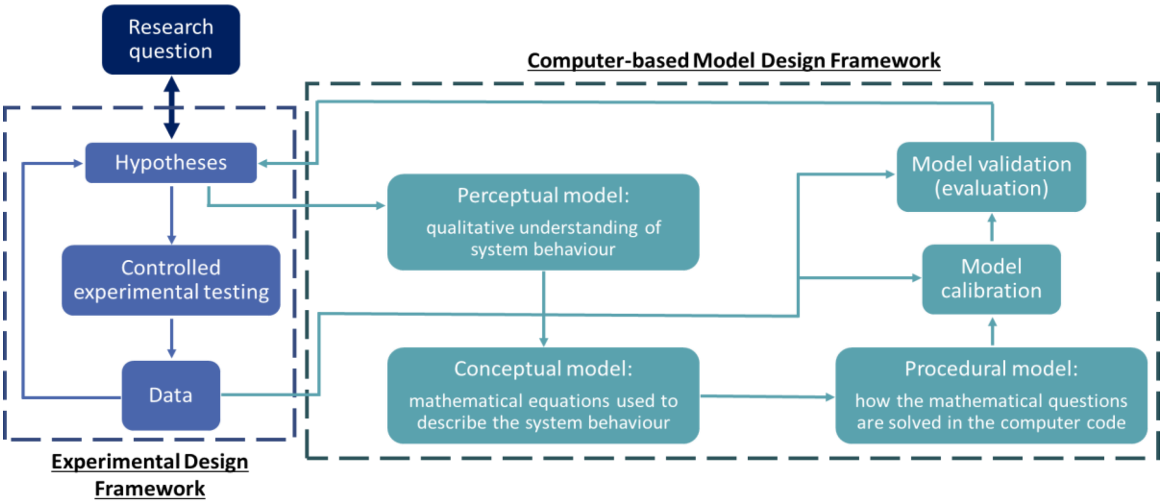

Figure 2-2: Generalised computer-based model development process and how this is integrated with the empirical experimental design framework as outlined by Krueger et al. (2007) and Vadas et al. (2013)

of models, with varying requirements depending on discipline and scale (Vadas et al., 2013). **Table 2-1** describes three common forms of modelling approaches, P balances, P budgets, P process-based models, that have been applied to legacy P management. The use and importance of these models could be considered analogous to the running of a business; such that knowing and understanding cash flows and operations are essential to managing a profitable business and so too is the knowledge and understanding of P flows and processes to global P sustainability.

Table 2-1: Different types of phosphorus (P) models, and analogies with business management

Phosphorus modelling	Business management
Phosphorus balance: focuses on the overall difference between a system's P inputs and outputs, indicates whether there is a surplus or deficit of P in a particular system (i.e. gives an insight as to whether P is accumulating or depleting over time in a given system).	Balance: overall company profits or losses over a given timescale.
Phosphorus budget model: an account or record of P input, outputs, and internal cycling within a system. Gives a more detailed overview of the overall flow of P via different pathways. Allows users to quantify different sources and sinks of P to highlight critical points in the system. Do not account for stocks of P already contained within the system.	Budget: the measurable flow of money between different departments or projects.
Phosphorus computer / process-based model: the use of mathematical representations to simulate P behaviour within a system. They typically go beyond simple budget accounting to capture interactions within systems and integrate various ecological processes (e.g. the role that C and N play in the cycling of P). Can also be used to predict how P will respond to changes in the system.	Company structure: The roles and work carried out by team members for the company, looks beyond the flow of money into the individual tasks or processes that are carried out that facilitate the flow of money within a company.

The heterogeneity of nature and the vast number of processes, both known and unknown, involved in P cycling, and the multiple motivations for developing P cycling insights, means that there will (probably) never be a single “universal” P model. As such, developers select the processes that are most important for describing the required outputs while ensuring the model is no more complex than necessary, the principle of parsimony (Smith & Smith, 2009). Understanding the question that is being asked or the decisions that are going to be informed by the modelled data is a critical step in selecting the most appropriate model.

Hydrological model development is typically guided by observed water quality data and rarely uses soil data for validation of the biogeochemical components of the model (Bouraoui & Dillaha, 2007; Chaubey et al., 2006; Lindström et al., 2010). Likewise biogeochemical modelling researchers will generally only use soil P data for model testing and validation (Janes-Bassett et al., 2020; Muhammed et al., 2018). This has perpetuated the divide between both modelling communities and could contribute to the legacy P debate. Bringing together biogeochemical and hydrological P model frameworks there is scope to address the “blind spots” of legacy P and to consider the best ways to develop future models that address the contemporary understanding of legacy P processes, integrating the needs of the crop with biogeochemical and hydrological modelling considerations.

2.3.2 Model development to address the blind spots of legacy phosphorus

The cycling of P in the soil and the delivery and impact of P entering the water as closely linked in the environment, so why do research questions and models limit their focus to just one aspect? Much work has been done to focus on improving understanding of P biogeochemical cycling and P transport, however this is not readily incorporated models (Menge et al., 2023). Most likely this is due to: 1) a disconnect between the empirical and modelling communities in research; 2) the complex nature of P cycling, particularly compared to C and N cycling; and 3) a lack of resources needed to devote to continuous model support and upgrading (Vadas et al., 2013). Frameworks for coupling P cycling and P transfer have been explored but this generally involves coupling or nesting existing models to accommodate changes in spatial and temporal scales.

As with the different views regarding legacy P, there is also a divide within modelling communities across the plant-soil biogeochemical cycles and soil-water quality / hydrological disciplines. Of those models that specialise on simulating and predicting P transfer from soil to watercourses (e.g. SWAT[5] (Chaubey et al., 2006), HYPE[6] (Lindström et al., 2010), GLEAMS[7] (Knisel & Davis, 2000), FARMSCOPER[8] (Gooday et al., 2015)), which typically aim to addresses water quality issues, can often neglect the cropping potential of legacy P. Of those that do represent crop uptake of P and soil dynamics in more detail (e.g. N14CP (Janes-Bassett et al., 2020), Roth-CNP (Muhammed et al., 2018), CASA-CNP (Wang et al., 2010), CENTURY (Metherell et al., 1993)), they generally do not address water quality issues.

Phosphorus routines in ecosystem models have been extensively reviewed (Lewis & Mcgechan, 2002; Pferdmenges et al., 2020; Reed et al., 2015) yet there are still knowledge gaps that could represent areas of potential model improvement.

2.3.2.1 Modelling legacy phosphorus spatial distribution and lag times

Phosphorus stocks in aquatic and terrestrial environments are highly variable temporally and spatially. Phosphorus is generally assumed to have low mobility in soils and sediments due to its propensity for strong adsorption to other particles and tendency to precipitate with metals in the soil (typically calcium, aluminium, and iron).

Within model development there is a need to be able to connect spatial grids, accounting for location and connectivity pathways (including slope and drainage) between different locations alongside lag times and P transformation processes (Nelson & Parsons, 2006). The possibility of connecting models in this way will allow hypothesis testing as part of a modelling framework to

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[5] Soil and Water Assessment Tool
[6] Hydrological Predictions for the Environment
[7] Groundwater Loading Effects of Agricultural Management Systems model
[8] Farm Scale Optimisation of Pollutant Emission Reductions framework

move from the plot scale to catchment scale. Hydrological models typically consider multiple pathways for P transport: groundwater and subsurface flow (particularly if there is artificial drainage), ground cover (including plant type and management practices); surface erosion and runoff (Bouraoui & Dillaha, 2007; Yuan et al., 2007). However, some of these can be difficult to measure so there is a need to find appropriate data that represents these factors (Easton et al., 2008).

Long-term monitoring data are essential for model development, the growing use of automated samplers, real-time remote sensing and machine learning / artificial intelligence have the potential to generate and analyse large data series (Drohan et al., 2019). These data can be used identify patterns between changing variables (such as soil moisture, temperature, nutrient content, rainfall intensity, etc.) and the mobilisation of P under different environmental conditions or in soils/sediments with different properties. When combined across the different disciplines (from soil science to limnology) big data could allow for more holistic models that consider the complex interactions between soil processes, plant growth, and water movement (Delgado et al., 2019). Thus, going some way to addressing the challenges posed by spatial distribution and variable and inconsistent lag times between P applications and eventual impact.

Integrating our understanding of legacy P and natural systems into models allows users to explore ideas (e.g. should different sorption algorithms be used at different modelling scales and how are these influenced by other soil properties?) and changes to the model in line with measured data. Modelling therefore facilitates the testing of hypotheses that could otherwise take years to test in the field (if they could be even tested at all). Integrated with this models are also a valuable tool to evaluate our empirical understanding of legacy P, identify knowledge gaps, generate ideas for experiments and establish a basis for model uncertainty (Vadas et al., 2013).

2.3.2.2 Speciation and (bio)availability of legacy phosphorus

Conceptually, legacy P is relatively easy to define, however in biogeochemical terms it is much harder to define what this store of P is in different environmental systems; and how it transitions between different forms after the initial P input (Doydora et al., 2020; Margenot et al., 2024). Understanding these changes will be critical for minimising the environmental risk and maximising the potential of legacy P stores (Rowe et al., 2016).

Phosphorus modelling in soils and water is generally conceptualised as a series of organic and inorganic pools. The number of pools and the turnover processes and rates between these pools varies between models but are largely based on the P conceptualisation as described by Jones et al (1984). While models may offer only minor modifications to the cycling of P in their routines or the data sources used to make assumptions, cumulatively this can lead to very different sizes of P pools in the simulation (Rothwell et al., 2022; Wang et al., 2020). This will ultimately influence the amount of P that is mobilised for plant uptake or transport.

This is particularly important for the representation of organic P forms. Despite their widespread occurrence in soils, the role of organic P in P cycling and P pollution of watercourses remains poorly understood (George et al., 2018). To date very few (if any) models simulate specific speciation of the different P forms in the soils. For some models, speciation in the organic P pools is implied based on fixed decomposition and mineralisation rates between the fast, slow (and passive) pools (Janes-Bassett et al., 2020; Muhammed et al., 2018; Wu et al., 2007). This, however, often fails to capture the role and complexity of microbial communities for P cycling (Achat et al., 2016; Janes-Bassett et al., 2020).

As with all model development the availability and quality of data is essential to its accuracy. “Available” P (as measured by tests such as; Olsen-P, Morgan’s-P, Mehlich-3) is commonly measured in agricultural systems and can be used to inform data inputs for model parameterisation and calibration. While there is some correlation with total soil P, the term “available P” is arguably a functional concept, influenced by a large number of biotic and abiotic factors, rather than a direct soil P measurement (Tiessen & Moir, 1993). To understand and model P, the kinetics of P exchange processes between different forms need to be quantified (Reed et al., 2015). Various techniques are available to address these challenges.

Sequential extractions, typically the Hedley fractionation method (Hedley et al., 1982),[9] has been used as tool to examine different forms of P in soils, providing an assessment of the relative availability of P in soils (Johnson et al., 2003; Yang & Post, 2011). They can also from the basis for modelling soil P dynamics (Yang et al., 2013) allowing for a more accurate representation of labile and stable P pools. Spectroscopic techniques such as nuclear magnetic resonance (NMR), X-ray absorption near-edge structure (XANES) and Fourier transform infrared (FTIR) spectroscopy take this further and have become increasingly used to provide more specific information about P speciation in soils and sediments (Kizewski et al., 2011). The main drawback to these techniques, however, is that the complexity and time required to analyse samples means that they are not common practice and having enough data to employ model testing and validation remains a challenge. Continued advancement in these techniques and when used in combination with P exchange techniques can provide a link between conceptualised P pools and P species to estimate turnover times under different conditions (Helfenstein et al., 2018). This could allow representations of P mobilisation and transformation in the environment to be translated into common model parameters and allow for a more dynamic approach to P modelling, particularly surrounding the cycling of organic P.

2.3.2.3 Modelling frameworks to allow system flexibility

The use of empirical data to initialise and validate model simulations generally fails to represent much of the natural environmental heterogeneity as measurement methods generally capture data at a specific point in time and in a specific location, for example soil or water P tests, soil moisture content, etc. Often the mechanistic approach to model P in the environment, while allowing for more simplistic model development may also not take into account more subtle changes. For example, using fixed stoichiometric ratios for plant growth may lead to overestimation of growth limitations and underestimations of nutrient use efficiency (Achat et al., 2016). Using simplified P extraction coefficients relating measurements of soil P to dissolved P concentrations in runoff

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[9] Labile and stable inorganic and organic P is extracted from samples using sequentially stronger extracting agents.

often also fails to include measures of other soil properties such as soil texture or metal content (Radcliffe et al., 2009). Additionally, while some models account for soil texture in their representation of P cycling and transfer (e.g. the CENTURY model; Metherell et al., 1993), most models assume a good soil structure (i.e., porous structure with small aggregates, no compaction). However, as approximately 40% of UK arable and grassland areas are at risk of soil compaction[10] (Graves et al., 2015). Allowing for poor soil structure in field scale models could give a better representation of P losses and plant uptake.

Being able to account for spatial and temporal variations within models remains a challenge as often the effects of these can be difficult to measure and/or de-couple their effects from other factors and processes (so called “equifinality”) (Beven & Freer, 2001). Model complexity therefore involves a trade-off between highly parameterized models with a good fit for measured data but limited applicability; and simpler models applicable to a wider range of scenarios but accounting for less environmental heterogeneity (Rosbjerg & Madsen, 2005).

Pferdmenges et al. (2020) suggest the development of a modelling framework that offers a modular approach representing varying complexities across different spatial and temporal scales, allowing users choice in the processes that are most important to the system of study and that could be used to compare and test different hypotheses. However, this would need consistent sampling and measuring techniques and data validation across all modules.

To meet the requirements of end-users, research efforts need to shift towards developing models that are based on expert knowledge but remain simple to use and easy to apply (Heathwaite, 2003). This statement should act as a reminder that modelling and field trials should be as coupled as the biogeochemical and hydrological processes that they are trying to represent.

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[10] Soil compaction is not only related to soil type and land use, but also to soil moisture, weather patterns, and in particular land management practices, including agricultural machinery traffic and animal stocking densities (Graves et al., 2015)

2.3.3 Legacy phosphorus modelling for informing policy decision

Crossing disciplinary boundaries from agronomy to biogeochemistry and hydrology; whether a model is used to influence national agricultural policy or used in the field by a farmer; their application can have real-world environmental, crop yield and economic impacts. Policymakers and environmental managers face difficulties in enforcing and designing effective mitigation strategies without clear temporal connections between P sources and impacts.

Significant barriers to achieving sustainability goals often arise from the disconnects between academic research and industry practices (Dwivedi et al., 2024). As part of this, having consistency in terminology between academic literature, policymakers, and industry is important. This review has already identified disconnects between modelling communities as well as two possible ways that legacy P can be viewed / defined in the scientific literature. Yet these do not necessarily take into account the perceptions of the wider industry. Chapter 6 of this thesis explores how a farmer-led definition of legacy P encompasses some of these views and where their definition may have diverged from the views represented here.

To effectively address legacy P management, it is crucial to integrate scientific understanding with practical farming practices. Farmers must be equipped with reliable tools that translate complex biogeochemical processes into actionable strategies. Arguably therefore, reliable P models, capable of running long-term scenarios, with regular updates to reflect ongoing empirical progress, will be essential for informing, and ultimately determining the success of, agricultural policy changes surrounding legacy P management (Vadas et al., 2013). These models must not only accurately predict P dynamics but also provide outputs that are accessible to farmers. By demonstrating tangible benefits and ease of integration into existing practices, such models could promote wider adoption of different mitigation practices among the farming community, ensuring that policy shifts are both effective and sustainable in the long run.

2.4 Conclusion

This review has demonstrated the multi-scaled and interdisciplinary nature of the past, present and future of P management. Key unifying concepts in the legacy P debate for crop productivity and water quality in the wider environment are: the (bio)availability or speciation of P; the variability and inconsistency in lag time between P source and impact, and the connectivity pathways between P source and impact. Mitigating the negative impact of water quality and realising the potential of legacy P will require an interdisciplinary approach including engagement between the academic research groups and the wider industry. Overall, this chapter has presented the evidence that legacy P can be both a potential resource for crop production and an environmental challenge for water quality.

Arguably to make decisions that consider both plant productivity and water quality will require a deeper understanding of P flows and processes in the environment. Models have the potential to reveal the blind spots in legacy P management but the disconnects between the modelling communities and empirical scientists need to be addressed. This will ultimately help to ensure that outcomes are directly relevant to the environment and stakeholders involved.

2.5 Acknowledgements

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- Margenot, et al. (in press). Legacy phosphorus in the Anthropogenic phosphorus cycle. *Nature Reviews Earth & Environment*
- Shober, et al. (2024). Towards a transdisciplinary and unifying definition of legacy phosphorus. *Journal of Environmental Quality*

3 Exploring the potential of soil legacy phosphorus to maintain long-term productivity under reduced fertiliser inputs: a modelling study using the grassland and winter wheat Long-term Experiments at Rothamsted Research, UK

3.1 Introduction

Phosphorus (P) is essential for all crop production and is one of the major nutrients defined in UK nutrient management regulations for crop production (AHDB, 2020a). Phosphorus has also been highlighted as a potential "agricultural pollutant" in the UK and its management on agricultural land is defined under UK legislation for water quality ("The Reduction and Prevention of Agricultural Diffuse Pollution (England)," 2018). The widespread introduction of P fertilisers following the Green Revolution in the 1950s, has meant that many cropping systems have received P inputs to meet yield demands. While application rates of P fertiliser in the UK have been declining since the early 1970s (FAO, 2021), greater global demand for mineral P fertiliser is increasing pressure on P supply sustainability and pollution concerns (Zou et al., 2022). The quantity and timing of the application of P, in the form of fertilisers, manures and wastes, in agroecosystems can also increase the potential of P mobilisation and transfer from soils to watercourses via surface and sub-surface pathways with serious consequences for water quality and ecology (Haygarth et al., 2005; Mekonnen & Hoekstra, 2018; Stackpoole et al., 2019; Withers & Bowes, 2018). Although recent discoveries of phosphate rock reserves in Norway could alleviate some of the supply pressure (IBU-tec, 2022), arguably this should not take away from efforts to reduce reliance on P fertiliser inputs to manage the environmental impact of P.

Phosphorus transfer from agricultural soils to water is predicted to increase by up to 30% by 2050s in response to climate change and the intensification of agricultural food production (Ockenden et al., 2017). UK farming policy and agri-environment schemes have implemented various land management strategies to reduce diffuse P pollution, from buffer strips to cover cropping. However, improvement of water quality at the catchment scale has been smaller and slower to respond than expected (Jarvie, Sharpley, Withers, et al., 2013; Sharpley et al., 2013) perhaps because of a legacy of past management practices and complex P release processes in catchments and watercourses (Jarvie, Sharpley, Spears, et al., 2013). As such, the agricultural industry will require large-scale changes to its fertiliser and manure management practices (Powers et al., 2016), potentially reducing P inputs by up to 80% (Ockenden et al., 2017), to reduce P pollution of watercourses in the future.

Phosphorus cycling in soils is complex, controlled by a range of physical, chemical, and biological factors. Most of the P from newly applied fertilisers and recycled in manures (approximately 71%) is supplied in a readily available inorganic water-soluble form (Darch et al., 2014). However, depending on the soil type, its condition and pH, it is estimated that typically less than 8% of P applied as fertilisers or manures is recovered by the current crop (Richards, 2019). The remainder is either lost from the soil system or retained in the soil in forms that are otherwise only sparingly available to plants, e.g. adsorbed to soil particles and organic matter, taken up by microbes, or organically complexed (Darch et al., 2014). Sorption and desorption processes are two of the main factors that control the availability of P in the soil for plant uptake, particularly following fertiliser applications (Pierzynski et al., 2005). Most research to date exploring P recovery in soil has considered only the interaction of inorganic orthophosphates with soil particles and the ability of soils to replenish these ions when removed by plants (Syers et al., 2008). Yet up to 90% of the P in the soil may be incorporated into organic compounds (Stutter et al., 2012) and must be mineralised before becoming plant available. The balance between the mineralisation and immobilisation of P is partly influenced by the C storage in the soil organic matter and the immobilisation of N, likely due to the relationship between C and N with microbial activity (Chen et al., 2003; Makino et al., 2003). Thresholds of C:P ratios in soils (and the addition of organic materials) have been used to predict the dominant biological processes influencing immobilisation and mineralisation (Generose Nziguheba & Else K Bünemann, 2005).

Agricultural strategies in many parts of the world have focused on applying P fertiliser in excess of crop requirement to ensure plant-optimum P concentrations in soil solution; overcome potential inefficient crop uptake; and maintain yields (Bindraban et al., 2020; Roberts & Johnston, 2015; Withers et al., 2014). Indeed, surplus P applied to agricultural land in the UK between 2000 and 2019 amounted to almost 150 kg P ha^{-1} (Defra, 2020c). Across Europe the cumulative applied P exceeded cumulative P uptake by crops by more than 755 kg P ha^{-1} between 1695-2007 and globally it is estimated that less than half the applied P in this time was taken up by harvested crops (Sattari et al., 2012). Over time the excess P has accumulated in the soil and has contributed to the eutrophication of surface waters because it is vulnerable to both leaching and loss by erosion (Condron, 2004; Kleinman et al., 2011; Withers & Bowes, 2018). However, this legacy P could also represent a reserve that has the potential to offset fertiliser P inputs and maintain long-term crop productivity (Rowe et al., 2016; Stutter et al., 2012), with some estimates suggesting that global P fertiliser use in 2050 could be up to 50% less than previously predicted when the role of legacy P for crop production is considered (Sattari et al., 2012; Stutter et al., 2012). A key barrier to simply reducing or stopping P inputs to agricultural land is uncertainty around the impact this would have on crop yields and a lack of understanding about how long it could take before the reduced availability of P in the soil limits production (Margenot et al., 2024).

Exploring and modelling P cycling processes within agricultural soils can help us increase our understanding of how soils and crops will respond to reduced P inputs (Haygarth et al., 2014). Since the mid-19th century, models have been used to describe and predict P behaviour in crop, soil, and water systems (AHDB, 2020d; Macdonald et al., 2018). These models have helped to formalise our understanding of P processes and identify key process knowledge or data gaps in P research. This approach offers a valuable opportunity to understand biogeochemical responses to P management changes (integrated with carbon (C) and nitrogen (N) cycling) that typically occur on multi-decadal timescales (Davies et al., 2016b; Janes-Bassett et al., 2020). Yet, few integrated C, N and P nutrient modelling studies have explored the impacts of P limitations on long-term agricultural productivity. Combining model simulations with empirical data from long-term agricultural (cereal and permanent grassland) experiments could improve our empirical understanding of how crops react to changes in nutrient management (Dungait et al., 2012) and challenge the historical philosophy of prophylactic P fertiliser management (Withers et al., 2014).

The aim of this chapter is to investigate the length of time that agricultural crops and grassland yields can be maintained using legacy soil P, using the biogeochemical model N14CP and empirical data. The model is used to simulate two plots that are part of the long-term agricultural experiments, the Broadbalk continuous wheat experiment and the Park Grass permanent grassland experiments, at Rothamsted Research, Harpenden, UK. Comparing the modelled outputs with measured data will provide a grounded modelling test bed for the following hypotheses: i) soil legacy P stocks will sustain modelled productivity for a finite period of time post-reduction of P fertiliser inputs[11]; ii) the length of time that productivity will supported will be dependent on the history of fertiliser use on the site; and iii) soils that have a longer history of high P fertiliser use, in excess of crop offtake, will have greater modelled soil total P (TP), thus larger potential P stores, at the start of the simulation period and as such will be able to

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[11] acceptable declines in productivity based on inter-annual variations in yield.

sustain productivity for longer. This study aims to provide useful insight to help challenge the mindset that crops need annual inputs of P to maintain yield and that by considering the total soil P stocks, rather than the "available" soil P, management decisions could be made meaning legacy P stores benefit production for many years.

3.2 Methods

3.2.1 The N14CP Model

The approach used the N14CP model, a dynamic, process-based soil biogeochemistry model, originally developed to simulate long-term soil organic carbon (SOC; including radiocarbon (^{14}C) dynamics), N and P cycling in temperate, semi-natural environments (Davies et al., 2016a; Tipping et al., 2012). The model was then extended to include agricultural environments, arable (cereals, root crops, legumes, and oilseed crops) and improved grassland; and agricultural management practices, such as tillage, grazing and fertiliser use (Janes-Bassett et al., 2020). N14CP has been rigorously tested both temporally and spatially using data relating to plant, soil, and dissolved forms of C, N and P from 82 natural sites across Northern Europe (Davies et al., 2016a), surveys containing >1000 datapoints across the UK (Janes-Bassett & et al., 2021; Tipping et al., 2019; Tipping et al., 2017), and 62 long term agricultural plots from 11 experimental sites across the UK and Northern Europe (Janes-Bassett et al., 2020).

The approach uses the P cycling processes of the model to investigate the long-term role of legacy P in providing agronomically sufficient P to grassland and cereal cropping systems in response to future P fertiliser management changes. Acceptable thresholds for productivity decline resulting from reduced P fertilizer inputs and the associated soil P limitation for plant growth will be established by referencing historical inter-annual variations in yield. This study will use the N14CP version developed by Janes-Bassett et al. (2020) to simulate and predict plant productivity with varying P fertiliser inputs on a cereal and an improved grassland site.

3.2.1.1 N14CP model processes

N14CP is designed to be driven by readily available input data. Simulations are spun up from the onset of the Holocene (10 000 BP in the model) and for each specified land use and/or plant functional type, N14CP uses a quarterly timestep[12] to simulate biogeochemical processes in soils (topsoil[13] and subsoil layers) and total vegetation biomass. Land use management for agricultural systems and nutrient inputs and outputs are defined either quarterly or annually, depending on the management practice[14]. A full model description can be found in Janes-Bassett et al. (2020) and Davies et al. (2016a); however, a summary of the P representation in the model is given here.

N14CP simulates net primary productivity (NPP) assuming Liebig's law of minimum (controlled by the most limiting factor of temperature, precipitation, available N, or available P). The nutrient availability is modified to consider the plant functional types and agricultural management practices, such as fertiliser additions and tillage. Harvested crop yield is then estimated based on simulated NPP, the above-ground biomass fraction, the carbon content of the dry matter, and the fraction of biomass removed during harvest. Phosphorus offtake is calculated based on the C:N:P stoichiometry of the harvested crops. There are four main P inputs to the N14CP model, weathering of the parent material, litter returned as plant residues or excrement from grazing livestock, atmospheric deposition, and P fertiliser additions (**Figure 3-1**). Phosphorus stores and fluxes are represented via interconnected inorganic and organic pools; coupled by C and N stoichiometric controls, undergoing several non-linear first-order rate constants (**Figure 3-1**). Two biomass P pools (coarse and fine) are linked to the C and N pools with literature-defined C:N:P stoichiometries given for each plant functional type[15]. Soil

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[12] The quarterly timestep is approximately aligned with the four seasons (Quarter 1: January, February, March. Quarter 2: April, May, June. Quarter 3: July, August, September. Quarter 4: October, November, December).

[13] Upper 15 cm of soil

[14] Total fertiliser input is specified annually. However, where modelled fertiliser application is split over two quarters (Q2 and Q3) half of the total amount fertiliser is applied in each quarter.

[15] For agricultural plant functional types, plant uptake of C, N, and P is all assumed to enter the fine biomass pool.

organic P (SOP) in the topsoil is compartmentalised into three pools: fast, slow, and passive, a second SOP pool is simulated in the subsoil, which has one compartment. Mineralisation of SOP is simulated alongside C and N and is characterised by a temperature- and pH-regulated first-order rate constant, with differing turnover rates for each soil organic matter pool. The immobilisation of P is regulated by the C storage in the fast, slow and passive compartments of the soil organic matter and is conditional upon the current C:P ratio. An upper and lower C:P limit control the extent of immobilisation, below which no immobilisation takes place and above which immobilisation is not constrained by C:P. A proportionality constant is also applied to P immobilisation that relates it to the N immobilisation rate constant.

In addition to P simulated within the organic pools, a pool representing inorganic P adsorbed to soil surfaces is simulated in both the topsoil and subsoil. Sorption and desorption of inorganic P are determined by first order rate constants that relate the topsoil P sorbed pool to the dissolved excess inorganic P following growth. Finally, P loss from the topsoil is represented

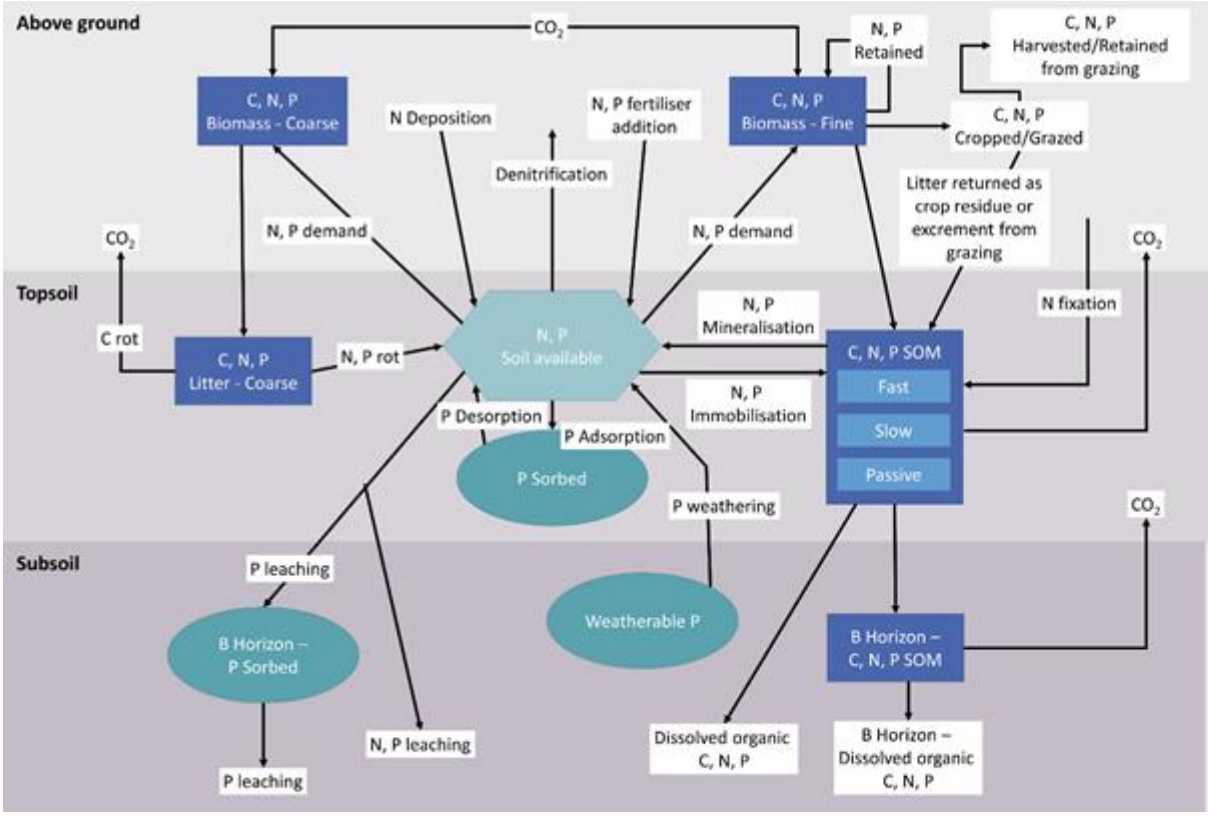

Figure 3-1: Schematic of N14CP model including the nutrient (carbon (C) / nitrogen (N) / phosphorus (P)) pools, and processes simulated (Janes-Bassett et al., 2020).

by leaching of inorganic P (that remains after plant uptake, immobilisation, and sorption) and loss of dissolved organic P. Some of this P accumulates in the subsoil before a fraction is subsequently leached.

3.2.2 Site data for model testing

Observed data for crop yield, soil C, and soil N stocks were collated from two long-term agricultural experimental sites based at Rothamsted Research, Harpenden, UK (Macdonald et al., 2018; Rothamsted-Res, 2020a, 2020b). The sites were selected to include one tilled arable site (continuous wheat crop, Broadbalk experimental Section 1 Plot 8) and one non-tilled improved permanent grassland site (Park Grass experimental plot 9/2b) with similar fertiliser management histories. Both sites have a long-term history of annual fertiliser inputs (**Table 3-1** and **Table 3-2**). Soils on these sites are described as moderately well drained silty clay loam over clay-with-flints or chalk and are classified as Chromic Luvisol (F.A.O.) or Aquic Paleudalf (U.S.D.A.) (Macdonald et al., 2018; Silvertown et al., 2006).

Table 3-1: Broadbalk experimental Section 1 Plot 8 historic fertiliser (nitrogen (N), phosphorus (P), potassium (K), sodium (Na), and magnesium (Mg)) treatments. Land use: arable, continuous winter wheat (Macdonald et al., 2018)

Years	Annual N Application rate (g N m^{-2} yr^{-1})	Annual P Application rate (g P m^{-2} yr^{-1})[a]	Annual K Application rate (g K m^{-2} yr^{-1})[b]	Annual Na Application rate (g Na m^{-2} yr^{-1})[c]	Annual Mg Application rate (g Mg m^{-2} yr^{-1})
1852-1967	14.4 [d]	3.5 [e]	9.0	1.6	1.1 [f]
1968-1984	14.4 [g]	3.5	9.0	1.6 / 0.0 [h]	1.1 / 3.5 [i]
1985-2000	14.4 [j]	3.5	9.0	0.0	3.5 [k]
2001-2020	14.4	0.0	9.0	0.0	1.2 [l]

[a] Applied as triple superphosphate
[b] Applied as potassium sulphate
[c] Applied as sodium sulphate
[d] Applied as ammonium sulphate
[e] Equivalent to 35 kg P ha-1 yr-1
[f] Applied as magnesium sulphate
[g] Applied as calcium ammonium nitrate
[h] 16 kg Na applied until 1973. No Na applied from 1974-1984
[i] 11 kg Mg applied as magnesium sulphate until 1973. 35 kg Mg applied as Kieserite every 3rd year from 1974
[j] Applied as ammonium nitrate since 1986
[k] Applied as Kieserite every 3rd year
[l] Applied as Kieserite

Broadbalk Section 1 Plot 8 (**Table 3-1**) has been managed for continuous winter wheat production since 1852 and has received annual fertiliser inputs, including 3.5 g P m^{-2} yr^{-1}

(equivalent to 35 kg P ha^{-1} yr^{-1}). Liming practices on this plot have been managed to maintain soil pH at a level which crop yield is not limited (Macdonald et al., 2018). From 2001 to 2021 the plot has received no applications of phosphate fertiliser in line with crop recommendations and soil concentrations of plant-available P (AHDB, 2020d; Macdonald et al., 2018).

Park Grass plot 9/2b (**Table 3-2**) has been managed experimentally as permanent grassland since 1856 and received annual fertiliser inputs, including 3.5 g P m^{-2} yr^{-1} (equivalent to 35 kg P ha^{-1} yr^{-1}), from 1856-2016. This plot has been managed with the application of agricultural lime to maintain a pH of 6. From 2017 to 2021 the plot has received half the previous application rate of phosphate fertiliser in line with crop recommendations and soil concentrations of plant-available P (AHDB, 2020d; Macdonald et al., 2018).

Table 3-2: Park Grass experimental Plot 9/2b historic fertiliser (nitrogen (N), phosphorus (P), potassium (K), sodium (Na), and magnesium (Mg)) treatments. Land use: permanent grassland (Macdonald et al., 2018)

Years	**Annual N Application rate (g N m^{-2} yr^{-1}) [a]**	**Annual P Application rate (g P m^{-2} yr^{-1}) [b]**	**Annual K Application rate (g K m^{-2} yr^{-1}) [c]**	**Annual Na Application rate (g Na m^{-2} yr^{-1}) [d]**	**Annual Mg Application rate (g Mg m^{-2} yr^{-1}) [e]**
1856-1874 [f]	9.6	3.5	22.5	1.5	1.0
1875-1959 [g]	9.6	3.5	22.5	1.5	1.0
1960-2016 [h]	9.6	3.5	22.5	1.5	1.0
2017-2020	9.6	1.7	22.5	1.5	1.0

[a] Applied as ammonium sulphate

[b] Applied as triple superphosphate

[c] Applied as potassium sulphate

[d] Applied as sodium sulphate

[e] Applied as magnesium sulphate

[f] Plots harvested for hay in June / July and the re-growth grazed by sheep

[g] Plots harvested for hay in June / July, a second cut then taken September / October

[h] Since 1960 yields have been estimated from strips cut with a forage harvester – simulated fraction of biomass removed during harvest increased from 19% to 38%.

3.2.3 Experimental fertiliser application rates

To explore how fertiliser management history influences the build-up of legacy soil P, alternative management histories were created for each of the sites (**Table 3-3**) based on observed site management during the long-term experiments. P fertiliser inputs starting in the mid-1800s ranged from 2.0 to 5.0 g P m^{-2} yr^{-1}. N14CP was then run to give the modelled total soil P at the start of the simulation period for each of the sites (**Table 3-3**).

The simulation period for the arable and grassland plots were set to 2001-2500 and 2017-2500 respectively. This commencement of the simulation period is based on the observed P management of the plots and aligns with when the long-term P management at the sites changed (**Table 3-4**). Simulations were extended to 2500 to ensure that yield responses could be seen, particularly for simulations with the greatest soil P reserves. Preliminary simulations to earlier years did not allow enough time to see significant changes in yields under some of the P management scenarios. For the simulation periods, annual P inputs were modelled at four different rates for both the arable and grassland plots (**Table 3-4**). Standard P (Std P) rates were used based on the fertiliser history of the plots. For the arable simulation, P fertiliser inputs were set to pre 2001 rates at 3.5 g P m^{-2} yr^{-1} (equivalent to 35 kg P ha^{-a} yr^{-1}), and for the grassland simulation, P fertiliser inputs were returned to pre 2017 rates also at 3.5 g P m^{-2} yr^{-1}. Phosphorus fertiliser application rates were then reduced by half (Half P) and 80% (Fifth P) compared to Std P inputs, 1.7 g P m^{-2} yr^{-1} and 0.7 g P m^{-2} yr^{-1}, respectively. Finally, the model was used to test the effect of no P additions (No P) for both the arable and grassland sites.

Table 3-3: Modified phosphorus (P) management histories for the grassland and arable sites with the modelled total soil phosphorus at the start of the simulation period.

Historical annual P application rate (g P m^{-2} yr^{-1}) [a]	Modelled total soil P at start of simulation period (g P m^{-2}) [b] Arable	Grassland
2.0	36	135
2.5	105	208
3.0	178	281
3.5 [c]	251	355
4.0	323	429
4.5	396	503
5.0	467	577

[a.] Wheat, 1852-2000; grassland, 1856-2016

[b.] Wheat, 2000; grassland, 2016

[c.] Standard historical application rate, equivalent to 35 kg P ha^{-1} yr^{-1}

Table 3-4: Annual phosphorus (P) input treatments during the simulation period for both the arable and grassland sites

P treatment	Description	Annual P Application rate for simulation period (g P m^{-2} yr^{-1}) [a]
Std P	P additions applied at the standard rate based on the observed site history	3.5 [b]
Half P	P additions applied at 50% of the standard rate	1.7
Fifth P	P additions applied at 20% of the standard rate	0.7
No P	P additions stopped	0.0

[a] Simulation period: arable, 2001-2500; grassland, 2017-2500

[b] Equivalent to 35 kg P ha-1 yr-1

Input driver data include climate (quarterly temperature and precipitation), geology (underlying weathered rock P content), atmospheric deposition (N, P, sulphur, 14C and base cation), plant functional type history and land management history. To set up the contemporary model C, N and P stocks (10,000 BP to present) and future model scenarios, input driver data, were determined for each site using data available in the literature and as defined by Janes-Bassett et al. (2020). Climate data for the simulation periods (2001 / 2016 to 2500) were based on 30-year mean quarterly temperature and precipitation, the effect of climate change on soil P cycling and crop yield was not within the scope of this study. Land use inputs pre-1850's were based on literature sources as defined by Janes Bassett et al. (2020).

From 1850's to present, tillage and harvesting agricultural management practices were based on field management records held by Rothamsted Research (Poulton & Glendining, 2023; Rothamsted_Research, 2021). Land management dates provided by Rothamsted Research generally aligned with the N14CP "seasons" (based on the quarterly timestep, aligned with the months of the year). However, some adjustments were necessary for the fertiliser application, harvest, and tillage seasons in certain instances (**Table 3-5**). This modification was required as N14CP, does not simulate plant growth during the first and fourth quarters. The simulations extending beyond 2020 adhere to the prevailing tillage and harvesting practices established over the preceding four decades, ensuring continuity with the most widely adopted management approaches.

Yield, soil C, soil N stocks, and soil P stocks (inorganic P and organic P) were extracted from the outputs of each of the model runs during the simulation period. Data were used to calculate the number of years before yield was reduced by more than 25% and 35% for arable and grassland plots, respectively using yield at the start of the simulation periods as a baseline. A 25% or 35% yield reduction was used based on observed average yield fluctuations from 1970 to 2018[16]. Modelled outputs from both the arable and permanent grassland plot were also compared against observed data from the Broadbalk site for between 1970 – 2018 analysing yield, soil C and soil N stocks in MATLAB[17]. These data were used as they coincide with P fertiliser management changes on the experimental plots. This was an exploration of how the model performs in predicting crop production in the short-term.

Table 3-5: Standard N14CP quarterly timestep seasons and N14CP data input adjustments made for fertiliser application, harvest, and tillage seasons in line with land management dates provided by Rothamsted Research (Poulton & Glendining, 2023; Rothamsted_Research, 2021)

N14CP seasonal quarters	Corresponding N14CP Months	Amended N14CP months for data input		
		Tillage input date	Fertiliser input date	Harvest input date
Q1	January February March	January February March	January February	N/A
Q2	April May June	April May June	March April May June	April May June July
Q3	July August September	July August September October	July August September	August September October
Q4	October November December	November December	October November December	November December January February March

3.2.4 Uncertainty analysis

To explore model output uncertainty for each site under the different P histories and treatments an uncertainty analysis was carried out on four model parameters, f_{Psorb}, $f_{Pdesorb}$, $[C{:}P]_{lower}$, and $k_{immobP:N}$ (**Table 3-6**). A sensitivity analysis of these parameters performed by Davies et al. (2016a) were shown to have the most influence on the outputs for P pools, inorganic P flux, dissolved organic P and NPP in N14CP. To explore these parameters a search (using 100 simulations) was made using a Latin Hypercube Sampling scheme to cover the parameter space. The search boundaries for the parameter values for f_{Psorb}, $f_{Pdesorb}$, were set based on the range

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[16] Arable: mean dry matter grain yield 1970-2018, 476.87 ± 101.00 g m^{-2}. Grassland: mean dry matter yield 1970-2018, 318.9 ± 117.74 g m^{-2} (Rothamsted-Res, 2020a, 2020b)

[17] Soil total P was not measured on these Plots

from 50 localised searches and a reduced globalised search as described by Davies et al (2016a). Boundary values for $[C\!:\!P]_{lower}$, and $k_{immobP:N}$ were set at ±25% of the standard parameter value for N14CP to effectively explore parameter uncertainty while balancing computational demand.

Table 3-6: Model parameter values set within the uncertainty analysis.

Parameter	Description	Standard model parameter set value	Uncertainty analysis parameter range
f_{Psorb}	Factor controlling sorption of inorganic P to soil surfaces	0.97	0.90-0.99
$f_{Pdesorb}$	Factor controlling desorption of inorganic P from soil surfaces	0.005	0.004-0.01
$[C\!:\!P]_{lower}$	C:P lower limit on immobilization restriction of P into SOM	100	75-125
$k_{immobP:N}$	Proportionality constant between P immobilization rate constant and N immobilization rate constant(s).	8.58	6.44-10.73

3.3 Results

3.3.1 Observed and simulated yield and soil organic carbon and soil nitrogen data

Observed yield data from the Broadbalk continuous wheat Plot 8 and the Park Grass permanent grassland Plot 9/2b for 1970 – 2018 show annual fluctuations, which are not generally as pronounced in the simulated data (**Figure 3-2**[18]). Observed data on the Broadbalk plot demonstrate a slight but non-significant (f(1) = 1.09, p = 0.30) decline in yields since 1970 and no significant change in yield since 2000, when P inputs were stopped (f(1) = 0.39, p = 0.54; **Figure 3-2**). Similarly, observed data on the Park Grass plot indicated a small but non-significant decrease in observed yield since 1970 (f(1) = 11.94, p = 0.17).

Looking at the short term model performance for the grassland simulations compared to the Park Grass observed data, results indicate that modelled grassland yields (M = 974 g m^{-2} yr^{-1},

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[18] A simulated drop in yield in 1974 on the continuous wheat site was a result of a later tillage season to reflect site management practices for that year. Simulated yield drops in 2003 and 2020 on the grassland site were a result of a modelled single annual harvest to reflect site management practices for that year; for other years, two harvests were taken from the plot.

SD = 97.02), are significantly greater than observed yields (M = 753.26 g m^{-2} yr^{-1}, SD = 144.57); t(48) = 8.84, p < 0.001; **Figure 3-2**). In contrast, comparing the outputs from the arable simulation with the Broadbalk observed data, modelled wheat yields (M = 333 g m^{-2} yr^{-1}, SD = 10.51) are significantly less than observed yields (M = 476.87 g m^{-2} yr^{-1}, SD = 101.00; t(48) = 9.95, p < 0.001; **Figure 3-2**). Modelled yields are within approximately 30% and 22% of observed wheat and grassland yields respectively.

In addition to yield data, SOC stocks have been measured periodically, on both Broadbalk continuous wheat Plot 8 and the Park Grass permanent grassland Plot 9/2b since the start of the long-term experiments. Outputs from N14CP suggest that modelled SOC for the arable site (M = 2545 g m^{-2}, SD = 49.2), is significantly greater than observed data (M = 2086 g m^{-2}, SD = 130.8; t(11) = 11.4, p < 0.001; **Figure 3-3**), although modelled SOC stocks are estimated to within 18% of observed SOC data and are within the bounds of the uncertainty analysis. On the other hand there is no significant difference (t(5) = 1.9, p = 0.11) between the grassland

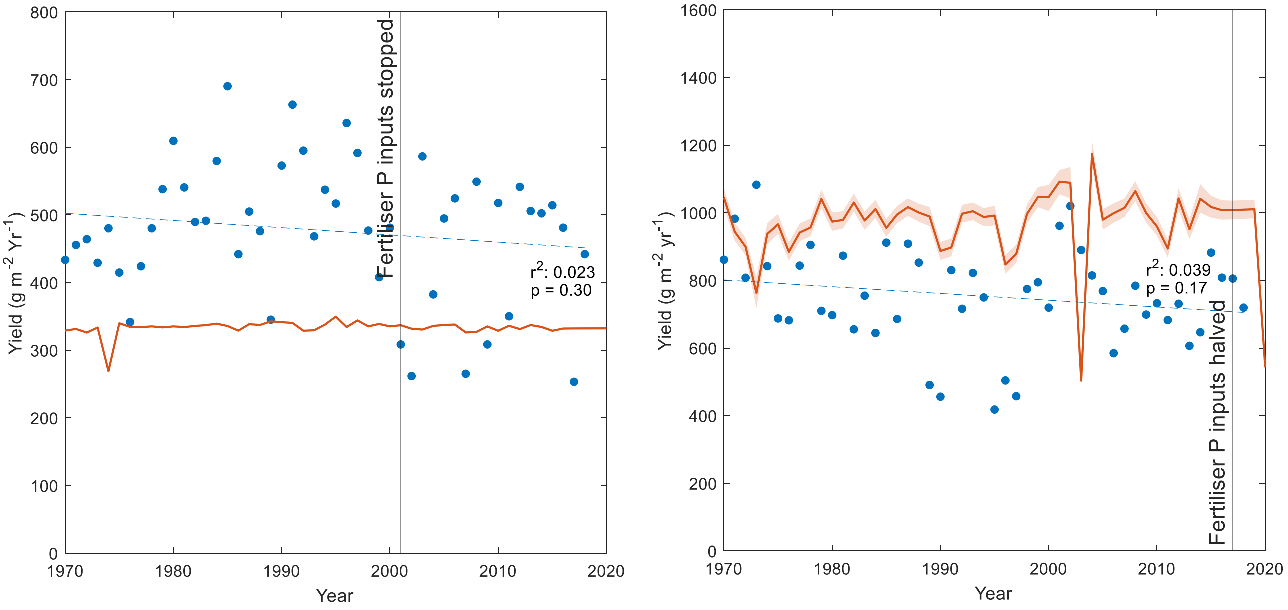


Figure 3-2: Modelled (line, shaded areas indicate 5th and 95th percentiles based on the uncertainty analysis) and observed (points) yield data for the arable (left) and permanent grassland (right) sites. Arable: modelled yield (M = 333 g m^{-2} yr^{-1}, SD = 10.51), is significantly less than observed data (M = 476.87 g m^{-2} yr^{-1}, SD = 101.00); t(48) = 9.95, p < 0.001. Grassland: modelled yield (M = 974 g m^{-2} yr^{-1}, SD = 97.02), is significantly greater than observed yields (M = 753.26 g m^{-2} yr^{-1}, SD = 144.57); t(48) = 8.84, p < 0.001.

modelled SOC (M = 4753 g m^{-2}, SD = 412.5), and observed data (M = 5736 g m^{-2}, SD = 1093.9; **Figure 3-3**).

Measurements of Soil N stocks have also been taken from both Broadbalk continuous wheat Plot 8 and the Park Grass permanent grassland Plot 9/2b since the start of the long-term experiments. Outputs from N14CP suggest that modelled soil N for the arable site (M = 203 g m-2, SD = 10.11), is significantly underestimated compared to observed data (M = 227 g m-2, SD = 14.35; t(11) = 4.50, $p < 0.001$; **Figure 3-4**), although modelled soil N stocks are estimated to within 11% of observed soil N data and are largely within the bounds of the uncertainty analysis. On the other hand there is no significant difference (t(4) = 1.13, p = 0.32) between the grassland modelled soil N (M = 451 g m^{-2}, SD = 32.65), and observed data (M = 503 g m^{-2}, SD = 113.23; **Figure 3-4**).

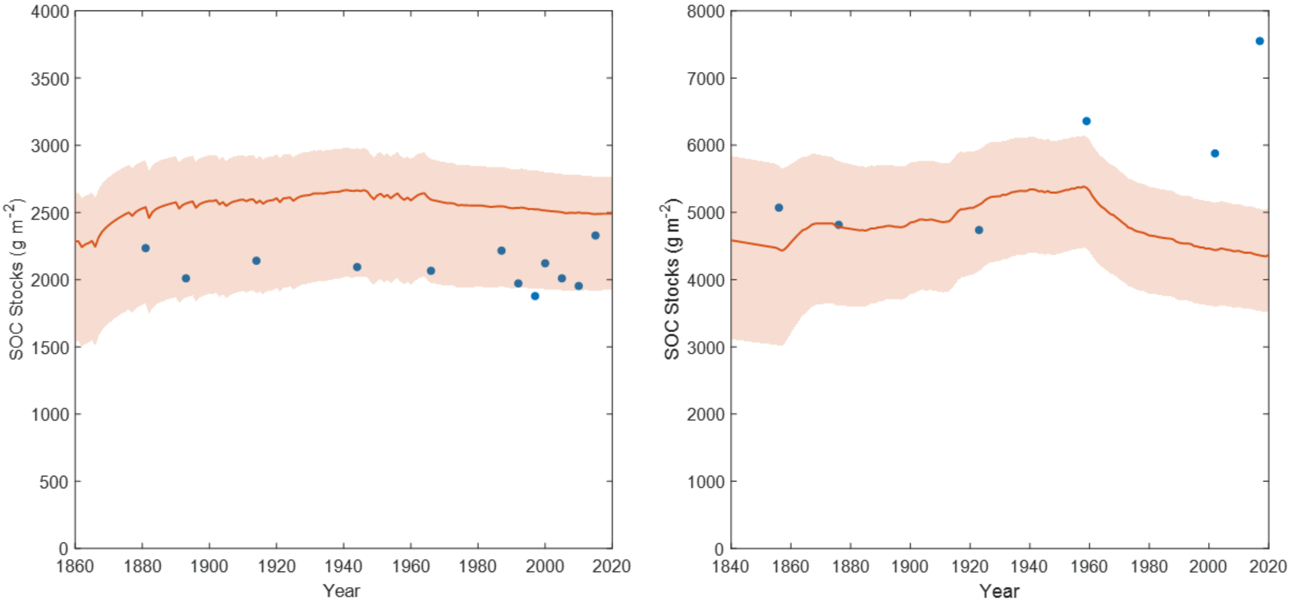


Figure 3-3: Modelled (line, shaded areas indicate 5th and 95th percentiles based on the uncertainty analysis) and observed (points) soil organic carbon (SOC) stocks for the arable (left) and permanent grassland (right) sites. Arable: modelled SOC (M = 2545 g m^{-2}, SD = 49.2), is significantly greater than observed data (M = 2086 g m^{-2}, SD = 130.8); t(11) = 11.4, $p < 0.001$. Grassland: modelled SOC (M = 4753 g m^{-2}, SD = 412.5), is not significantly different compared to observed data (M = 5736 g m^{-2}, SD = 1093.9); t(5) = 1.907, p = 0.11.

Unfortunately, soil total P measurements were not available for the Broadbalk continuous wheat Plot 8 and the Park Grass permanent grassland Plot 9/2b as this is not typically measured on all plots.

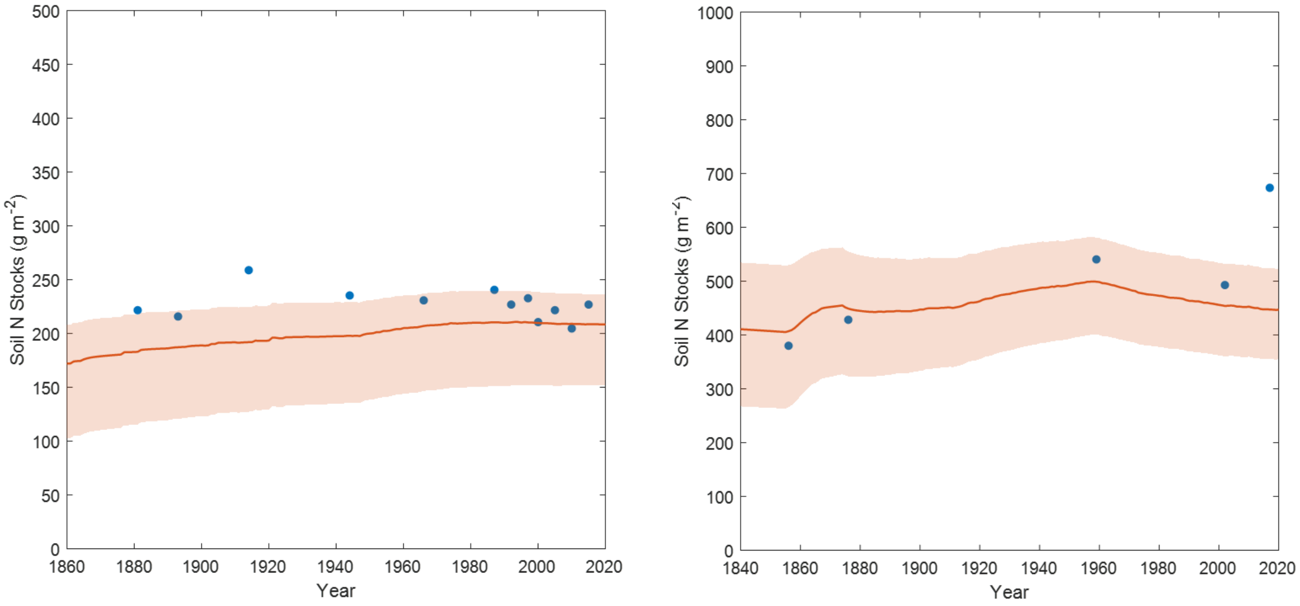
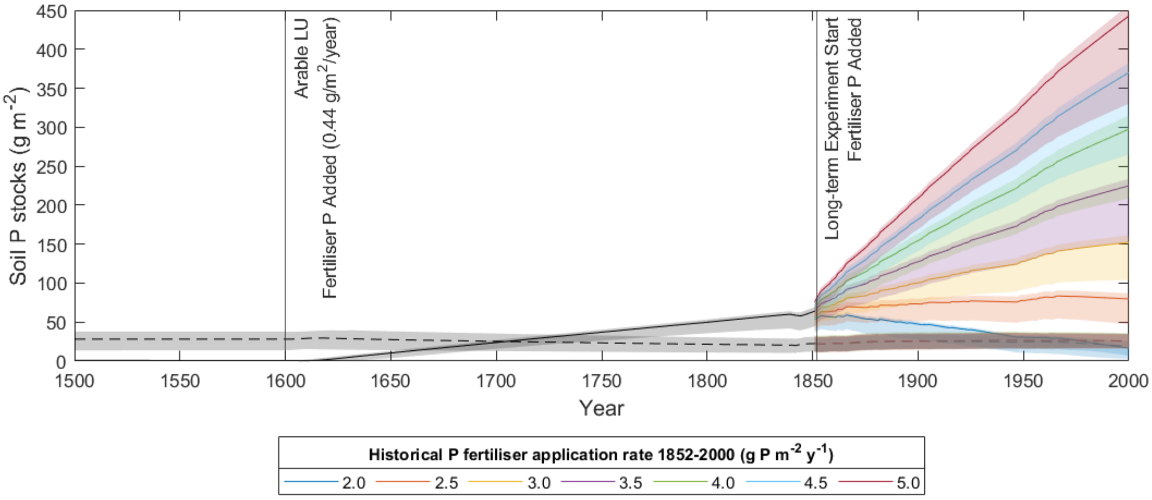


Figure 3-4: Modelled (line, shaded areas indicate 5th and 95th percentiles based on the uncertainty analysis) and observed (points) soil nitrogen (N) stocks for the arable (left) and permanent grassland (right) sites. Arable: modelled soil N (M = 203 g m^{-2}, SD = 10.11), is significantly less than observed data (M = 227 g m^{-2}, SD = 14.35); t(11) = 4.50, p < 0.001. Grassland: modelled soil N (M = 451 g m^{-2}, SD = 32.65), is not significantly different compared to observed data (M = 503 g m^{-2}, SD = 113.23); t(4) = 1.13, p = 0.32.

3.3.2 Modelled soil phosphorus and yield timeseries

N14CP was used to investigate the potential changes in soil P stocks during the Broadbalk and Park Grass experiments on these plots and how these might change under the four different P management scenarios (**Table 3-4**). Prior to years 2000 (arable) and 2016 (permanent grassland) N14CP inputs for land use and management were based on historical data for the sites.

For both sites, before the use of fertiliser P, modelled data suggest that organic P forms are the main pool of P in the soil, making up more than 90% of total soil P during this period. The addition of fertiliser P, thus inorganic P, in the model causes a small increase in total organic P before reaching a steady state (**Figure 3-5**). For the arable site, historical (1600-1840) annual fertiliser P applications of 0.44 g P m^{-2} yr^{-1} [19] caused a modelled increase in soil inorganic P (59 g P m^{-2} over 240 years), suggesting that applications of P were in excess of crop offtake (**Figure 3-5**) with N14CP outputs predicting that yield (and therefore P offtake) was limited by N availability. Since the start of the long-term experiments (1852-2000) modelled total soil P has increased by approximately 2.5 times for the arable crop, again indicating that P inputs were greatly in excess of offtake resulting in an accumulation of P in the soil. N14CP data suggest



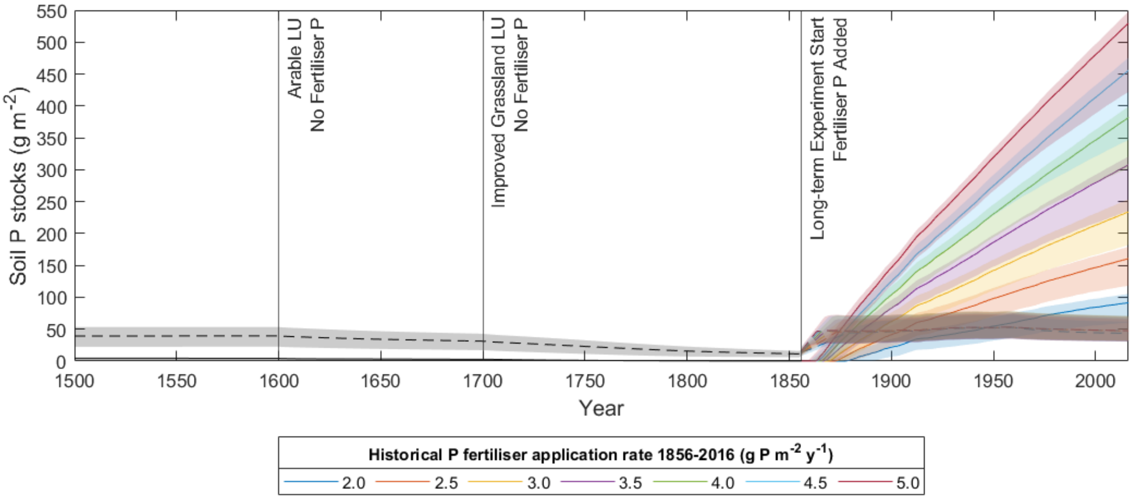


Figure 3-5: Modelled soil inorganic (solid line) and organic (dashed line) phosphorus under seven theoretical historical phosphorus fertiliser application scenarios for the arable (top) and permanent grassland (bottom) sites. Management history prior to the start of the long-term experiment, 1852 (arable) and 1856 (permanent grassland), was kept constant. Soil phosphorus stocks were used to demonstrate the effect of past management on "legacy P" stocks in the soil. Shaded areas indicate 5th and 95th percentiles based on the uncertainty analysis.

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[19] Rate of fertiliser addition based on literature values for historical fertiliser use for the land type and area.

that this legacy P is mainly in inorganic P forms. The evolution of legacy P in soil can also be seen in the modelled permanent grassland plots, where since the Park Grass experiment start date (1856) total soil P has increased by approximately 17 times (**Figure 3-5**).

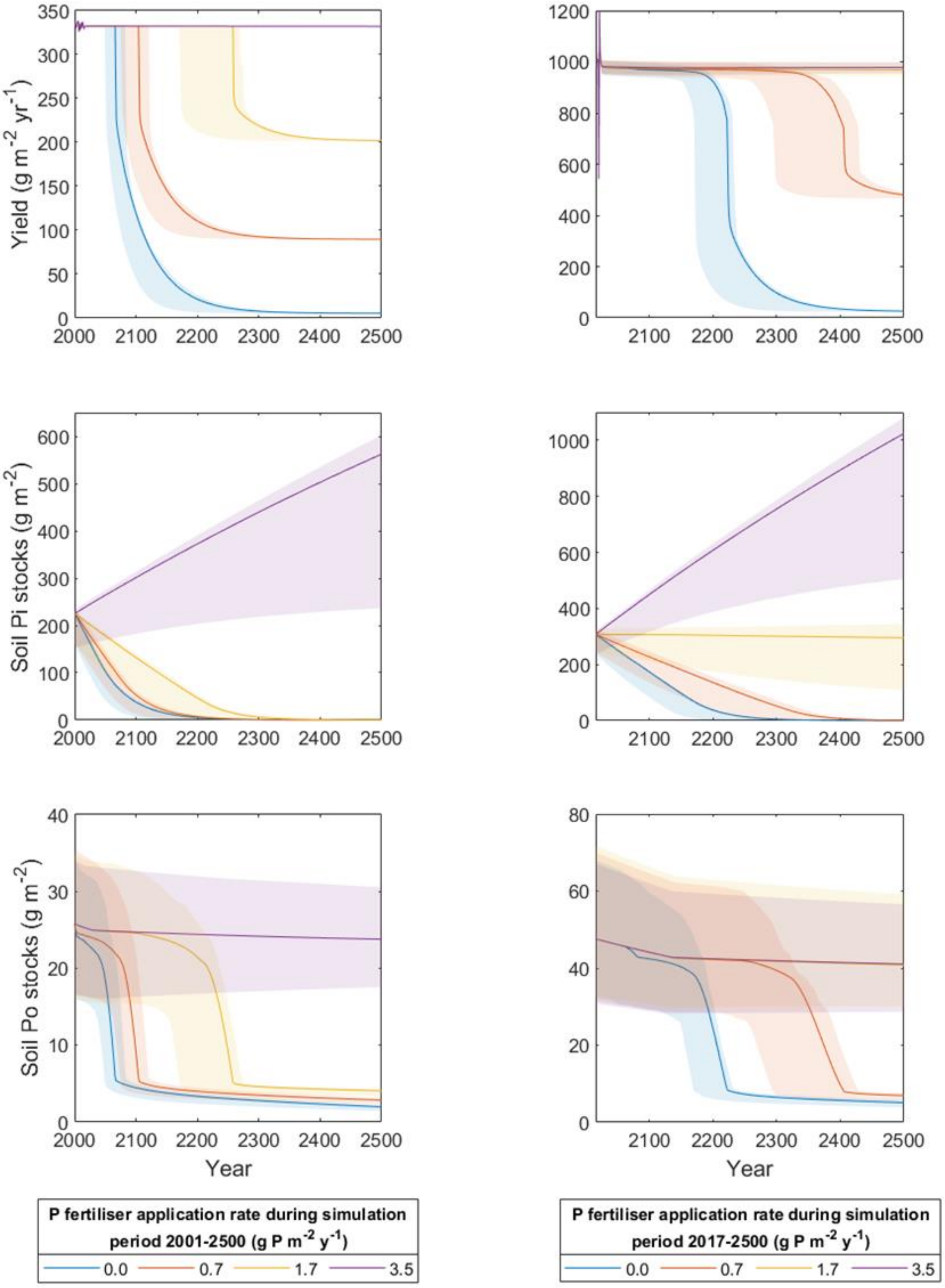

Figure 3-6: Modelled timeseries for the yield (top), soil inorganic phosphorus stocks (Pi, middle) and soil organic phosphorus stocks (Po, bottom) from the start of the simulation period for the arable (2001, left) and permanent grassland (2017, right) under four different fertiliser treatment scenarios. Prior to the start of the simulation period N14CP inputs for land use and management were based on historical data for the sites. Shaded areas indicate 5th and 95th percentiles based on the uncertainty analysis.

In the simulations for the future period, changes to the P management scenarios on the plots indicate that when P application rates were maintained at 3.5 g P m^{-2} yr^{-1} (StdP), soil total P continues to increase (**Figure 3-6**). However, for both sites under the NoP and FifthP scenarios modelled timeseries (**Figure 3-6**) shows that stocks of inorganic P rapidly decline. As this pool diminishes in the model, P is then acquired from organic pools until a maximum C:P ratio is reached. Shortly after this point, the availability of P in the model severely limits crop production and there is an initial rapid yield reduction in the arable plot, followed by a slower decline to a steady state that matches the incoming inorganic P. For the NoP scenario N14CP suggests that the very low availability of P is unable to support crop production of more than 5 g m^{-2} yr^{-1}. However, the reduction in grassland yield to a steady state is more gradual, following the depletion of soil organic and inorganic P, yet under the NoP scenario modelled yields are still reduced to less than 26 g m^{-2} yr^{-1}. The mechanisms and controlling factors that led to a significant downturn in yields, particularly under the No P scenarios, are discussed later. A similar decline in soil total P to below the modelled threshold for plant access to P and subsequent rapid reduction in yield can also be observed for the arable crop when P fertiliser applications are reduced by half (HalfP, 1.7 g P m^{-2} yr^{-1}), yet for the grassland site halving the P application rate does not greatly decrease soil total P and there is very little reduction in yield during the simulation period.

3.3.3 Predicting number of harvests

N14CP was used to investigate the number of harvests that could be sustained, at baseline yields[20], before it is reduced by more than 25% (arable) or 35% (grassland)[21] when relying on soil P stores for all or part of the crops' P demand. Modelled soil P stocks at the start of the

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[20] Set to the yield at the start of the simulation period, 335 g m^{-2} yr^{-1} in 2000 and 1006 g m^{-2} yr^{-1} in 2016 for the arable and grassland sites respectively.

[21] A 25% or 35% yield reductions were based on observed average yield fluctuations from 1970 to 2018.

simulation periods were based on theoretical P inputs from the start of the long-term experiments (**Table 3-3**).

For both sites, N14CP predicts that when P application rates are maintained at 3.5 g P m^{-2} yr^{-1}, yield can be sustained to the end of the simulation period, irrespective of the starting total P stock. This is also true for the grassland plot under the Half P (1.7 g P m^{-2} yr^{-1}) scenario. Under reduced fertiliser inputs, Half P (arable only), Fifth P and No P scenarios, modelled yield data suggests a linear positive relationship between Total soil P at the start of the simulation period and the number of years to yield impact (**Figure 3-7**).

For the arable crop, predicted plant productivity can be maintained at baseline levels for between 7 (0 – 9, 95% confidence interval) and 149 (105 – 159, 95% confidence interval) years in the absence of P fertiliser inputs during the simulation period (**Figure 3-7**). This is increased to approximately 26 (4 – 36, 95% confidence interval) and 471 (287 – 500, 95% confidence interval) years when the fertiliser applications are reduced by half compared to the standard application rate. Similarly, the grassland plot simulations suggest that under No P treatment,

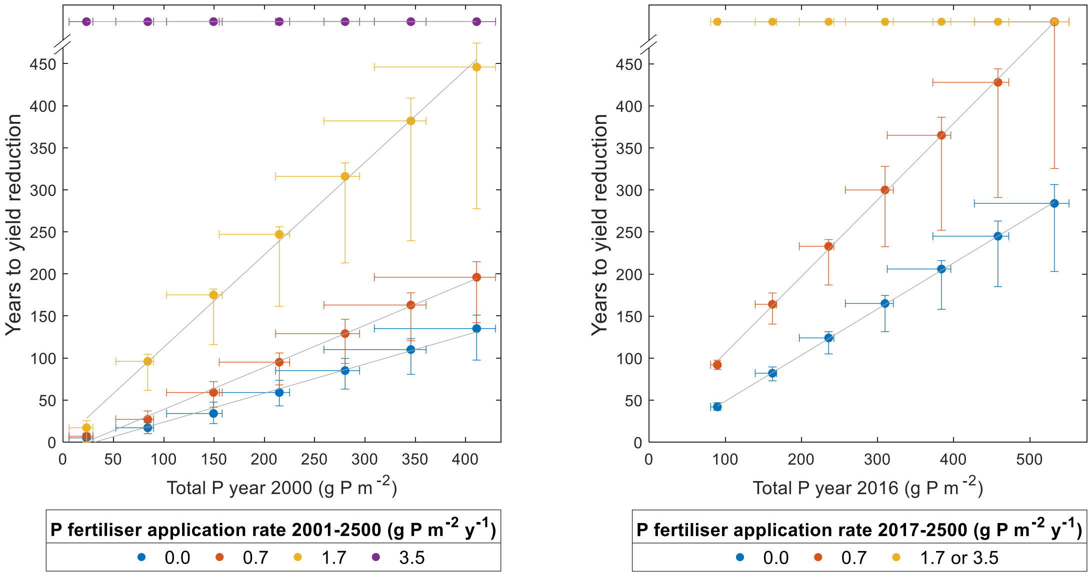

Figure 3-7: Modelled number of years before arable (left) and grassland (right) yields are reduced by more than the threshold (arable: 25%, baseline yield 412 g m^{-2} yr^{-1} in 2000; grassland: 35%, baseline yield 1136 g m^{-2} yr^{-1} in 2016) at different starting soil total P stocks under each of the future P management strategies. Error bars indicate 5th and 9th percentiles based on the uncertainty analysis.

yields can be maintained for between 71 (62 – 78, 95% confidence intervals) and 333 (225 – 349, 95% confidence intervals) years depending on the fertiliser history. This is increased to 157 (130 – 168, 95% confidence intervals) and at least 500[22] (367 – 500, 95% confidence interval) years under the Fifth P treatment scenarios (**Figure 3-7**).

3.4 Discussion

3.4.1 Model testing using observed data

N14CP is a fairly simple ecosystem model, it utilises readily available input data and requires limited site-specific calibration. It is one of few models to integrate C, N and P cycling for a range of land use types (Achat et al., 2016) and has been extensively tested against empirical data from long-term experimental sites (Davies et al., 2016a; Davies et al., 2016b; Janes-Bassett et al., 2020). Here the N14CP model has simulated long-term soil nutrient stocks and yields for two experimental agricultural plots, modelled data were tested against long-term historical measured data.

N14CP modelled yields were significantly greater than observed yields for Park Grass Plot 9/2b (N14CP: M = 974 g m^{-2} yr^{-1}, SD = 97.02; Plot 9/2b: M = 753.26 g m^{-2} yr^{-1}, SD = 144.57; t(48) = 8.84, $p < 0.001$). These data are in contrast with the arable plot (Broadbalk Plot 8) where N14CP was significantly underestimating yield (N14CP: M = 333 g m^{-2} yr^{-1}, SD = 10.51; Plot 8: M = 476.87 g m^{-2} yr^{-1}, SD = 101.00; t(48) = 9.95, $p < 0.001$). The average modelled yields for these plots are within approximately 30% and 22% of the observed yields for wheat and grassland, respectively. This represents a slight decline in performance compared to previous work with N14CP, where modelled yields deviated from observed data by only 15% (Janes-Bassett et al., 2020). The differences between the modelled and observed yields for both plots suggest that yield representation in N14CP could be improved.

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[22] Model simulations not run past 2500

However, when exploring SOC and soil N data, the differences between observed and modelled stocks since the start of the long-term experiments typically fall within the modelled 95% confidence interval based on the uncertainty analysis (**Figure 3-3** and **Figure 3-4**) suggesting that C and N cycling is reasonably well constrained within the model.

Both plots had observed topsoil P, measured using the Olsen P method. However, these measurements were excluded from the analysis because they are not directly comparable to the modelled P outputs.

To improve model performance, future development could prioritise the mechanisms within the model that control biomass removal through harvest for the different crop types and the acquisition of soil nutrients for plant productivity. Incorporating some degree of site-specific calibration, such as adjustments for temperature and precipitation, may also be beneficial. However, the model's temporal resolution inherently limits its ability to simulate yield variability in detail. For instance, relying on average quarterly temperatures cannot capture critical factors like extreme temperature events or diurnal fluctuations, both of which significantly influence crop growth and yield.

The model predictions presented here suggest that N14CP provides a reasonable modelling test bed for exploring soil legacy P and long-term crop yields under different future management scenarios, although it is acknowledged that modelled representation of yields could be improved for both crop types and that the inclusion of measured total P data from these sites would strengthen this work.

3.4.2 The potential of legacy P to support crop production

In general, it is widely accepted that legacy P has the potential to support crop production for several years, particularly in soils with a history of P inputs in excess of P removal by crops (Rowe et al., 2016). Measured yield data since 2001, under No P treatments, for the arable crop, demonstrates that yield has not significantly changed compared to pre-2001 yields under the standard fertiliser regime, supporting findings in the wider literature. Reducing P fertiliser application rates allows adsorbed, precipitated and organic P pools to sustain plant productivity. However, this will at some point sacrifice plant productivity and may only be suitable for the initial depletion of P-rich soils (Menezes-Blackburn et al., 2018).

The long-term crop yields for a cereal and a permanent grassland cropping modelled here indicate that under No P fertiliser conditions wheat and grassland productivity could be maintained at baseline levels, utilising stores of legacy soil P, before crop yield is impacted (arable: 7-149 years; grassland 71-333 years). Estimates from N14CP demonstrate a broad range of outcomes, particularly for soils with greater P stocks at the start of the simulation period. This reflects the complex interactions represented by the computational approaches within N14CP and the uncertainty analysis methods taken. However, the period over which legacy soil P can be utilised without a reduction in crop yield is heavily influenced by not only the total amount and form of P in the soil (organic or inorganic), but also by several factors including soil texture, soil pH, soil structure, plant species, land management practices (e.g. tillage), etc. (Rowe et al., 2016). Indeed, some long-term field studies suggest that yield penalties can occur within less than 10 years despite soil tests indicating that P stocks in the soil are adequate or even high (McDowell & Condron, 2012; Withers et al., 1994). As such, there is still a clear distinction between the amount of soil P that is in the soil and the amount that can be utilised by the crop.

Plant type and land management practices are accounted for in this model and the parameters used to define these are based on broad literature searches (Janes-Bassett et al., 2020). The clay content of soils is known to influence the adsorption and desorption of P in soils and soil pH has also been demonstrated to greatly influence the availability of P, with a pH of between 6 and 6.5 generally being considered appropriate for most soils; (Blackwell et al., 2019). However, N14CP has a simplified representation of soil type (podzol or rankers/other soils) and limited sensitivity to the influence of soil pH on P availability. Varying f_{Psorb} and $f_{Pdesorb}$

within the model could reflect the varying sorption capacities of different soil textures, however, N14CP is not directly sensitive to the influence of soil pH on P availability.

As previously mentioned N14CP also does not account for finer scale heterogeneity of inter-annual variations in yield caused by the impact of flooding, droughts, pests, disease etc. which may have a greater influence on short-term production compared to fertiliser inputs (Dodd et al., 2012) and would be better captured in models with sub-daily timesteps (Metherell et al., 1993; Wu et al., 2007). Although it is worth noting that reducing the timestep of the model and having a finer temporal resolution would make long-term simulations such as these very computationally demanding.

Where historical applications of P were in excess of crop requirement (more than 2.5 g P m^{-2} yr^{-1} (arable) and 2.0 g P m^{-2} yr^{-1} (grassland); **Figure 3-5**) this has been shown to greatly increase the length of time that legacy P can maintain yields in the arable and grassland systems modelled in this study by increasing the amount of total P stored in the soils. Estimated number of harvests for the No P future scenarios based on recorded historical P inputs demonstrate that wheat yields have the potential to be maintained at current levels for 50 – 83 years and for grassland yields, the potential is longer, from 155 – 217 years. N14CP estimates in this study show that for soils with a history of the highest P inputs for many years (i.e. soils with the greatest amount of legacy P) potentially could support wheat and grassland production without any P inputs for up to 149 (105 – 159, 95% confidence interval) and 333 (225 – 349, 95% confidence interval). Results also suggest that the permanent grassland plot can maintain baseline yields using legacy soil P for longer than cereal crop production, reflecting the differences in the mechanisms within the model that control biomass removal through harvest[23] and to a lesser extent the modelled total soil P at the start of the simulation period (**Table 3-3** and **Figure 3-5**).

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[23] Fraction of biomass removed during harvest is modelled at 0.38 and 0.50 for grassland and cereal crops, respectively

The estimated number of harvests, without major yield penalties, for land with a history of excess anthropogenic P inputs supports previous work by Menezes-Blackburn et al. (2018) who estimated that total soil P stocks would support 352 ± 26 years' worth of agricultural production (arable and grassland combined) based on a simple P offtake mass balance approach. This highlights the potential of soil P to be mobilised for future agronomic use. However, for land that does not have high P reserves, the estimated number of harvests that can be supported were reduced to approximately 30 years and 70 years for arable and grassland production, respectively. These figures are more in line with other studies that suggest that withholding P fertilisers could lead to loss of production in under 50 years (Dodd & Mallarino, 2005; Dodd et al., 2012; Johnston et al., 2016). The wide range of findings within the literature again, highlights the difference between the potential of legacy P to support production and the actual access that plants have to the soil P.

Modelled results show that the inorganic P pool is rapidly depleted under reduced P fertiliser inputs, P is then acquired from soil organic matter pools in N14CP (**Figure 3-6**). Resulting in a potential 40% and 56% decline in SOC during the simulation period for the arable and grassland plots, respectively (**SI Figure 3-1**). This curvilinear decline of inorganic P is supported by the literature (Coad et al., 2014; Tyson et al., 2020) and can be explained by the relative availability of different forms of inorganic P in the soil, categorised in terms of their accessibility, extractability, and plant availability (Johnston & Poulton, 2019). As inorganic P is depleted, plants and soil microbes must mineralise organic P sources (Blake et al., 2003a). Although using the nutrients associated with soil organic matter does not immediately impact on crop yield (Edmeades, 2003; Johnston et al., 2009) it can lead to problems such as soil compaction or soil erosion, which can reduce the efficiency of P fertilisers and increase P losses from the cropping system (Dick & Gregorich, 2004). The wider benefits of maintaining and building soil organic matter to achieve more sustainable agriculture particularly in the face of climate change is well recognised (Johnston et al., 2009). Indeed, organic P inputs and soil organic matter content can increase the fraction of legacy P that can be utilised by plants through the blocking of P adsorption sites on soil particles by organic compounds (Hawkins et al., 2022). Therefore, strategies to "mine" excess soil P in agricultural systems, need to be balanced with strategies that try to build soil organic matter (Siedt et al., 2021; Vandecasteele et al., 2014; Vanden Nest et al., 2014).

Previous work with N14CP has highlighted the need to improve its ability to simulate P cycling for sites that receive very little P compared to N additions (Janes-Bassett et al., 2020). The simulations and uncertainty analysis carried out in this study aimed to modify some of the key parameters that influence P cycling within the model. However, it is unlikely that in an agricultural setting such a rapid and extreme decrease in yields would be witnessed (**Figure 3-6**). For example plots on the Park Grass and Broadbalk continuous wheat experiments that have received no fertiliser since the 1850s are still producing yields of approximately 360 g m^{-2} yr^{-1} and 90 g m^{-2} yr^{-1} respectively (Rothamsted_Research, 2021), albeit much lower than their experimental counterparts that receive annual supplies of fertilisers and/or manures (Macdonald et al., 2018). Indeed, this is supported by observed data collected by Janes-Bassett et al. (2020) and Johnston and Poulton (2019) for agricultural plots receiving no P fertiliser inputs for 175 years.

Within N14CP plant control over nutrient uptake is largely controlled by stoichiometric demand (Davies et al., 2016a). N14CP's simplified representation of nutrient pools and in particular plant access to organic P has been identified as a key knowledge gap (Janes-Bassett et al., 2019). N14CP does not incorporate many plant or microbial strategies for P acquisition which are extremely important for P cycling in terrestrial ecosystems (Richardson et al., 2011; Vance et al., 2003). As soil conditions change over time under different land management regimes so too will microbial community structures, impacting organic P acquisition in the soil (George et al., 2018). The agronomic and ecological significance of organic P and the extent that changes in microbial community structures impact P utilisation has been studied for decades; yet, quantifying and modelling its contribution is still a challenge and will continue to require integrated and cross-disciplinary research (George et al., 2018; Haygarth et al., 2018).

The inputs and mechanisms that support the persistent yields in agricultural sites with long-term no P inputs will be explored further in Chapter 4 of this thesis. However, it is unclear whether there may be a need for a fundamental shift in our understanding of P cycling in low P systems or if this is reflects a limitation inherent to the model itself.

3.4.3 Future opportunities

In response to the environmental consequences of decades of high P application rates to soils, strategies for the controlled depletion of excessive P in soils have been introduced into standard nutrient recommendations and have led to a shift towards a concept of “feed the crop, not the soil” (Withers et al., 2014). Ideally, sustainable P fertiliser management should ultimately balance fertiliser inputs with crop outputs, to support agricultural productivity while moving toward closing the P cycle in agricultural systems (Elser & Haygarth, 2020; Haygarth et al., 2014).

Ultimately where soil P stocks are high, allowing them to fall could bring benefits to i) the land manager in not purchasing P fertiliser while still maintaining yield and ii) to the environment by decreasing the risk of diffuse P pollution (Johnston et al., 2016). The amount of legacy P in intensively managed agricultural soils is often linked to farming type; with soils associated with long-term high manure inputs primarily having the greatest soil P stocks; compared to farms that primarily use inorganic P fertilisers (Withers et al., 2001). However, despite being widely used, many of the current soil P tests are not accurate enough for precise P fertiliser assessment. Therefore, having accurate soil analyses of the total inorganic and organic P (not just the “available P”) will be critical in helping to predict the capacity of legacy P to deliver agronomically sufficient P for production (Sattari et al., 2012). Indeed, controlled pot experiments in a range of soil types have demonstrated that P uptake by plants, and threshold values for fertiliser response, can be more accurately predicted by measurements of total P than by available P in bicarbonate extracts (Recena & et al., 2019). Thus having the potential to improve the accuracy of assessing fertiliser requirements for optimum crop production by accounting for the role of organic P to supply P to plants (Recena & et al., 2019). However, it will be important to integrate this knowledge into updating models, to enhance long-term predictions particularly in complex and dynamic agricultural systems.

The uncertainties in modelling how long soil P can support crop production and the wide variability in empirical data from P drawdown experiments makes determining the exact number of harvests that can be supported by these residual P pools a challenge. Computer-based models have the potential to be used by famers and land managers alongside existing nutrient management planning strategies and soil testing regimes. However, there needs to be a consideration towards the perceived usefulness and ease of use of these models which are a major drivers for the adoption of new technologies by farmers (Mccormack et al., 2021). There are also further socioeconomic barriers to famers and land managers to adopting No P input practices (Daxini et al., 2018). Strategically lowering the application rate of P (rather than discontinuing it entirely) to just below the crop's P requirement (such as the Half P or Fith P scenarios) could therefore be a more pragmatic approach to utilising legacy P for crop production, with less risk to yield reductions. This method results in a more gradual decline in soil P stocks, although may not quickly address ongoing concerns of diffuse P pollution (Ockenden et al., 2017). Chapter 6 of this thesis will delve deeper into this perspective and will explore some of the social barriers that farmers and land managers encounter in effectively managing soil legacy P.

Overall, the data highlight the decadal to centennial timescales of P cycling processes and the long term effect of past management practices. These data can also help to demonstrate why the response to implementation of conservation measures to reduce excess soil P in soils and diffuse P pollution of watercourses has been slower and smaller than expected (Meals et al., 2010; Sharpley et al., 2013). However, there is also the added complication that while adopting reduced P fertiliser regimes and improving soil P use by crops and pastures may help to alleviate the pressures of P fertiliser availability and price volatility (Menezes-Blackburn et al., 2018) arguably, by increasing solubilisation, desorption and bioavailability of soil P through promoting plant access to legacy P (Chassé & Ohno, 2016; Doydora et al., 2020; Edwards et al., 2016; Richardson et al., 2009; Rowe et al., 2016), it is also possible that short-term P losses may also increase through leaching and run-off (Menezes-Blackburn et al., 2018; Vanden Nest et al., 2014). As such any future P management policies need to take into account this lag time between implementation and changes in soil P stocks and the possible consequences of exploiting soil P pools.

3.5 Conclusion

This study, combining long-term modelling and empirical data, has illustrated that legacy P has the potential to sustain crop productivity for a continuous wheat crop and permanent grassland site. Results demonstrated that in agricultural systems, legacy P stocks were heavily influenced by the historical management of the site, with histories of P fertiliser use in excess of crop requirement resulting in greater legacy P resources at the start of the simulation periods for both sites. The amount of time yield can be supported without any P inputs depended on the total P stocks in the soil at the start of the simulation period. The modelled number of years to yield reduction under a No P management scenario ranged from less than 10 years for an arable crop, where soil P stocks were less than 40 g P m^{-2} before P fertiliser additions were stopped, to more than 300 years for a grassland crop, where starting soil P stocks were approximately 580 g P m^{-2} before P fertiliser additions were stopped.

While N14CP has demonstrated the evolution of legacy P build up and drawdown, it should be acknowledged that the mass-balance mechanisms in the model that control plant nutrient uptake are largely controlled by stochiometric demand. This representation does not fully account for the actual plant accessibility of the P in the soil particularly for more stable inorganic and organic P forms. Extending conceptual definitions of legacy P to include chemical (and biological) descriptions, could be used alongside more rigorous testing of soil total P and/or organic P from long-term field trials. These findings should then be incorporated into modelled representations of P processes to further the understanding of the long-term biogeochemical and crop responses to the drawdown of legacy P stores in agricultural soils.

Overall, this research has demonstrated that the N14CP model can be used as a test bed for exploring long-term yield responses to changes to P management strategies, although addressing model limitations and integrating measured total P data from these sites would further enhance the robustness and applicability of this work. Importantly, these findings challenge the mindset that crops require annual P inputs to maintain yields, particularly in soils with high total P reserves. This research underscores the potential for more sustainable P management practices, contributing to both agricultural productivity and environmental stewardship.

3.6 Acknowledgements

We thank the Lawes Agricultural Trust and Rothamsted Research for information and data from the e-RA database. The Rothamsted Long-Term Experiments - National Bioscience Research Infrastructure (RLTE-NBRI) is funded by the UK Research and Innovation - Biotechnology and Biological Sciences Research Council (UKRI-BBSRC) under award BBS/E/RH/23NB0007 (2023-2028). The RLTE-NBRI is also supported by the Lawes Agricultural Trust.

4 Exploring phosphorus sources and use to assess long-term persistent yields in low-phosphorus input agricultural systems through N14CP modelling

4.1 Introduction

Phosphorus (P) dynamics in many agricultural systems, are heavily influenced by anthropogenic activity, such as fertilisers inputs, and the recycling of manures[24], and other organic materials[25]. Long-term no-input agricultural systems are rare and are typically confined to experimental plots. However, they do represent an interesting scenario for P cycling in soils as there is a (large) annual net removal of nutrients, including P, through the harvested crop. Although much lower in yield, sites with little or no fertiliser inputs still are able to support crop growth, even after several decades (Aref & Wander, 1998; Macdonald et al., 2018). Exploring P cycling in these no-input systems, through the development and use of biogeochemical models, to investigate the persistent soil P stocks could help to understand the P processes linked to legacy P management and P drawdown in agricultural systems when we are looking to reduce or stop P inputs.

The spatial and temporal heterogeneity of P inputs in the landscape creates a complex and dynamic starting point for P modelling. Many biogeochemical P models rely on user inputs of annual fertiliser and manure P applications (Della Peruta et al., 2014; Metherell et al., 1993; Muhammed et al., 2018; Wu et al., 2007). However, contributions of P from other sources (such as, atmospheric deposition, weathering of primary materials, animal deposits, water-driven

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[24] Applied as an organic soil amendment in the form of slurry or farmyard manure to the whole field or as incidental applications from grazing livestock.

[25] These can include materials such as wastewater treatment biosoilds or by-products of food manufacturing or processing.

pathways (e.g., leaching and run-off) are typically less represented in P model development (**Figure 4-1**). This is largely because these contributions are relatively minor compared to fertiliser and manure P inputs and are considered to have little agronomic impact. Nevertheless, in the absence of anthropogenic P inputs, these other sources of P may play a more important role in the agronomic P supply to crops.

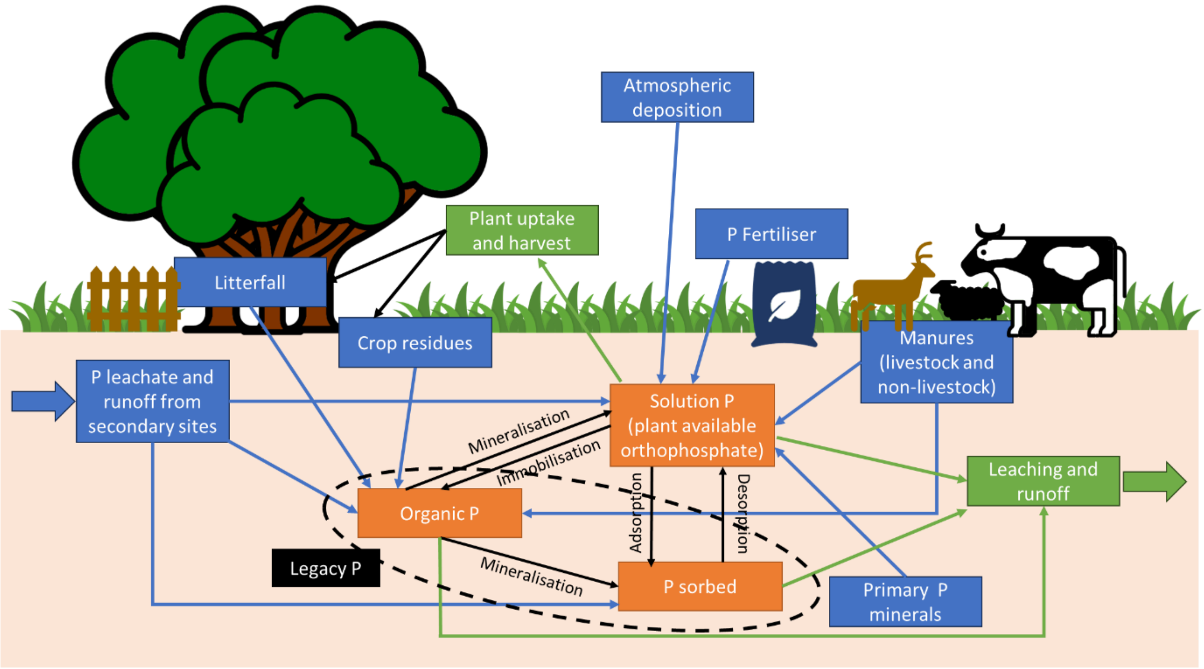

Figure 4-1: A simplified conceptual representation of the phosphorus cycle in agricultural systems (adapted from Janes-Bassett et al (2020)).

4.1.1 Modelling phosphorus in agricultural systems

4.1.1.1 Fertilisers, manures, and crop residues

Anthropogenic inputs of P are interwoven into many modern agricultural practices and as such are a key input for process-based models. Phosphorus input recommendations to agricultural systems typically range from approximately 10 – 30 kg P ha^{-1} yr^{-1} for most arable, grass, and forage crops[26] (AHDB, 2020d). This is typically supplied as ‘new’ phosphate fertiliser or ‘recycled’ organic wastes (mostly livestock manures). Crop residues are also a source of P to

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[26] Values based on RB209 recommended P application rates for crops grown on P index 2 soils, the agronomic target P index for soils (equivalent to 16-25 mg P l^{-1} extracted using the Olsen-P method).

the following crop and the amount of P that is returned to the soil varies depending on the crop grown and the harvest index of the crop (Damon et al., 2014).

4.1.1.2 Phosphorus weathering

Phosphorus originates from geological deposits found within the Earth in the form of sedimentary rocks, apatite, and other forms of P minerals, as well as igneous rock sources. These sedimentary rocks are the main form of P (95%) that is mined for fertiliser (Elser & Haygarth, 2020). The parent material of a soil determines the inherent supply of the P that are released as organic P forms or iron- and aluminium-based P compounds over time by weathering processes (Anderson, 1988). The amount of P within parent material can vary greatly, from 200 mg P kg^{-1} to 8000 mg P kg^{-1} (Tiessen, 2005). Over time, P weathered from the parent material is depleted; with older, highly weathered soils often eventually displaying signs of P-limitation (Wardle et al., 2004). Temperature, soil moisture, and biological activity are known to have an influence on weathering processes, although the full extent of their influence is difficult to observe and decouple from other effects (Newman, 1995). Previous studies have indicated that weathering processes are the main supply of P to semi-natural ecosystems (Anderson, 1988; Walker & Syers, 1976). However, Janes-Bassett et al. (2020) suggest that despite high additions of nutrient inputs to agricultural land, the cycling of carbon (C), nitrogen (N) and P are still sensitive to the P-content of parent materials. Weathering rates can be influenced further by land use change and agricultural land management practices such as tillage (Hartmann et al., 2013).

4.1.1.3 Atmospheric deposition of phosphorus

Atmospheric deposition of P can also be a significant source of non-anthropogenic P to terrestrial systems, although at much lower rates, compared to atmospheric N deposition and anthropogenic P inputs (Tipping et al., 2014). Phosphorus can enter the atmosphere through various sources, including dust carried from soils and deserts, marine aerosols, biological aerosol particles, volcanic ash, biomass burning, as well as emissions resulting from the combustion of oil, coal, and phosphate fertilizer production (Graham & Duce, 1979; Mahowald et al., 2008; Newman, 1995). Larger, denser particles are limited to short-distance movement, while P in fine dust has the capability to travel vast distances, spanning thousands of kilometres (Newman, 1995). Average atmospheric P deposition is estimated to be approximately 0.027 g total P m^{-2} yr^{-1} (Tipping et al., 2014). For many agricultural systems using P fertiliser or manure inputs this can account for less than 1% of P recommendations[27] (AHDB, 2020d, 2020e), yet in low or no-P input systems this P input typically is not accounted for.

Phosphine gas is volatile constituent of the P cycle (Reddy et al., 2005) and makes up about 10% of the P in the atmosphere (Morton & Edwards, 2005). It is found universally in two forms: free gaseous phosphine, commonly detected in marsh gases and rice fields, and matrix-bound phosphine, which can be observed in anoxic soils and sediments, as well as in products from wastewater treatment facilities (Fu & Zhang, 2020). Again, transport pathways and contributions of phosphine gas to P flows are under-researched and typically not accounted for in P models and management plans (Morton & Edwards, 2005; Sharpley et al., 2015).

4.1.1.4 Legacy phosphorus

The term soil “legacy” P has emerged in recent years to describe stores of P that have built up in agricultural soils because of excess anthropogenic P inputs of fertilisers and/or manures. While the concept of "legacy” P has become widely recognised due to the realisation of the environmental consequences of intensive human use of P fertilisers, arguably applications of manure during the 17th century (Brunt, 2007) could have also been in excess of crop requirement. In line with our understanding of P cycling and long-term stores of P, these applications could have then led to an increase in soil P stocks. These accumulated phosphorus reserves could have agronomic potential decades to centuries later, especially in systems where there is a net export of P. This underscores the significance of considering historical practices in contemporary agricultural management strategies (Menezes-Blackburn et al., 2018).

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[27] Agronomic recommendations based on the Nutrient Management Guide (RB209): recommendations based on soil P concentration as determined by the Olsen-P extraction method.

4.1.1.5 Phosphorus mobilisation between sites

Land in close proximity to sites receiving high P inputs could be exposed to higher rates of P from water-driven pathways (Sims et al., 1998). Phosphorus in soils (and applied fertilisers or manures) are mobilised either via solubilisation or physical detachment of particulate material (Haygarth et al., 2005). Fresh applications of manures and fertilisers can also undergo “incidental” P losses before they are incorporated into the soil (Preedy et al., 2001). There is evidence to suggest that in systems with high soil P that there is likely to be greater P mobilisation (Heckrath et al., 1995). The downslope mobilisation and delivery of P from high P sites could therefore serve as an important P input to semi-natural and agricultural sites that receive little or no P inputs from fertilisers or manures (Ceulemans et al., 2013) yet is often not considered in long-term P management plans.

4.1.1.6 Plant responses to phosphorus deficiency

Plants can respond to P deficiency by increasing the N to P ratio of their biomass, with high N:P ratios indicating P-limited plant growth (White & Hammond, 2008). Plant stoichiometry can vary greatly within and between plant types and although the amount and availability of P in the soil plays a large part in plant productivity, when soil P is scarce, plants are able to adapt to reduce the amount of P taken up for growth (Güsewell, 2004). However, in most agricultural systems the N:P ratio of the crop biomass is not considered for nutrient planning applications.

4.1.2 Modelling phosphorus and N14CP

Much of the scientific understanding of P biogeochemical cycling in agricultural systems has been developed from inductive and empirical research using a conventional experimental design framework (Krueger et al., 2007; Vadas et al., 2013). While experimental research is essential to test hypotheses and to develop an understanding of key P processes, it cannot evaluate all possible system interactions and relies on the availability of measurable data (Beven, 1989; Haygarth et al., 2005). Bridging this gap, computer-based models have been developed alongside the inductive and empirical P research to help describe processes that cannot be physically measured (Krueger et al., 2007). One of the other benefits of using models is their ability to conceptualise our understanding of natural systems so users can begin to explore ideas and changes to the model, in line with empirical data, to run scenarios that could otherwise take years to test in the field if they could be even tested at all.

This chapter will use the biogeochemical model N14CP to simulate total soil P stocks and grassland yields. Previous studies investigating P cycling in agricultural systems using the N14CP model have demonstrated that it can predict C and N cycling as well as crop yields well for semi-natural environments (Davies et al., 2016a) and systems receiving abundant fertiliser (Janes-Bassett et al., 2020 & Chapter 3 of this thesis). However, in agricultural systems where there is no fertiliser or P applied (particularly on sites where N is applied but not P), predicted yield responses are greatly underestimated compared to the observed yields of these plots (Janes-Bassett et al., 2020). This suggests that there may be a greater amount of P in the soil that can be taken up by the plant than the model is able to predict.

The aim of this research is to investigate the persistence of soil P stocks and sustained crop yields in agricultural systems with long-term no-P inputs, using the N14CP model. It is hypothesised that N14CP should simulate long-term soil P pools and yield well for grassland plots receiving annual inputs of fertiliser. However, this chapter will investigate the disparity between N14CP model outputs and the observed persistence of soil P stocks and crop yields without P inputs. This study will systematically evaluate different factors not typically considered by N14CP and the effects they have on modelled soil P stocks and crop yield. Specifically, the P factors include: 1) elevated atmospheric P deposition; 2) historic manure applications; 3) annual non-fertiliser P imports (e.g. the P contribution of leaf litterfall and non-livestock animal excretion); 4) P mobilisation between plots; 5) elevated stocks of weatherable P from parent material; and 6) flexible plant stoichiometry in response to P stress. By exploring these factors, the chapter seeks to improve both the accuracy of P cycling models and our understanding of how long-term P drawdown occurs in systems with significant legacy P stocks, supporting more sustainable agricultural practices.

4.2 Methods

The approach in this chapter will test simulated topsoil C, N, and P stocks and crop yield against observed soil total, organic and inorganic P stocks, measured C and N stocks, and observed yield data from two contrasting long-term field trial sites in the UK.

4.2.1 Observed data

4.2.1.1 Site details

Observed topsoil C, N, and P data and crop yield data were collected from two long-term agricultural experimental plots on the Park Grass classical experiment site at Rothamsted Research, Harpenden, UK (Macdonald et al., 2018; Rothamsted-Res, 2020b; Rothamsted_Research, 2021). Plots 3d and 4/1d have been managed experimentally as permanent grassland since 1856. Both plots are adjacent to each other and are not hydrologically separated. The soils on this site are described as moderately well drained silty clay loam over clay-with-flints or chalk, and are classified as Chromic Luvisol (F.A.O.) or Aquic Paleudalf (U.S.D.A.) (Macdonald et al., 2018; Silvertown et al., 2006). Plot 3d has not received any fertiliser or $CaCO_3$ (to manage soil pH) since 1856, the model has been set up with a baseline pH of 5.3 (based on the pH in 2011). Plot 4/1d has been treated with annual applications of triple superphosphate at an application rate of 3.5 g P m^{-2} yr^{-1} (equivalent to 35 kg ha^{-1} $year^{-1}$) from 1856 to 2016. From 2017 to 2021 the plot has received half the previous application rate of phosphate fertiliser in line with crop recommendations and soil stocks of plant-available P (AHDB, 2020c; Macdonald et al., 2018). Again plot 4/1d has not received any $CaCO_3$ amendments to manage soil pH and the model has been set with a baseline pH of 5.3 (based on the pH in 2011).

4.2.1.2 Soil nutrient analysis

Archived topsoil (0 – 23 cm) samples from 1985, 1991, 1998, 2001 and 2005 for each of the plots were analysed for organic and inorganic P. Data was previously published by Davies et al. (2016b). Analysis of organic P forms involved extraction with NaOH-EDTA solution followed by ^{31}P NMR analysis (Turner and Blackwell, 2013). Soil P pools were estimated by combining the P concentrations with reported bulk densities.

Archived topsoil (0 – 23 cm) samples from 1856, 1876, 1923 (C only), 1959, 2002 and 2017 for each of the plots were analysed for percentage soil organic C (SOC) and soil N content. These were converted to kg SOC ha^{-1} and kg N ha^{-1}, respectively, based on measured soil bulk densities for both plots[28] (information and data provided by Rothamsted Research from the e-RA database, unpublished).

For all observed data, results for a soil depth of 23 cm were proportionally adjusted to correspond to a depth of 15 cm to align with N14CP model parameters. To note, for all observed data there were no analytical or sample replications[29] available so there is no measure of uncertainty attributed to these data.

4.2.2 N14CP Model Summary

N14CP soil biogeochemistry model is designed to simulate the long-term cycling of C, N, and P in temperate semi-natural and agricultural systems (Davies et al., 2016a; Janes-Bassett et al., 2020). The model performs well when applied to the majority of semi-natural and agricultural land uses across the UK and Northern Europe (Davies et al., 2016a; Janes-Bassett et al., 2020; Janes-Bassett & et al., 2021; Tipping et al., 2012; Tipping et al., 2019; Tipping et al., 2017). Baseline model runs in this this paper will use the N14CP version developed by Janes-Bassett et al. (2020) to simulate and predict soil P stocks and plant productivity for the two contrasting agricultural sites. N14CP is driven by climate, geology, land use and management, and atmospheric deposition input data. Using a quarterly timestep, N14CP simulates biogeochemical processes in soils and specified plant functional types. Functioning over broad time and space with limited need for site specific calibration, N14CP can be used to simulate

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[28] Where bulk density was not measured in a given year, there was assumed to be no change in bulk density from the previous measured value.

[29] Replications were not included due to cost, time and complexity involved in the NMR methodology used to analyse organic P.

over decades and centuries and includes transitions between different land uses. A full model description can be found in Janes-Bassett et al. (2020) and Davies et al. (2016a); however, a brief summary of the P representation in the model is given here.

In current model versions, P enters the soil system from four sources, weathering of the parent material, atmospheric deposition, litter returned as plant residues or excrement from grazing and P fertiliser additions. Integrated with C and N, P cycling is represented via interconnected inorganic and organic pools in topsoil (0-15 cm) and subsoil compartments. N14CP simulates net primary productivity (NPP) and crop yield based on Liebig's law of minimum, prioritising the most limiting factor among temperature, precipitation, available N, or available P. Phosphorus mobilization from the topsoil is represented by leaching of inorganic P (remaining after plant uptake, immobilisation, and sorption) and dissolved organic P. A portion of this P accumulates in the subsoil in organic and inorganic forms before eventually undergoing further leaching. Connections between modelled grid cells are not yet considered.

4.2.3 Exploring alternative phosphorus sources in low input agricultural systems

This study explores sources of P to a crop that are not typically considered in N14CP that may be important for (modelling) crop production in low P input systems. This study investigated four different annual inputs of P to N14CP: i) increased atmospheric deposition of P; ii) the influence of historic P inputs on legacy P stores in the soil; iii) P inputs from litterfall (adjacent woodland) and other forms of miscellaneous annual inputs; and iv) P mobilisation between sites. The impact of increasing the potential pool of P that can be accessed through the weathering of the parent material and the control of P uptake by plants through variable plant stoichiometry under P limited scenarios was also investigated.

As with any measures to modify the key inputs to a model for one site, it is important to make sure these changes do not alter the model performance for other sites, as such any modelled changes to the no-input site (Plot 3d) were also made for Plot 4d and comparisons were made between the two plots. A summary of the baseline model values, and the modifications made to N14CP in this work are presented in **Table 4-1**.

4.2.3.1 Additional annual phosphorus inputs

4.2.3.1.1 Atmospheric phosphorus deposition

In baseline N14CP model versions (Janes-Bassett et al, 2022), atmospheric P deposition at a rate of 0.027 g m^{-2} yr^{-1} was included from year 1800. For this study, atmospheric P deposition rates were increased to 0.1 g total P m^{-2} yr^{-1} from 1800, following the introduction of intensive agricultural production (**Table 4-1**). This value is based on the maximum atmospheric P deposition rate included in the review of Tipping et al. (2014) and reflects current literature that has observed localised areas of high P deposition in areas with a high intensity of agricultural production (Mahowald et al., 2008). A lower pre-industrial P deposition rate (0.006 g total P m^{-2} yr^{-1}) was included in the model runs prior to 1800 (**Table 4-1**), this is to reflect non-anthropogenic P deposition. This value was again based on the review conducted by Tipping et al. (2014), taking the 5th percentile value from the global total P range included in the study.

Table 4-1: A summary of the baseline and modified N14CP model phosphorus (P) input parameters.

Parameter	Baseline N14CP input [a] [Years input applied to]	Modified P input [a] [Years input applied to]	Reference
Atmospheric deposition	0.027 g m^{-2} yr^{-1} [1800-2022]	0.006 g m^{-2} yr^{-1} [Pre 1800] 0.1 g m^{-2} yr^{-1} [1800-2022]	Tipping et al., 2014
Historic P inputs (arable land use 1500-1600)	0.0 g m^{-2} yr^{-1} [1600-1700]	1.1 g m^{-2} yr^{-1} [1600-1700]	Brunt, 2007
Miscellaneous P inputs (litterfall, non-livestock animal input)	0.0 g m^{-2} yr^{-1} [1856-2020]	Inorganic P: 0.002 g m^{-2} yr^{-1} Organic P: 0.006 g m^{-2} yr^{-1} [1856-2020]	De Frenne et al., 2022); Sohrt et al., 2017; Staelens et al., 2003
P Mobilisation	0.0 g m^{-2} yr^{-1} [1856-2020]	Used annual N14CP total dissolved P leaching outputs from adjacent plots to inform additional P inputs. [1856-2020]	**SI Table 4-1**
Initial pool of weatherable P	350 g m^{-2}	1000 g m^{-2}	Davies et al., 2016a
Plant stoichiometry (C:P / N:P ratio)[a]	350 / 10 [1856-2020]	560 / 16 [1856-2020]	White & Hammond, 2008

[a] Excludes any fertiliser inputs
[b] Applied to Plot 3d only

4.2.3.1.2 Historic phosphorus inputs and the legacy phosphorus effect

In previous model versions for simulations at UK sites, historic applications of manures in the 17th century were not previously accounted for on sites with evidence of historic agricultural use. However, literature (Brunt, 2007) supports the addition of manures to arable land in the UK at this time. Based on this manure (N and P) inputs were included in N14CP simulations at a rate equivalent to 35 tonnes manure ha^{-1} every 4 years, with annual applications equivalent to 8.75 tonnes manure ha^{-1} yr^{-1} (Brunt, 2007) (**Table 4-1**).

4.2.3.1.3 Miscellaneous phosphorus inputs

As discussed, P is imported through P fertiliser addition, and it is also recycled in the system as litter returned through plant residues or excrement from grazing. However, the model does not account for multiple plant types within a single site, nor does it account for inputs from non-grazing animals. For agricultural sites that are adjacent to woodland, it is likely that leaf litterfall could be a source of nutrients for the crop up to 20 m away (Staelens et al., 2003). Assuming a wooded area around a site with an approximate area of 0.2ha of woodland within 20m of the cropped area; a max P litterfall of 3.0 kg P ha^{-1} yr^{-1} (Sohrt et al., 2017); and an estimate of 10% of leaf litterfall falling between 10-20 metres from the woodland this would give a P input to the crop of 0.006 g P m^{-2} yr^{-1} added to the soft litter pool in N14CP (**Table 4-1**).

Within peri-urban landscapes domestic animals such as dogs can contribute to N and P inputs to land. Inputs from domestic animals are considered as net inputs, because these animals are fed off-site, often with a protein rich diet, which is in contrast to livestock or other grazing animals which recycle nutrients within the ecosystem (De Frenne et al., 2022; Schütz et al., 2006). Urine inputs up to 5 kg N ha^{-1} yr^{-1} and 0.13 kg P ha^{-1} yr^{-1} from 4.2 dogs ha^{-1} day^{-1} have been reported in some peri-urban ecosystems near major towns and cities (De Frenne et al., 2022). Reducing the number of dogs using the site per day (0.6 dogs ha^{-1} day^{-1}) to reflect a lower local population (ONS, 2021), an input of 0.07 g N m^{-2} yr^{-1} and 0.002 g P m^{-2} yr^{-1} was input into the model from the start of the long-term experiment (**Table 4-1**).

4.2.3.1.4 Phosphorus mobilisation between plots

There are no physical barriers to prevent mobilisation of dissolved P between the Park Grass plots, as such it is reasonable to expect that some P may be mobilised to adjacent plots either via surface or sub surface pathways. To account for this, modelled N14CP runoff and leaching total dissolved P outputs from immediately adjacent plots were used as inputs. Using the Park Grass experimental plot outline, for Plots 4/1d and 3d dissolved P inputs were considered from Plot 4/2d and 4/1d, respectively from the start of the long term experiments (**Table 4-1, SI Table 4-1**). This suggests maximum P inputs of approximately 0.25 g P m^{-2} yr^{-1} added to the available P pool in N14CP.

4.2.3.2 Initial pool of weatherable phosphorus

Within N14CP, this initial pool of weatherable P (P_{weath}) is given as a fixed input to the model and the rate of P release is based on first-order kinetics influenced by temperature and moisture. It is also assumed that the initial condition of P is site-specific and would not change between plots. Site-specific calibration in previous work (Janes-Bassett et al., 2020) estimated that P_{weath} within accessible substrate for the Park Grass sites would be approximately 350 g P m^{-2}. For this work, the initial pool of weatherable P was increased to 1000 g P m^{-2}, based on global search boundaries set by Davies et al. (2016a), (**Table 4-1**).

4.2.3.3 Variable plant stoichiometry

Vegetation in N14CP is represented by biomass pools which are defined by C:N:P ratios for broad plant functional type classifications, in the case of Park Grass Plots 4/1d and 3d, improved grassland. Literature values have been used to parameterise C:N:P stoichiometry, however plants can vary the C:N:P ratio of their biomass in response to nutrient availability (Güsewell, 2004). To reflect a reduced P uptake by plants in P-limited system, the C:P ratio of the plant soft biomass pool was increased from 350 to 560 to reflect a C:P of 10 and an N:P of 16. This is based on research that leaf N:P ratios greater than 16 suggest P-limited plant growth (White & Hammond, 2008). Changes to the plant stoichiometry were only applied to Plot 3d between 1700-2020 in response to the no fertiliser management practices for this plot (**Table 4-1**).

4.2.4 Exploring the model uncertainty for key model parameters

To explore model output uncertainty for each site under the different P histories and treatments an uncertainty analysis was carried out on four model parameters, f_{Psorb}, $f_{Pdesorb}$, $[C:P]_{lower}$, and $k_{immobP:N}$ (Chapter 3, **Table 4-2**). To explore these parameters a search (using 100 simulations) was made using a Latin Hypercube Sampling scheme to cover the parameter space.

Table 4-2: Model parameter values set within the uncertainty analysis (Chapter 3 of this thesis).

Parameter	**Description**	**Standard model parameter set value**	**Uncertainty analysis parameter range**
f_{Psorb}	Factor controlling sorption of inorganic P to soil surfaces	0.97	0.90-0.99
$f_{Pdesorb}$	Factor controlling desorption of inorganic P from soil surfaces	0.005	0.004-0.01
$[C:P]_{lower}$	C:P lower limit on immobilization restriction of P into SOM	100	75-125
$k_{immobP:N}$	Proportionality constant between P immobilization rate constant and N immobilization rate constant(s).	8.58	6.44-10.73

4.3 Results

4.3.1 Observed data and N14CP baseline model runs

Observed soil C, N, P and yield data from the Park Grass experimental plots 4/1d and 3d were analysed periodically throughout the long-term experiment (**Figure 4-2**, **Figure 4-3** and **Figure 4-4**). Where there are no fertiliser additions (Plot 3d) soil P stocks are significantly less than the plot receiving annual inputs of phosphate fertiliser (4/1d) ($t(4) = 28.92$, $p < 0.001$)[30]. In the absence of fertiliser inputs, organic P contributes approximately 77% of the measured P in the soil, this contrasts with the P only plots where P inputs appear to accumulate in the soil in inorganic P forms and contributes approximately 76% of the measured P for Plot 4/1d. Between Plots 3d and 4/1d, observed SOC and total soil N stocks show no significant difference ($t(5) =$

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[30] Plot 3d Observed: M = 77 g total P m^{-2}, SD = 3.52. Plot 4/1d Observed: M = 306 g total P m^{-2}, SD = 15.23.

0.08, $p = 0.94$ [31] and $t(4) = 0.03$, $p = 0.98$ [32], respectively) (**Figure 4-3** and **Figure 4-4**). Similarly, for most years, observed crop yields for Plot 4/1d are greater than Plot 3d however these differences are not significant ($t(4) = 2.23$, $p = 0.09$)[33] (**Figure 4-2**).

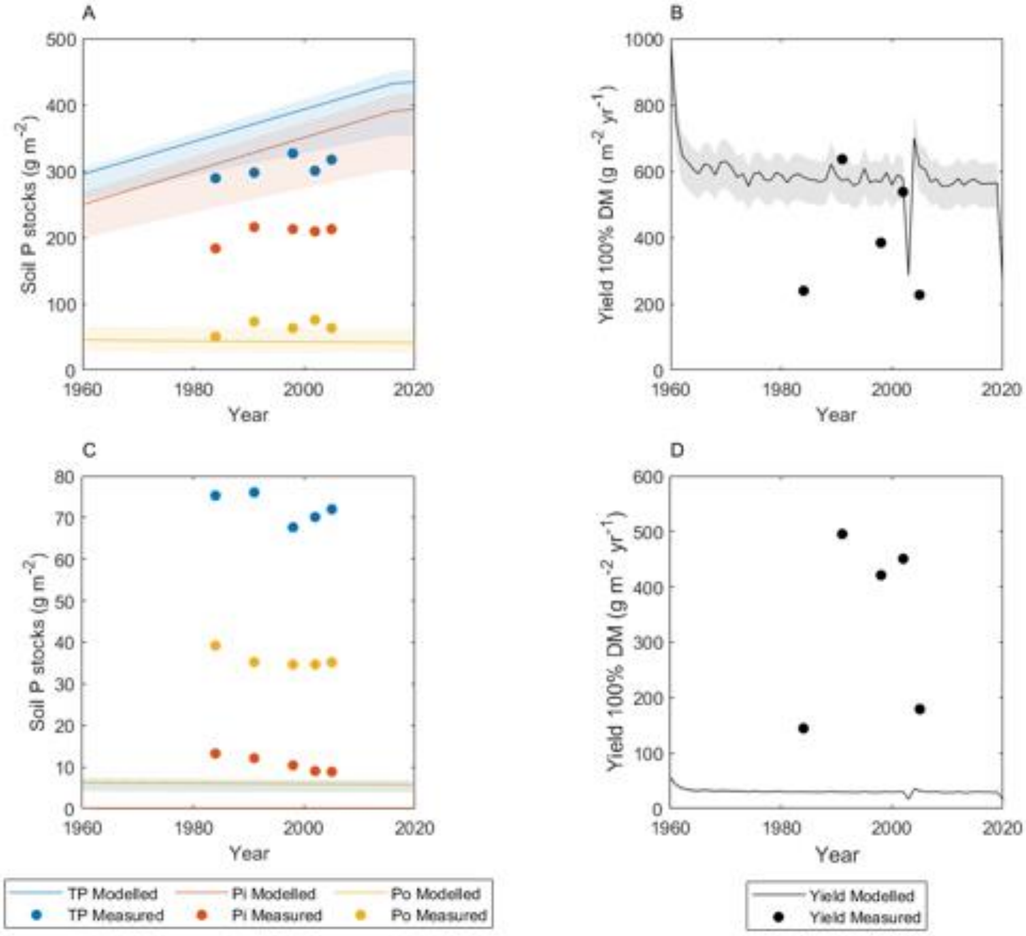

Figure 4-2: (A) Plot 4/1d (phosphorus (P) only fertiliser plot) baseline modelled (line, shaded areas indicate 5th and 95th percentiles based on the uncertainty analysis) and observed (points) soil P stocks (total (TP), inorganic (Pi), and organic (Po) phosphorus). Plot 4/1d modelled TP stocks ($M = 383$ g m^{-2}, $SD = 20.08$) are significantly greater than measured TP stocks ($M = 306$ g m^{-2}, $SD = 15.23$); $t(4) = 11.21$, $p < 0.001$. (B) Plot 4/1d (P only fertiliser plot) baseline modelled yields (line, shaded areas indicate 5th and 95th percentiles based on the uncertainty analysis) and observed yields (points). Plot 4/1d modelled yields ($M = 582$ g m^{-2}, $SD = 18.79$) are not significantly different to the observed yields ($M = 405$ g m^{-2}, $SD = 180.74$); $t(4) = 2.05$, $p = 0.109$. (C) Plot 3d (no fertiliser plot) baseline modelled (line, shaded areas indicate 5th and 95th percentiles based on the uncertainty analysis) and observed (points) soil P stocks (TP, Pi, and Po). Plot 3d modelled TP stocks ($M = 6$ g m^{-2}, $SD = 0.06$) are significantly less than the observed TP stocks ($M = 72$ g m^{-2}, $SD = 3.52$); $t(4) = 42.64$, $p < 0.001$. (D) Plot 3d (phosphorus only fertiliser plot) baseline modelled yields (line, shaded areas indicate 5th and 95th percentiles based on the uncertainty analysis) and observed yields (points). Plot 3d modelled yields ($M = 30$ g m^{-2}, $SD = 0.89$) are significantly less than the observed yields ($M = 338$ g m^{-2}, $SD = 163.45$); $t(4) = 4.20$, $p = 0.014$.

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[31] Plot 3d Observed: M = 5427 g SOC m^{-2}, SD = 350.49/ Plot 4/1d Observed: M = 5437 g SOC m^{-2}, SD = 410.22.

[32] Plot 3d Observed: M = 444 g total N m^{-2}, SD = 46.80. Plot 4/1d Observed: M = 445 g total N m^{-2}, SD = 59.59.

[33] Plot 3d Observed: M = 338 g m^{-2} yr^{-1} 100% DM, SD = 163. Plot 4/1d Observed: M = 405 g m^{-2} yr^{-1} 100% DM, SD = 180.74.

N14CP baseline runs appear to be overestimating total P stocks by approximately 20% compared to the measured data for Plot 4/1d, largely due to the over-estimation of soil inorganic P stocks. Whereas organic P stocks appear to have a better modelled fit with the observed data for this plot (**Figure 4-2**). However, it is worth noting again that the observed data collected here does not include any analytical or sample replicates so uncertainty in this data cannot be accounted for. In contrast, modelled SOC and soil N stocks are significantly underestimated compared to measured data for Plot 4/1d ($t(5) = 5.82$, $p = 0.002$ [34] and $t(4) = 10.34$, $p < 0.001$ [35], respectively), but for soil N stocks these are generally within the bounds of uncertainty

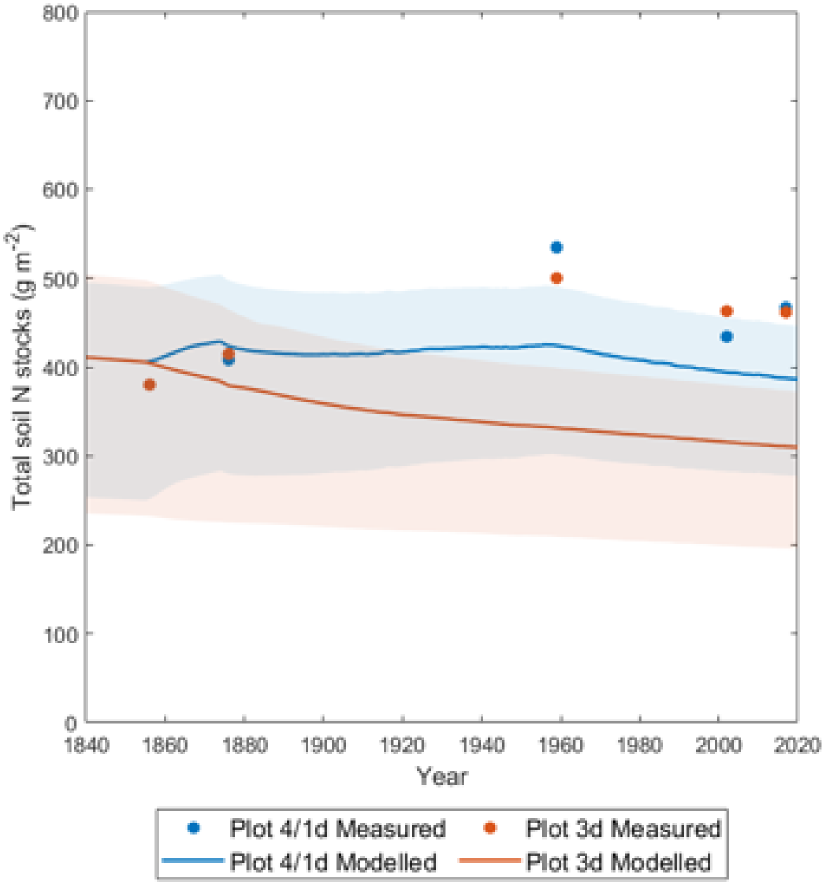

Figure 4-3: Modelled (line, shaded areas indicate 5th and 95th percentiles based on the uncertainty analysis) and observed (points) soil nitrogen (N) stocks for Park Grass Plots 3d and 4/1d. Plot 3d: modelled soil N (M = 348 g N m^{-2}, SD = 41.60), are significantly less than observed soil N data (M = 444 g N m^{-2}, SD = 46.80); t(4) = 15.83, p < 0.001. Plot 4/1d: modelled soil N (M = 407 g N m^{-2}, SD = 16.77), are significantly less than observed data (M = 445 g N m^{-2}, SD = 59.59); t(4) = 10.34, p < 0.001.

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[34] Plot 4/1d Observed: M = 5437 g SOC m^{-2}, SD = 410.22. Plot 4/1d Baseline Modelled: M = 4327 g SCO m^{-2}, SD = 370.52.

[35] Plot 4/1d Observed: M = 445 g N m^{-2}, SD = 59.59. Plot 4/1d Baseline Modelled: M = 407 g m^{-2}, SD = 16.77.

(**Figure 4-3** and **Figure 4-4**). Observed and modelled yields are not significantly different for Plot 4/1d (t(4) = 2.11, p = 0.102)[36], however observed yields do show much greater annual variation compared to the modelled data[37] (**Figure 4-2**).

Modelled SOC, soil P and N stocks and yield for Plot 3d are significantly less than the observed data and follow a different trend over time (**Figure 4-2**, soil total P [38]: t(4) = 42.64, p < 0.001; yield [39]: t(4) = 4.20, p = 0.014; **Figure 4-3**, soil total N [40]: t(4) = 15.83, p < 0.001; **Figure 4-4**,

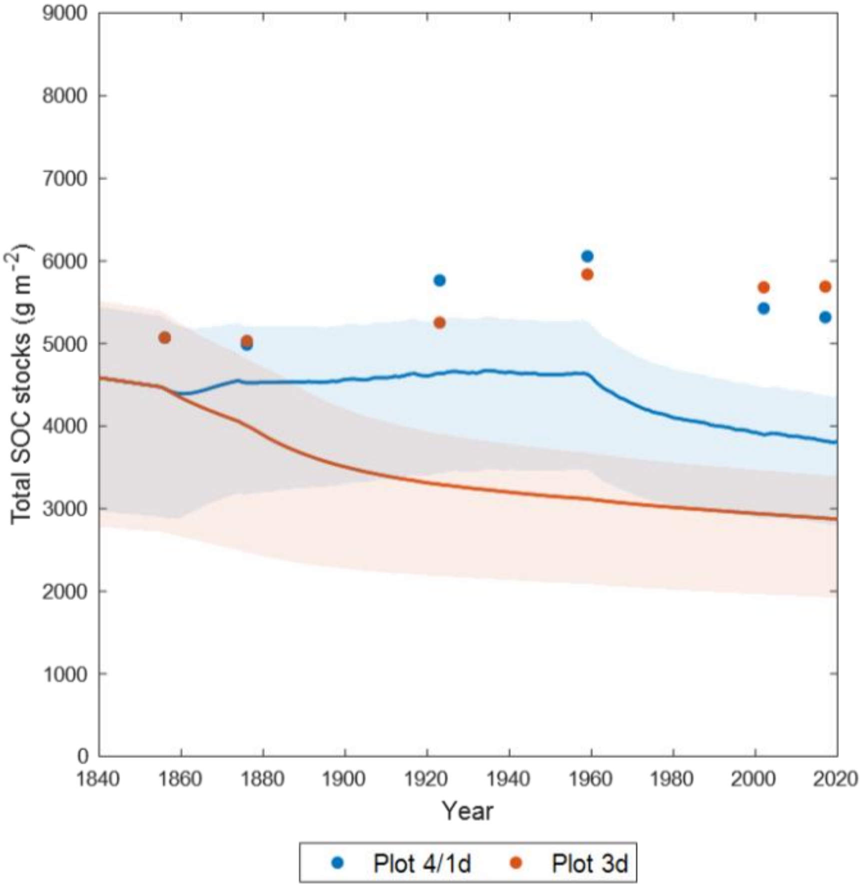

Figure 4-4: Modelled (line, shaded areas indicate 5th and 95th percentiles based on the uncertainty analysis) and observed (points) soil organic carbon (SOC) stocks Park Grass Plots 3d and 4/1d. Plot 3d: modelled SOC (M = 3449 g m-2, SD = 637.48), is significantly less than observed data (M = 5427 g m-2, SD = 350.49); t(5) = 5.07, p = 0.004. Plot 4/1d: modelled SOC (M = 4327 g m-2, SD = 370.52), is significantly less than observed data (M = 5437 g m-2, SD = 410.22); t(5) = 5.82, p = 0.002.

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[36] Plot 4/1d Observed: M = 404.80 g m^{-2} yr^{-1} 100% DM, SD = 180.74. Plot 4/1d Baseline Modelled: M = 591 g m^{-2} yr^{-1}, SD = 22.87

[37] The modelled yield drop in 2003 was a result of a modelled single annual harvest to reflect site management practices for that year; for other years, two harvests were taken from the plot.

[38] Plot 3d Observed: M = 72 g P m^{-2}, SD = 3.52. Plot 3d Baseline Modelled: M = 6 g P m^{-2}, SD = 0.06.

[39] Plot 3d Observed: M = 338 g m^{-2} yr^{-1} 100% DM, SD = 163.45. Plot 3d Baseline Modelled: M = 30 g m^{-2} yr^{-1} 100% DM, SD = 0.89

[40] Plot 3d Observed: M = 444 g N m^{-2}, SD = 46.80. Plot 3d Baseline Modelled: M = 348 g N m^{-2}, SD = 41.60.

SOC [41]: t(5) = 5.07, p = 0.004.). Mean yields on this plot are underestimated by approximately 300 g m^{-2} yr^{-1} equivalent to an annual P input deficit of approximately 0.9 g m^{-2} yr^{-1} (equivalent to approximately 9.0 kg P ha^{-1} yr^{-1}). Six possible sources/inputs of P that could be important for sustaining the current level of crop production and soil P stocks under prolonged no fertiliser conditions were explored using N14CP.

4.3.2 Exploring N14CP sensitivity to alternative phosphorus sources

4.3.2.1 Additional annual phosphorus inputs

Increasing the amount of atmospheric P deposition simulated in N14CP, increased modelled soil inorganic P stocks in 2020 by 14 g m^{-2} and less than 1 g m^{-2} for Plots 4/1d and 3d, respectively (**Figure 4-5A** and **Figure 4-7A**). For Plot 3d this additional input was not sufficient to explain the gap between the modelled and observed soil P stocks, with N14CP total soil P stocks remaining significantly less than observed data (t(4) = 42.39, p < 0.001)[42]. Despite a very small change in soil P stocks, modelled yields on Plot 3d showed an increase of 34% in 2020 as a result of increased P deposition inputs to N14CP (**Figure 4-8A**). However, this increase was not sufficient to meet the observed P requirement of the crop and Plot 3d modelled yields were significantly less than observed yields (t(4) = 3.39, p = 0.03)[43]. For Plot 4/1d the additional P from increased atmospheric P deposition increased modelled yield by just 1% (**Figure 4-6A**).

N14CP data suggest that the historic P applications at the specified manure loadings from the years 1600-1700 may have been in excess of crop requirement, resulting in approximately 6 g m^{-2} accumulation of P in the soil during this period (**Figure 4-5B** and **Figure 4-7B**). However,

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[41] Plot 3d Observed: M = 5427 g SOC m^{-2}, SD = 350.49). Plot 3d Baseline Modelled: M = 3449 g SOC m^{-2}, SD = 637.48.

[42] Plot 3d Observed: M = 72 g P m^{-2}, SD = 3.52. Plot 3d Pdep Modified modelled: M = 7 g P m^{-2}, SD = 0.08.

[43] Plot 3d Observed: M = 338 g m^{-2} yr^{-1} 100% DM, SD = 163.45. Plot 3d Pdep Modified modelled: M = 88 g m^{-2} yr^{-1} 100% DM, SD = 2.54.

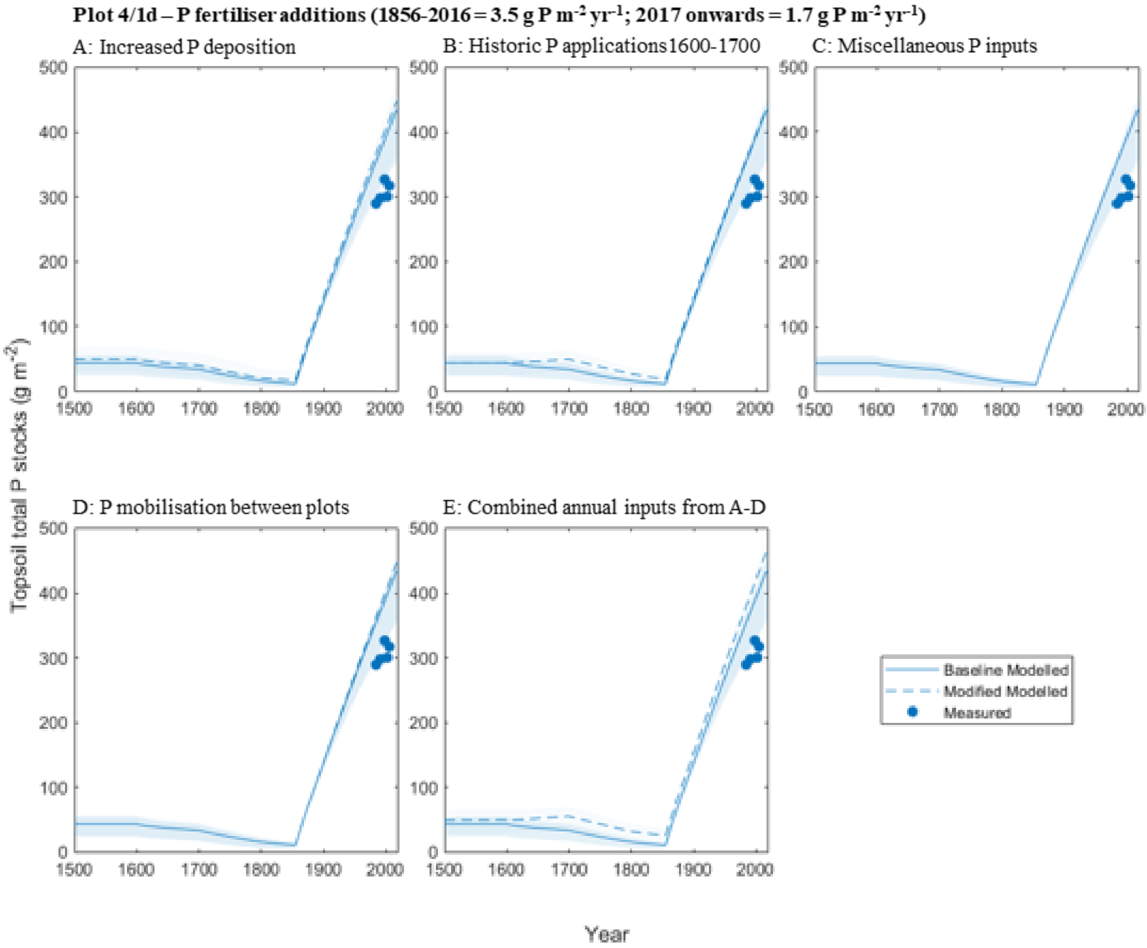

Figure 4-5: Plot 4/1d (phosphorus (P) only fertiliser plot) baseline modelled (solid line, shaded areas indicate 5th and 95th percentiles based on the uncertainty analysis), observed (points) and modified modelled (dashed line) soil total P stock timeseries. N14CP modifications based on annual P inputs for (A) increased P deposition; (B) historic P applications 1600-1700; (C) miscellaneous P inputs; (D) P mobilisation between plots; and (E) combined annual inputs from A-D.

P applications, in the form of manures, during the 17th century had very little impact on the either the soil P stocks or grass yield in the 20th and 21st century (**Figures 3B – 6B**). The legacy P effect contributed to just a 2-3% increase in modelled yields in 2020 for both Plots 3d and 4/1d compared to the baseline modelled data. For Plot 3d the inclusion of Historic P applications was not enough to explain the persistent observed soil P and yield measurements (**Figure 4-7B** and **Figure 4-8B**).

Similar to the previous scenarios, the influence of mixed land use (P input from litterfall of adjacent woodland and domestic animals that access the land) were not sufficient to meet the soil P stocks and the crop P demand for Plot 3d (**Figure 4-7C** and **Figure 4-8C**), with modelled

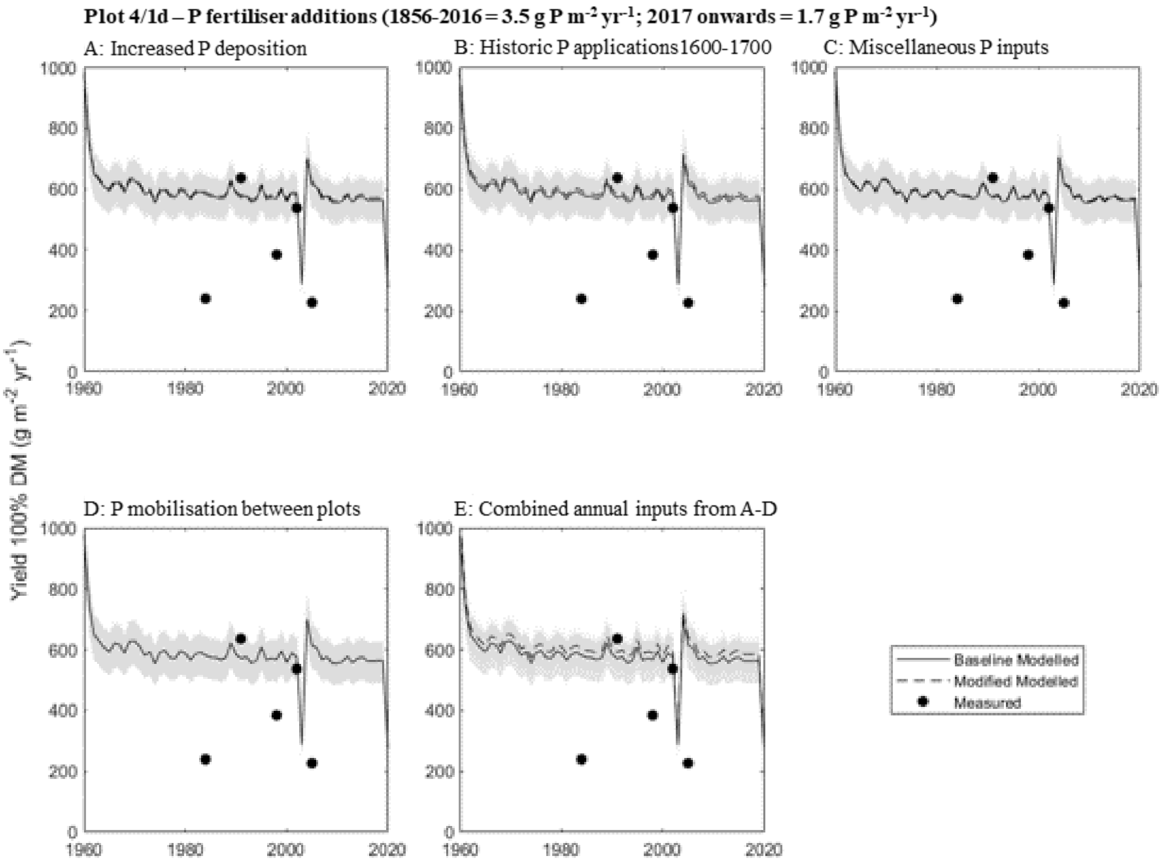

Figure 4-6: Plot 4/1d (phosphorus (P) only fertiliser plot) baseline modelled (solid line, shaded areas indicate 5th and 95th percentiles based on the uncertainty analysis), observed (points) and modified modelled (dashed line) grassland yield timeseries. N14CP modifications based on annual P inputs for (A) increased P deposition; (B) historic P applications 1600-1700; (C) miscellaneous P inputs; (D) P mobilisation between plots; and (E) combined annual inputs from A-D.

data still significantly less than observed values (soil total P [44]: $t(4) = 42.64$, $p < 0.001$; yield [45]: $t(4) = 4.17$, $p = 0.01$). For Plot 4/1d these inputs made less than 1% change to modelled yields and soil total P (**Figure 4-5C** and **Figure 4-6C**).

To consider the impact of P mobilisation between the Park Grass plots, modelled total dissolved P outputs from adjacent plots were input to Plots 3d and 4/1d. For plot 3d there was a mean annual P inputs from adjacent plot 4/1d of approximately 0.13 g m^{-2} yr^{-1} with a maximum annual input of approximately 0.26 g m^{-2} yr^{-1} (**SI Table 4-1**). Similarly, P mobilisation from adjacent plots to Plot 4/1d accounted for an additional 0.01-0.17 g m^{-2} yr^{-1}. For Plot 4/1d, the amount of

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[44] Plot 3d Observed: M = 72 g P m^{-2}, SD = 3.52. Plot 3d MiscP Modified: M = 6 g P m^{-2}, SD = 0.06.

[45] Plot 3d Observed: M = 338 g m^{-2} yr^{-1} 100% DM, SD = 163.45. Plot 3d MiscP Modified: M = 32 g m^{-2} yr^{-1} 100% DM, SD = 0.93.

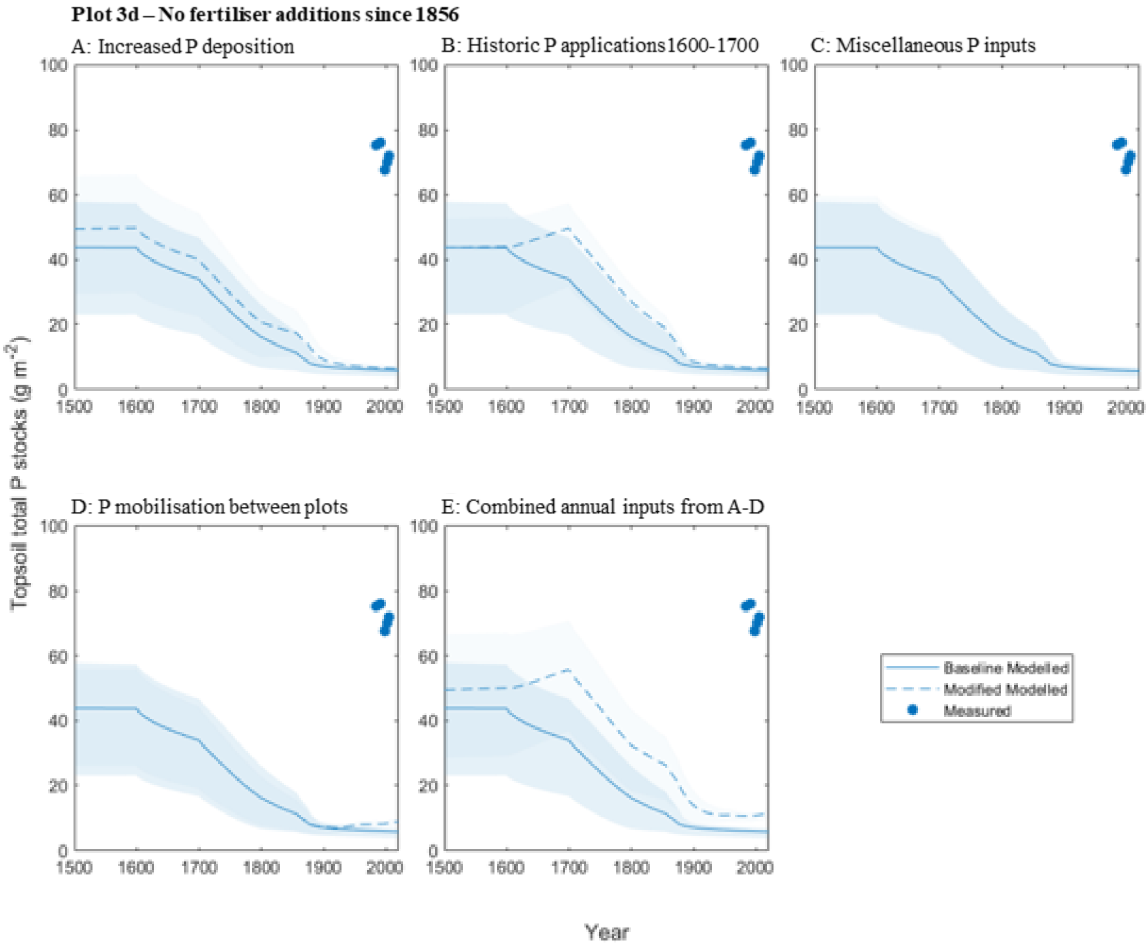

Figure 4-7: Plot 3d (no fertiliser plot) baseline modelled (solid line, shaded areas indicate 5th and 95th percentiles based on the uncertainty analysis), observed (points) and modified modelled (dashed line) soil total phosphorus stock timeseries. N14CP modifications based on annual P inputs for (A) increased P deposition; (B) historic P applications 1600-1700; (C) miscellaneous P inputs; (D) P mobilisation between plots; and (E) combined annual inputs from A-D.

dissolved P modelled to enter via mobilisation pathways was slightly less than the amount of dissolved P modelled being lost from the plot via the same pathways (**SI Table 4-1**). Accounting for additional dissolved P inputs from adjacent plots had very little impact on soil P stocks for either Plots 3d and 4/1d (**Figure 4-5D** and **Figure 4-7D**). Yields on plot 4/1d also did not change greatly (**Figure 4-6D**, 0.1% increase). However, for Plot 3d, modelled yields increased by more than 6.5 times compared to baseline modelled yields (**Figure 4-8D**).

The four annual P input scenarios were combined to explore the cumulative effects of increased atmospheric deposition, historic P inputs, mixed land use inputs and dissolved P inputs via P mobilisation pathways. For Plot 4/1d modelled total soil P stocks and yields in 2020 increased

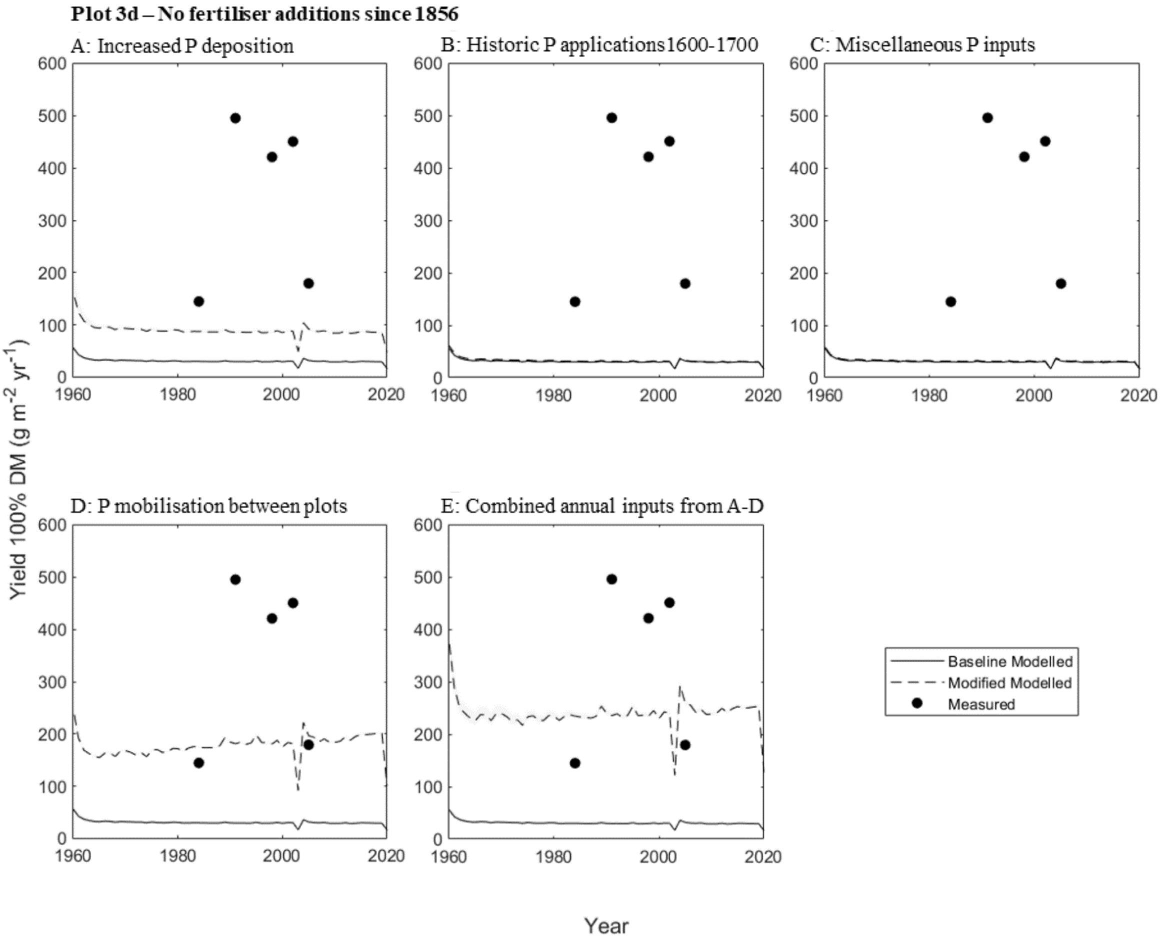

Figure 4-8: Plot 3d (no fertiliser plot) baseline modelled (solid line, shaded areas indicate 5th and 95th percentiles based on the uncertainty analysis), observed (points) and modified modelled (dashed line) grassland yield timeseries. N14CP modifications based on annual P inputs for (A) increased P deposition; (B) historic P applications 1600-1700; (C) miscellaneous P inputs; (D) P mobilisation between plots; and (E) combined annual inputs from A-D.

by approximately 31 g m^{-2} and 11 g m^{-2} yr^{-1} at 100% DM respectively (**Figure 4-5E** and **Figure 4-6E**). Compared to observed yield data, the modelled yields for the combined P input scenarios for Plot 4/1d were not significantly different (t(4) = 2.31, p = 0.08) [46]. In contrast, modelled soil P stocks for Plot 3d under the combined annual P input scenario almost doubled by the end of the simulation period (**Figure 4-7E**), however these are still significantly less than observed values (t(4) = 38.23, $p < 0.001$)[47]. The combined increased annual P input scenario had a large impact on Plot 3d modelled yields, with 2020 yields increasing from the modelled baseline of

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[46] Plot 4/1d Observed M = 405 g m^{-2} yr^{-1} 100% DM, SD = 180.74. Plot 4/1d Annual P Modified: M = 605 g m^{-2} yr^{-1}, SD = 19.66

[47] Plot 3d Observed: M = 72 g P m^{-2}, SD = 3.52. Plot 3d Annual P Modified: M = 11 g P m^{-2}, SD = 0.14.

16 g m^{-2} yr^{-1} 100% DM to 127 g m^{-2} yr^{-1} (**Figure 4-8E**). These modelled data are now not significantly different to the observed yield values (t(4) = 1.30, p = 0.26)[48], although do not show the same magnitude of inter-annual fluctuations as the observed values.

4.3.2.2 Initial pool of weatherable phosphorus

Baseline modelled data suggest that total P stocks prior to conversion of the land to agricultural land uses, around the year 1600, was just over half that of contemporary soil P stocks observed on Plots 3d (**Figure 4-9A** and **C**). To explore the effect soil parent material P stocks on contemporary P pools, the initial pool of weatherable P in the model was increased by approximately 2.5 times compared to the baseline (and previously calibrated) P_{weath0} value. Increasing the initial pool of weatherable P increased the soil total P stock of the soils for both plots by approximately 60% in 1600 (**Figure 4-9A** and **C**). However, for Plot 3d modelled soil P stocks rapidly declined after this date and by the early 20th century, modelled total soil P stocks had declined to less than 10 g m^{-2} in the absence of any P inputs. Although there was a slight rise in modelled yield for plot 3d (approximately 5 g m^{-2} yr^{-1} at 100 DM, **Figure 4-9D**) as a result of increasing the amount of weatherable P, modelled grassland yields remained significantly less than observed yields (t(4) = 4.05, p = 0.02)[49].

The effect of increasing the initial pool of weatherable P had little effect on modelled contemporary total soil P (1.9% increase compared to baseline modelled data) and yields (3.2% increase compared to baseline modelled data) for Plot 4/1d (**Figure 4-9A** and **B**). Although modelled yields did slightly increase in this scenario, modified modelled yield data was not significantly different to observed yield data (t(4) = 2.25, p = 0.09) [50].

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[48] Plot 3d Observed: M = 338 g m^{-2} yr^{-1} 100% DM, SD = 163.45. Plot 3d Annual P Modified: M = 240 g m^{-2} yr^{-1}, SD = 10.46

[49] Plot 3d Observed: M = 338 g m^{-2} yr^{-1} 100% DM, SD = 163.45. Plot 3d P_{weath0} Modified: M = 40 g m^{-2} yr^{-1}, SD = 1.03

[50] Plot 4/1d Observed M = 405 g m^{-2} yr^{-1} 100% DM, SD = 180.74. Plot 4/1d P_{weath0} Modified: M = 600 g m^{-2} yr^{-1}, SD = 19.51

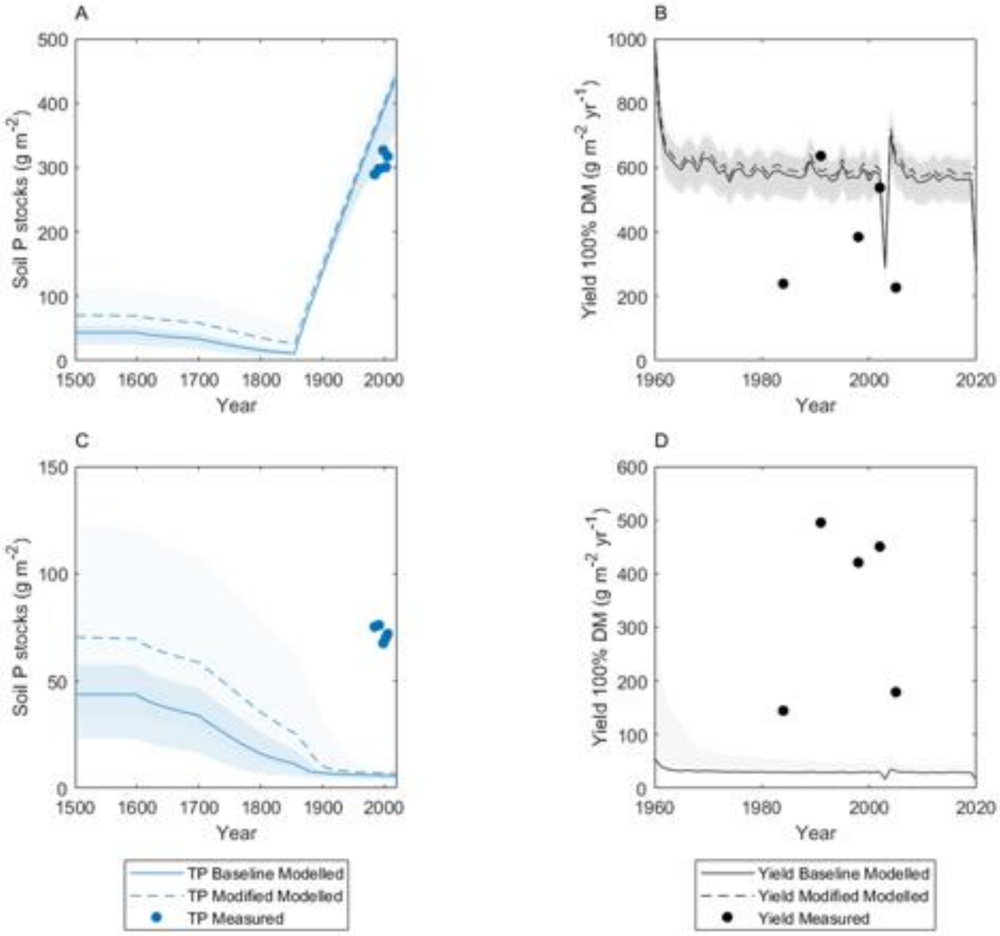

Figure 4-9: Timeseries of baseline modelled (solid line, shaded areas indicate 5th and 95th percentiles based on the uncertainty analysis), observed (points) and modified modelled data (increased initial pool of weatherable phosphorus; dashed line); (A) Plot 4/1d (phosphorus only fertiliser plot) total soil P stock; (B) Plot 4/1d grass yield; (C) Plot 3d (no fertiliser plot) total soil P stock; and (D) Plot 3d grass yield).

4.3.2.3 Variable plant stoichiometry

Changes to the plant stoichiometry were applied to Plot 3d between from 1700-2020 in response to the agricultural management practices for this plot. No changes were made to Plot 4/1d as soil P was not considered a limiting factor to crop growth. Increasing the C:P ratio of soft plant biomass in the model slowed down the reduction of soil total P following the predicted onset of agricultural management of the site in 1700 (**Figure 4-10A**). However, by the early 2000s modelled soil P stocks and yields were still less than observed data (soil total P [51]: t(4) = 42.54, p < 0.001; yield [52]: t(4) = 3.86, p = 0.02) (**Figure 4-10**).

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[51] Plot 3d Observed: M = 72 g P m^{-2}, SD = 3.52. Plot 3d High C:P Modified: M = 6 g P m^{-2}, SD = 0.91.

[52] Plot 3d Observed: M = 338 g m^{-2} yr^{-1} 100% DM, SD = 163.45. Plot 3d High C:P Modified: M = 54 g m^{-2} yr^{-1}, SD = 1.34.

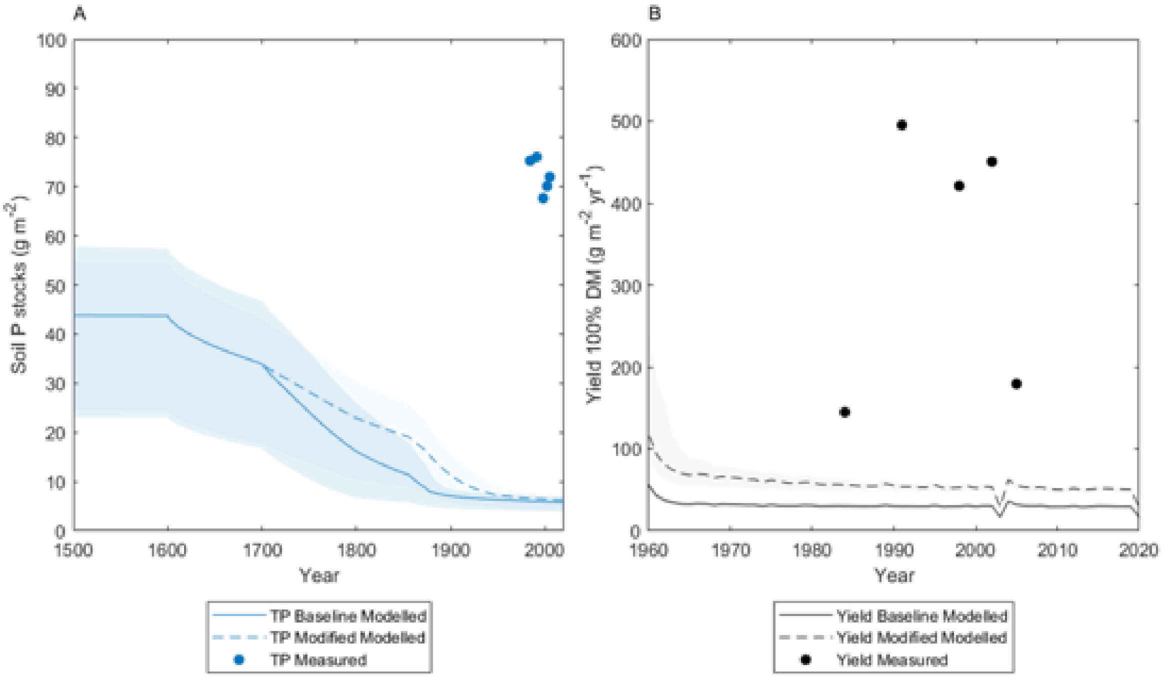

Figure 4-10: Timeseries of baseline modelled (solid line, shaded areas indicate 5th and 95th percentiles based on the uncertainty analysis), observed (points) and modified modelled data (increased C:P ratio of plant biomass; dashed line; (A) Plot 3d (no fertiliser plot) total soil P stock; and (B) Plot 3d grass yield).

4.3.2.4 Combined scenarios

Individually the additional P inputs to the model from the previous scenarios were not enough to account for the persistent soil P stocks and yields on Plot 3d, receiving no fertiliser input. The effects of the combined changes to soil total P and grass yield for both Plots 3d and 4/1d can be seen in **Figure 4-11**. Modelled soil P stocks increased by approximately 7.5 times in 2020 for Plot 3d under this scenario (**Figure 4-11C**). Despite this increase, modified N14CP soil P stocks remained significantly less than the observed total P stocks ($t(4) = 24.09$, $p < 0.001$)[53]. Modelled soil P for Plot 4/1d also showed an approximately 11% increase compared to the baseline N14CP data (**Figure 4-11A**), as such modelled soil P stocks remained significantly greater than observed data ($t(4) = 16.28$, $p = 0.15$)[54].

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[53] Plot 3d Observed: M = 72 g P m^{-2}, SD = 3.52. Plot 3d Combined P Modified: M = 40 g P m^{-2}, SD = 0.84.

[54] Plot 4/1d Observed: M = 306 g P m^{-2}, SD = 15.23. Plot 4/1d Combined P Modified: M = 427 g P m^{-2} SD = 22.08

Modelled yields for Plot 4/1d increased marginally under the combined P scenario compared to the baseline N14CP model runs with mean yields increasing by 17 g m^{-2} yr^{-1} at 100 DM and modelled yields remained not significantly different to observed yields (**Figure 4-11B**)[55]. Similar to the modelled soil total P, the modified N14CP P inputs had a greater effect on the yields for Plot 3d compared to Plot 4/1d, increasing yield by more than 16 times compared to the baseline scenario (**Figure 4-11D**). Modelled yields for this plot are now being overestimated compared to the observed values, although this is not quite statistically significant (t(4) = 2.43, p = 0.05)[56].

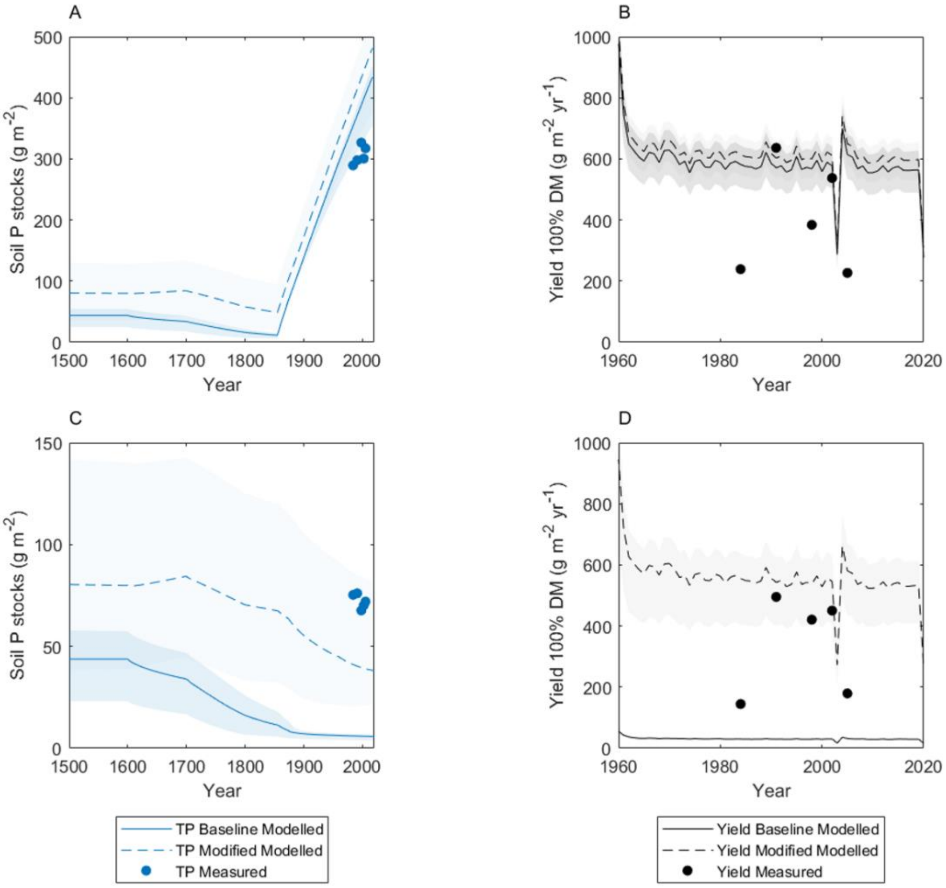

Figure 4-11: Timeseries of baseline modelled (solid line, shaded areas indicate 5th and 95th percentiles based on the uncertainty analysis), observed (points) and modified modelled data (combined scenario based on modified annual P inputs, increased initial pool of weatherable P and increased C:P ratio of plant biomass (plot 3d only); dashed line; (A) Plot 4/1d (phosphorus only fertiliser plot) total soil P stock; (B) Plot 4/1d grass yield; (C) Plot 3d (no fertiliser plot) total soil P stock; and (D) Plot 3d grass yield).

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[55] Plot 4/1d Observed M = 405 g m^{-2} yr^{-1} 100% DM, SD = 180.74; Plot 4/1d Combined P Modified: M = 615 g m^{-2} yr^{-1}, SD = 20.08; t(4) = 2.43, p = 0.07

[56] Plot 3d Observed: M = 338 g m^{-2} yr^{-1} 100% DM, SD = 163.45. Plot 3d Combined P Modified: M = 553 g m^{-2} yr^{-1} 100% DM, SD = 16.93

4.4 Discussion

4.4.1 Baseline model performance and comparison with observed data

4.4.1.1 Plot 4/1d – phosphorus fertiliser inputs only

Baseline N14CP modelled data were compared with observed soil P stocks (total, organic and inorganic P), SOC stocks, soil N stocks, and yield for Plot 4/1d (P fertiliser only) of the Park Grass long term experimental site. Overall, the model showed a reasonably good fit with observed data, capturing some of the temporal trends for soil P, SOC, and soil N (**Figure 4-2A, B**, **Figure 4-3**, and **Figure 4-4**). However, differences between modelled and observed data ranged from 10% to 40%, which is higher than the typical variation of around 15% reported in previous work with N14CP (Janes-Bassett et al., 2020).

The largest differences were seen in the inorganic P and SOC data, suggesting that, representation of these parameters in N14CP could be improved. Adjusting model parameters as part of the uncertainty analysis may help to account for some of the variability in soil properties. However, N14CP currently lacks many plant and microbial mechanisms critical to SOC and P cycling, which are fundamental processes in terrestrial ecosystems (Richardson et al., 2011; Vance et al., 2003). Furthermore, it is important to note that measurement uncertainty for SOC, N, and P analysis can range from 5% to 35% (Goidts et al., 2009; Jarosch et al., 2015; Turner, 2008) but due to the lack of analytical or sample replications available there was no measure of uncertainty attributed to observed data. This highlights the importance of improved model representation of some key processes (with site-specific calibrations where appropriate) and the need for data replicates for model testing and validation.

4.4.1.2 Plot 3d – no fertiliser inputs

As expected, baseline model runs greatly underestimated soil P stocks and grassland yield compared to observed data for Plot 3d (no fertiliser) (**Figure 4-2C** and **D**). Following the systematic changes made to the P inputs and processes within N14CP[57], overall findings from this work suggest that these are not sufficient to account for the observed total soil P stocks of Plot 3d of the Park Grass long term experiment (**Figure 4-11C**).

4.4.1.3 Total, organic and inorganic phosphorus stocks

Inorganic P forms, in particular orthophosphates, account for much of the P that is applied to agricultural sites as fertilisers and manures (approximately 35-75% of the total P in manures is in the form of inorganic orthophosphates (Pagliari & Laboski, 2012)). N14CP model predictions suggest that, from the beginning of the long-term experiments, the P fertiliser inputs to Plot 4/1d have exceeded the crop requirement, leading to a rapid accumulation of P stores primarily in inorganic P forms (**SI Figure 4-1**). The accumulation of inorganic P in the soil following long-term P fertiliser additions is supported by the observed data from this plot, with modelled and observed inorganic P stocks contributing approximately 90% and 75% of the total soil P, respectively by 2005. Many long-term field studies exploring the effects of high P fertiliser and manure use (i.e. P inputs exceeding P offtake) and the accumulation of P have also demonstrated an increase in the inorganic P pools, based on common soil P tests (e.g. Olsen P, Mehlich-3, Morgan's P, etc.) (Blake et al., 2003b; Negassa & Leinweber, 2009; Rowe et al., 2016; Sharpley et al., 2004). However, some of the accumulated inorganic P is immobilised to organic forms of P. Although not readily available for crop utilisation, soils contain 30-90% organic P, much of which will be contained within plant residues or microbial cells (Bardgett, 2005; Stutter et al., 2012). While P fertiliser has had a large effect on the inorganic P pools in the soil (an increase of 395 g P m^{-2} compared to the no-fertiliser plots), compared to Plot 3d (no fertiliser) soil organic P stocks for Plot 4/1d were only increased by approximately 27 g P m^{-2}. Data from this work have demonstrated that modelled soil organic P stocks are significantly

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[57] (1) elevated atmospheric P deposition; (2) historic applications of manure; (3) annual non-fertiliser P imports (e.g. the P contribution of leaf litterfall and non-livestock animal excretion); (4) P mobilisation between plots; (5) elevated concentrations of weatherable P from parent material; and (6) flexible plant stoichiometry in response to P stress on soil P concentrations and crop yield.

less than the observed data suggesting that less of the excess P applied is being immobilised into the soil organic matter pools within the model.

Phosphorus mineralisation and immobilisation within N14CP are proportional both to the C and N storage in the fast, slow, and passive soil organic matter pools. In the absence of fertiliser inputs, the organic P pools represent a larger proportion of the Total P in the soil, contributing to 77% of the total soil P in the soil. The quantifying the contribution of organic P to agricultural production is highly debated and remains poorly understood (George et al., 2018), for systems with high inorganic P inputs work has even shown that P mineralisation can be inhibited and through the repression of phosphatase synthesis (Janes-Bassett et al., 2022). Organic P plays and important role in the supply of nutrients to semi-natural systems and low-P soils. Tropical soils typically contain low total P but proportionally high stocks of organic P compared to labile P (G Nziguheba & E. K. Bünemann, 2005). Investigating how they utilise organic P for crop growth could help to improve existing model responses to organic P and model impacts of systems where P fertiliser use is reduced or eliminated.

The modelled scenarios used to explore the soil P stocks observed were applied to both Plot 3d and Plot 4/1d. Proportionally, the modelled increases in soil P stocks and yield had a greater impact for Plot 3d (**Figures 3 – 9**) compared to Plot 4/1d. The reduced responses to these P scenarios on Plot 4/1d are likely due to N limitation, as reflected within the N14CP model outputs. As a result, any P that is applied above that which can be supported by the available N for plant growth would likely be stored in soil P pools and / or transported out of the soil system (Craine & Jackson, 2010). Whereas the additional P availability in the scenarios for Plot 3d is preferentially being used for plant productivity, reflecting the greater yield response modelled by N14CP compared to the changes in soil total P and the inherent prioritisation of available nutrients for plant production in the model. This supports the literature that demonstrates that crop responses to P application are expected when soil test P stocks are low, or below a critical P level, with greater responses to P application expected with lower soil P stocks (Bai et al., 2013; Johnston & Poulton, 2011, 2019; Tang et al., 2009). The combined P scenarios suggest that the additional P is sufficient to meet the crop demand, for the modelled amount of N in the soil, to achieve yields similar to observed yields for Plot 3d, yet this does still not explain the significantly lower soil P stocks seen in the model outputs.

4.4.2 Exploring N14CP sensitivity to alternative phosphorus sources

Most biogeochemical P cycling models designed for agricultural systems do not consider P deposition or other natural forms of P inputs to the system (such as from mixed land uses). When exploring these annual inputs alone the contributions to annual P inputs were small (P deposition: 0.1 g P m^{-2} yr^{-1}, Miscellaneous P inputs: 0.008 g P m^{-2} yr^{-1}), so it is not surprising that these inputs did not contribute much to increasing modelled soil P stocks and annual yields for Plot 3d. Additionally, these values were derived from upper estimates, for atmospheric P deposition, leaf litterfall from adjacent woodland and non-livestock P inputs, found in the literature, so in all likelihood we are still overestimating their contribution to crop productivity for Plot 3d. However, with the increasing evidence of the role of agroforestry[58] and mixed cropping to promote a more resilient agricultural industry and contribute towards environmental targets (Rois-Díaz et al, 2017), expanding N14CP to implement mixed land cover types is something that may need to be considered.

One of the rationales for increasing the initial pool of weatherable P (from 350 g P m^{-2} to 1000 g P m^{-2}) prior to running the N14CP model was because modelled soil P stocks at the start of the long-term Park Grass experiment were 60 g P m^{-2} less than the contemporary total soil P measurements for Plot 3d. Increasing the initial pool of weatherable P to 1000 g P m^{-2} had a large impact on the modelled soil P stocks prior to the start of the long-term experiment but did not explain the measured total P soil stocks nor grassland yields for Plot 3d (**Figure 4-9C** and **D**). Exploring the wider literature, total soil P data in 1856, at the start of the Park Grass experiment as analysed by (Crews & Brookes, 2014), were approximately 150 g P m^{-2}. This is similar to other experimental sites in the same locality (TP stock approximately 130-175 g/m2

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[58] Agroforestry: the combined practice of conventional agriculture and forestry.

for the Broadbalk and Exhaustion Land experiments, (Blake et al., 2003b)) yet modelled total soil P stocks are approximately 90 g P m^{-2} less than the measured data. This suggests that soil P stocks before the start of the long-term experiment are still being underestimated.

Based on historical land use data prior to the long-term experiments it is likely that agricultural practices were common on this land since the 1600s. In previous versions of the model (Janes-Bassett et al., 2020) the use of manures was not considered for agricultural production at this time. However, when historic manure applications were introduced in this study, modelled results from these scenarios suggest that there was an accumulation of P in the soil. Modelled yields (for the proposed cereal crops) on the land during the 17th century are likely overestimated in this instance due to using modern cultivars to specify the harvest index, plant stochiometric ratio and above ground biomass for each of the plant functional types and differences in land management. Comparing historic wheat yield data from this time with modelled outputs it could be N14CP is estimating yields at more than double the estimated output in this scenario (Clark, 1991). Consequently, this could lead to an underestimation of the P accumulation in the soil during this period and therefore how much “legacy P” could have been available for subsequent production. Although by doubling the total P stock between 1600 and 1700 and extending agricultural inputs to include manure applications between 1700 and 1800, based on the trend seen in the modelled outputs this would still not likely account for the observed contemporary soil P stocks.

Phosphorus mobilisation and delivery can impact P cycling in terrestrial and aquatic systems (Haygarth et al., 2005) and in systems with high total P stocks (and those with low P sorption capacities or artificial drainage), P leaching can have substantial environmental implications (Sims et al., 1998). Again, it is important to note that within the Park Grass long term experiment the experimental plots are not hydrologically separate and there are no physical barriers to prevent mobilisation of P between the plots. It is therefore important to consider the location and connectivity pathways between the plots (and the wider environment) as well as accounting for any lag times within these connections and P transformation processes (Nelson

& Parsons, 2006). Currently N14CP does not model the movement of P between sites. To simulate the hydrological connectivity between the Park Grass experimental plots, the total dissolved P outputs modelled by N14CP from adjacent plots were used as annual P inputs for the current plot. These inputs were assumed to enter the plant available pool of P, although it is recognised that soluble forms of organic P can be lost via leaching pathways (Addiscott & Thomas, 2000; McDowell et al., 2021).

Phosphorus loss by leaching in N14CP is likely to be underestimated as it assumes that leaching will only occur after plant uptake immobilisation and sorption of soil P, and does not take into account the impact of excess soil water (Janes-Bassett et al., 2020) or soil drying and re-wetting, which can release substantial amounts of organic P to solution (Turner & Haygarth, 2001). The P losses in N14CP also do not fully reflect P losses via surface erosion and runoff which are typically better represented in models with a shorter timestep that can take into consideration the rainfall intensity and duration (Bouraoui & Dillaha, 2007). For longer timesteps, these factors can often be challenging to define so it will be important to find appropriate data that represents them (Easton et al., 2008) before it can then be conceptualised into our modelled understanding of these systems in N14CP.

Plant tissue P requirements and the responses to P availability in the soil vary greatly within and between species and genotypes (Güsewell & Koerselman, 2002). Plants respond to low P availability via: remobilisation of P within the tissues (such as mobilise P from older leaves for root proliferation); reduction or replacement of P in cellular compounds; exudation of metabolites or enzymes into the soil; and changes in root morphology (White & Hammond, 2008). The N:P or C:P ratio of plant tissue is therefore used as a proxy to understand the competitive ability of a plant / species that is growing on P limited soils (Güsewell, 2004). The mechanistic approach to model P in the environment, while allowing for a more simplistic model may not take into account changes in for example using fixed stochiometric ratios for plant growth can lead to overestimation of growth limitations and underestimations of nutrient use efficiency (Achat et al., 2016).

In the absence of P (and N) fertiliser inputs on Plot 3d resulted in a modelled P limitation shortly after the start of the long-term experiments in 1878 (baseline model data **Figure 4-2C**). This suggests that from 1856 there was sufficient stores of P in the soil to support crop production based on the available N present. Increasing the N:P ratio in the model reduced the rate of P depletion in the soils with modelled P limitation within the system now occurring in 1947, reflecting a lower P demand for production. Yet decreasing the amount of P that is taken up by the plant in the model to reflect the low P stocks in the soil was not enough to explain the sustained yields alone. In the combined N14CP scenario, N14CP model outputs suggest that NPP was most limited by N, rather than P. However, based on observed yields for Park Grass experimental plots receiving abundant manure and fertilisers, for all scenarios, Plot 3d would likely have N and P colimitation; a relatively common occurrence in natural and semi-natural systems (Craine & Jackson, 2010; Craine et al., 2008).

Incorporating flexible plant stoichiometry into N14CP would require determining thresholds for soil total P and N where plant responses would indicate a deficiency. The concept of a “critical” soil P threshold for crop productivity is commonly used by agronomists to optimise yield and fertiliser applications, ensuring that there is sufficient P readily available for plant uptake (Johnston & Poulton, 2011, 2019). For example, a typical threshold of 16 – 25 mg P kg^{-1} soil based on Olsen P analysis is used in UK agricultural systems with soil P stocks below this threshold resulting in a yield penalty (AHDB, 2020a). However, there is little evidence in the literature to define a total P threshold, that may indicate plant responses induced by P stress.

Measured soil P stocks for Plot 3d show a decline between 1984 and 2005 supporting a net offtake of P while still maintaining similar levels of plant productivity. This rate of decline is similar to the rate of decline modelled after the introduction of agricultural land uses (**Figure 4-2C**). This suggests that when there is P available for crop production the mechanisms in the model that determine the rate of plant uptake and P removal are working well but the problem remains that the model cannot account for the initial high soil P stocks.

Reflecting on the mechanisms in N14CP, potential limitations of the model are reflected in the simplified representation of organic P immobilisation and mineralisation and the cycling of P between the topsoil and subsoil. The role of root exudates and deeper rooting systems are not represented in the model as plant access to nutrients is limited to the topsoil only. This is extended to the modelled one-way delivery of P from the topsoil to the subsoil (excluding weathered P), i.e., the effects of bioturbation and mycorrhizal exchange are also not modelled. While the importance of these types of processes in low P environments is well recognised (Raghothama & Karthikeyan, 2005) conceptualising their contribution and incorporating limited empirical data for model calibration and/or validation remains a challenge.

Overall, the persistent contemporary soil P stocks that support crop production on the long-term experimental plots still cannot be explained in modelled predictions, despite the model changes that were applied. Although the combined scenario modelled P is closer to the observed data, it is likely that the changes made were over-estimated. This suggests that there are other factors that are not considered in N14CP and that the represented processes, or our conceptual understanding of P processes in the no-input agricultural systems is flawed. However, because N14CP appears to perform reasonably well for a wide range of other cropping and natural systems (Davies et al., 2016a; Davies et al., 2016b; Janes-Bassett et al., 2020), do these differences reflect a gap in our empirical understanding of P in these low P cropped systems, something that is yet to be fully conceptualised into modelled views? From a modelling perspective this work highlights the importance of using models and empirical design frameworks alongside one another. This work could also raise the question of how useful long-term plot experiments, that are not hydrologically separate from adjacent plot treatments, are in building and testing computer-based models. That is not to diminish the relevance and importance of some of these valuable historic sites, just that further considerations should be taken regarding any belowground factors affecting long-term crop production, in this instance, nutrient / P cycling including its mobilisation, delivery and impact between plots.

4.5 Conclusion

Long term experiments such as the Park Grass experiment and other similar experiments in the UK and USA have observed persistent crop yields for plots that have not received any fertiliser or manure inputs for more than 100 years (Aref & Wander, 1998; Macdonald et al., 2018). Long-term biogeochemical modelling of agricultural systems using N14CP have previously been unable to account for the persistent yields and observed soil nutrient stocks for these no-input and no P agricultural systems (Janes-Bassett et al., 2020) suggesting that there is a greater amount of P in the soil and available to plants than the model is able to predict. To explore how agricultural systems could support no fertiliser or no-P inputs, the biogeochemical model N14CP was used to systematically test different sources of P that are not typically considered in P management or many other computer-based models.

The current understanding of modelled P processes in N14CP for conventional agricultural sites (i.e., those that replace nutrient offtake from crops with fertiliser or manure applications) appeared to have a reasonably good fit with observed data, although it is recognised that addressing some of the model and data limitations could strengthen this work. However, N14CP could still not account for the persistent soil P stocks and the yields in sites with no P inputs, even when considering alternative sources of P inputs and different plant stoichiometries. The question still therefore remains as to what is missing in our conceptualisation of these systems within N14CP and how much does this reflect a gap in empirical understanding of no-input agriculture? Addressing these questions will help build understanding the P processes linked to legacy P management and long-term P drawdown in agricultural systems where P inputs are being reduced or withdrawn.

4.6 Acknowledgements

We thank the Lawes Agricultural Trust and Rothamsted Research for information and data from the e-RA database. The Rothamsted Long-Term Experiments - National Bioscience Research Infrastructure (RLTE-NBRI) is funded by the UK Research and Innovation - Biotechnology and Biological Sciences Research Council (UKRI-BBSRC) under award BBS/E/RH/23NB0007 (2023-2028). The RLTE-NBRI is also supported by the Lawes Agricultural Trust.

5 Long term organic production relies on intensive livestock production for the supply of phosphorus for crop production – a Substance Flow Analysis for an organically farmed estate in the UK

5.1 Introduction

More than 95 million hectares of land in the world was managed to organic standards in 2022, an increase of approximately 26% compared to the previous year (Willer et al., 2024). While currently representing only 2% of global agricultural production, Organic food markets are growing in response to pesticide, fertiliser and animal welfare concerns. In the UK a total of approximately 500,000 hectares are farmed organically by circa 3,200 producers (Defra, 2024b). Certified organic farming systems have to meet strict organic regulations which limits the type of nutrient inputs that can be applied to agricultural land (soilassociation.org, 2024a) with most synthetic fertilisers not permitted for use on organic farms. For phosphorus (P), this means that fertilisers such as triple superphosphate and diammonium phosphate, which underpin agronomic P resources in conventional agriculture, cannot be used.

Consequently, farmers and land managers typically rely on the recycling of P through animal or green manures or the application of a limited number of organic-approved fertilisers, which can include ground rock phosphate. The use of these sources poses several challenges to growers as their nutrient contents are often highly variable (Fuentes et al., 2006; Pagliari & Laboski, 2012) and they do not necessarily provide nutrients at agronomically optimum ratios (Schröder, 2005) or in crop available forms (Watson et al., 2006). As a result, organic farming systems are often considered to have more complex relationships between internal P flows and environmental factors than conventional systems, requiring a more integrated farming system approach and the need to understand P management over more than single cropping seasons (Watson et al., 2002).

One key principle for sustainable P management for agricultural production is to balance the nutrients taken off the land for crop and livestock production against those that are put back in, a concept of "feed the crop not the soil" (Withers et al., 2014). However, this has not always been common practice. The widespread introduction of P fertilisers into many agricultural systems that promoted excess P applications to meet yield demands, meaning P has accumulated in soils. Within the UK, it is estimated that that total soil P stocks in agricultural soils are typically higher than in most European countries and contain a much greater proportion of available P compared to non-agricultural soils, reflecting the decades of surplus anthropogenic P inputs (Panagos et al., 2022). Although applied P surpluses in the UK have been declining since the 1970s, when records indicate that they peaked at approximately 20 kg P ha^{-1} yr^{-1}, (Withers et al., 2001), P surpluses in 2019 were still estimated to be around 5.4 kg P ha^{-1} yr^{-1} (Defra, 2020c).

Phosphorus surpluses in conventional farming systems are unevenly distributed between different farm types, with those associated with livestock production (e.g. arable land receiving inputs from pig and poultry units and intensively managed grassland and forage crops) primarily having the greatest P surpluses; and farms with low or no manure inputs generating small surpluses or P balances (Cordell et al., 2022; Spiegal et al., 2020; Withers et al., 2001). However, in contrast to conventional farming systems, many organic farming systems have been shown to operate at a P deficit, relying on stores of P within the soil from before organic conversion to supply any shortfall in P to the growing crops (Ohm et al., 2017). These P stores may represent a key input of P to the system, but there is a need to understand the long-term flows of P to be able to estimate how long production can be sustained using legacy P sources (this has been explored further in Chapters 3 and 4 of this thesis). Intensive organic livestock production has the potential to offset this deficit via the recycling of manures and the import of livestock feeds (Rowe et al., 2016).

Improving the sustainability of P in agricultural systems, whether that be minimising the P surplus or preserving the long-term productivity of farming systems that are in P deficit, should be achieved through optimising P recovery and recycling and minimising wastes and losses of P (Gosling & Shepherd, 2005; Withers et al., 2015). Nutrient budgets are important tools that describe nutrient flows into, out of and within farming systems, similar to financial budgets for businesses. These can be used by farmers and land managers to aid nutrient management, assisting in the spatial and temporal planning of nutrient applications within crop rotations (Watson et al., 2002).

Watson et al (2002) and Jarvis (1999) describe three main types of nutrient budget that mainly differ based on the boundaries that are used to define the system under investigation:

- Gate Budgets (or Nutrient Balance) – these calculate the flows of nutrients between imported sources (such as purchased livestock, fertilisers and purchased feed) and exported sources (such as livestock and/or their products and harvested goods). These balances are less suitable for organic systems as they do not consider internal flows of nutrients, or nitrogen (N) fixation.
- Surface / Field Budgets – these budgets describe the difference between total nutrient inputs and removal in crop and/or animal offtake. These budgets are commonly used at the field scale (such as a field nutrient management plan) to determine crop nutrient requirements.
- System Budgets / Models – e.g. substance flow analysis (SFA). These budgets are the most comprehensive and provide detailed information on inputs, outputs, losses, and internal flows for different compartments within the whole system.

Substance Flow Analysis is one method of system budget that can be used to calculate nutrient use efficiency and identify any hotspots of inefficiency in a system. Substance Flow Analyses can be applied at a range of temporal and spatial scales (Chowdhury et al., 2014). Analysis and evaluation of the SFA can then facilitate targeted action (Brunner, 2010).

While most nutrient budgets studied are applied to the cycling of N (Watson et al., 2002), they can be applied to any nutrient. Detailed P SFA models for food systems in Europe (including the agriculture, processing, consumption and waste management) have been published (Chowdhury et al., 2014; Cordell et al., 2012; Rothwell et al., 2020; Rothwell et al., 2022; Zoboli et al., 2016). Yet detailed P SFA models have not been applied at an individual farm scale as a measure of P use efficiency across different agricultural land uses.

The case study described in this chapter reports an SFA for P that describes both farm-gate P balances and internal P cycling an estate with an organic farming system with multiple livestock and arable enterprises. This study will highlight the benefit of SFA-based P budgets for managing legacy P on a farm-level scale and provide an evidence base to underpin the complex management decisions to promote a more sustainable P future for organic agriculture or other farming systems that do not rely on inputs of processed P fertilisers. Within this the budget will be used to test two hypotheses:

1. long-term organic production on this estate relies on the recycling of manures from intensive livestock production to support crop production but to achieve a net P balance some inputs of P fertilisers are needed; and
2. in a system where there are multiple stakeholders a lack of focus on whole-farm nutrient management leads to a P imbalance on some intensively managed parcels.

5.2 Methods

5.2.1 Estate description and data sources

This SFA has been developed for a 1,600 ha mixed organic farming estate in Norfolk, England (**Table 5-1**) and includes the major flows and stores of materials containing P that are relevant to agricultural practices on this estate. The conversion of the estate to organic agricultural practices began in 1998 and now all crops and livestock are managed according to UK organic standards. Multiple stakeholders are involved in the management of the livestock and arable enterprises on this estate. The system boundary for the SFA is the “farm-gate” so considers all agricultural land and the farming enterprises owned and managed by the estate and its tenants. Imports of P are considered as flows of P within materials / livestock that are bought or moved into the estate. Exports of P are considered as flows of P within products / livestock that are sold / moved off the estate as well as P losses to water.

Table 5-1: Background estate data for 2020 including total area, total farmed area and arable cropping areas with mean topsoil phosphorus (P) measurements based on the Olsen P extraction method and corresponding P indices. Data compiled from estate records (pers. comm. June 2023); P indices based on thresholds outlined in AHDB (2020).

Estate Area	**Land area (ha)**	**Mean Olsen P (mg L^{-1}) / P Index**
Total Area	1,589	
Total Agricultural Land	1,291	34 / 3
Arable / Tillage	562	41 / 3
Temporary Grassland	367	29 / 3
Permanent Grassland	362	29 / 3
Cropping	**Approximate area grown (ha)**	**Mean Olsen P (mg L^{-1}) / P Index**
Cereals	159	38 / 3
Wheat	53	18 / 2
Barley	16	57 / 4
Oats	90	28 / 3
Vegetables	168	45 / 3
Carrots	69	62 / 4
Leeks	13	23 / 2
Onions	29	39 / 3
Potatoes	57	30 / 3
Forage Crops	645	32 / 3
Temporary Grass/Silage	367	29 / 3
Lucerne	55	43 / 3
Beet - fodder	12	24 / 2
Maize - fodder	132	43 / 3
Mixed forage - pea and barley mix	16	17 / 2
Turnips - fodder	63	71 / 5

Livestock enterprises on the estate include a cattle dairy herd, beef and sheep production for meat, a free-range outdoor broiler enterprise, an outdoor pig enterprise (although the relationship with the stakeholders for this enterprise has since ceased at the time of writing this work), and a herd of (semi-wild) Fallow and Red Deer on the estate (**Table 5-2**). Livestock are primarily fed on home-grown forage and maize produced on the 1,300 ha of land in a typical seven-year arable rotation or permanent pasture. As part of the arable rotation, 130 ha yr^{-1} of land on the estate is managed for organic root vegetable production, alongside cereal crops, and forage crops. Finally, temporary grass and legume leys are a key component of the crop rotation (**Table 5-1**). In addition to the livestock and arable enterprises, the estate also comprises approximately 600 ha of traditional grazed parkland, and woodland. The estate also manages approximately 90 ha of agricultural land under agri-environmental schemes including wild bird cover, field margins and pollinator blocks / strips.

Table 5-2: Livestock enterprises on the estate for 2020 including number of livestock in each category and, where known, the breed. Data based on estate records (pers. comm. June 2023).

Livestock enterprises	Number (head)[a]	Breed (where known)
Dairy	891	Jersey
Beef	192	
Sheep	764	Lleyn
Pigs	290	
Poultry	216,000	
Deer	600	Fallow (500) and Red (100)

[a] Includes breeding and young stock where applicable

The SFA model has been developed for a single year; 2020. Ideally the SFA model would have been applied to a whole rotation but, this was limited by the availability of records from the estate management teams. Information regarding material mass flows within the estate were extracted from estate data, data on organic and conventional farming practices in the UK (including industry reports), and scientific literature. The P content of the materials was obtained from different published sources. Estimated P losses to water were based national figures calculated by Elliott (2019) using the FARMSCOPER model for land in agri-environment schemes. Phosphorus flows were calculated by multiplying the material mass flow by the assigned material P content and are expressed in kilograms of P per year (kg P yr^{-1}). Comprehensive details of flow descriptions and data sources for P contents and material mass flows can be found in the Supplementary Information (**SI Table 5-1** and **SI Table 5-3**).

5.2.2 Substance Flow Analysis model and data uncertainty

This SFA follows methods used to create similar models that have been applied to the movement of P within the UK food system (Rothwell et al., 2020; Rothwell et al., 2022). The SFA model was built using the free software STAN (version 2.7.101). This software utilises data uncertainty for data reconciliation, error propagation, and final model balancing (Cencic, 2016; Cencic & Rechberger, 2008).

Data uncertainty for P flows on the estate were assigned following the systematic approach outlined by Laner et al. (2016) and Zoboli et al. (2016). In brief, flow data are assigned an evaluation score based on quality indicators including reliability, completeness, composition, temporal correlation, geographical correlation, further correlation, and expert opinion (**Table 5-3**). The evaluation scores for the flow data are then translated in a final co-efficient of variation (**Table 5-4**). Flow data in the model are expressed as the mass flow and the standard error (**SI Table 5-1** and **SI Table 5-2**).

Final model balancing and data reconciliation was computed using Gauss's law of uncertainty propagation, which involves taking the square root of the sum of the squares of all the given uncertainties associated with the flows going in and out of a process. As the standard deviation serves as a weighting factor in the reconciliation process, it means that values with greater uncertainty are more heavily reconciled compared to those with lesser uncertainty. The effect of the reconciliation process on the input data was analysed to assess the degree of confidence in the input data. If the difference between an input value and a reconciled value was less than 5% it was considered that there was a good level of confidence in the input data.

Full information regarding the P flow input data, assigned uncertainty for the different P flows, and the reconciled output flow data from STAN can be found in the Supplementary Material. For this SFA model mean value change from inputted flow data and the STAN reconciled data was 0.69% (range: 0.00% - 4.79%) suggesting good confidence in the input data.

5.2.3 System description

This model comprises 2 main P stocks (referred to as processes in the STAN software) and 38 flows of P on the Estate. The SFA represents the movement of total P, including imports (natural and anthropogenic), exports (including losses), and flows between processes, that make up the agricultural enterprises on the estate. The major components of the SFA are divided into the *Livestock* and *Crops & Grass* systems. These processes are expanded to include sub-processes that account for the different animal types and crops produced on the estate.

Table 5-3: Indicators and criteria applied to assess the quality of input data. Four evaluation scores, where 1 represents the best and 4 the worst. Based on Zoboli et al., 2016.

Indicator	Definition	Evaluation Score 1	2	3	4
Reliability	Refers to the documentation of the data and reflects the transparency regarding the sampling, collection, and verification procedures.	Methodology of data generation is well documented and consistent (e.g., Standard documentation - Metainformation of National Statistics; laboratory analytical methods).	Methodology of data generation is described, but not fully transparent.	Methodology is not described, but principle of data generation is clear.	Methodology of data generation is unknown (data presented without any meta-information).
Completeness	Describes how complete the available data are in comparison to the actual values of interest.	Complete acquisition of data (no extrapolation; for aggregated flows, data available for all goods).	Partially fragmented data (minor need for extrapolation; for aggregated flows, data available for majority of goods).	Fragmented data (considerable need for extrapolation; for aggregated flows, data available for minority of goods).	Highly fragmented data (major need for extrapolation; for aggregated flows, data available for less than one third of the goods).
Composition	Describes the level of information on the P composition of the goods.	Value is expressed in detailed categories (adequate to select correct P concentration for each category) or no categories exist (single / uniform P concentration).	Value is expressed in large categories.	Value is only partially expressed in categories.	No information on the composition is available (no basis to select appropriate P concentration).
Temporal correlation	Takes into account the extent the available information diverges from the datum of interest.	Value relates to the correct year.	Deviation of 1 to 5 years.	Deviation of 6 to 10 years.	Deviation of more than10 years.
Geographical correlation	Takes into account the extent the available information diverges from the datum of interest.	Value relates to the studied region.	Value relates to comparable region / economy / society.	Value relates to less-comparable region / economy / society.	Socio-economically different region.
Further correlation	Reflects deviations other than temporal or geographical, such as parameters of a specific type of technology or process.	Value relates to the same product, the same technology, etc.	Value relates to similar technology, product, etc.	Values deviates from technology / product / . . . of interest, but still acceptable.	Value deviates strongly from technology . . . of interest; correlation unknown.
Expert judgment	If no data are available input values are determined through expert judgments.	Formal statement from qualified expert.	Robustly based estimation.	Weakly based estimation.	Speculation or crude assumption

The *Livestock* system considers the all the livestock enterprises managed on the estate and their associated inputs, and outputs. This includes the cycling of P via live animals as well as grazing, forage, and excreta. For the purposes of this work, the P content of animals sold off the estate for meat processing is calculated as animal liveweight at the time of export.

The C*rops and Grass* system represents the change in soil P stocks in response to the management practices on the land. This includes the associated P inputs from seeds, fertilisers and manures as well as atmospheric P sources. Phosphorus exports are calculated from crop offtake (whether this be for internal forage and feed production or sold for human consumption) and losses to water. The net change in soil P stocks in this process represents the annual P balance (surplus or deficit) to soil stocks on the estate.

Table 5-4: Coefficients of variation (%) for quality indicators according to evaluation score and sensitivity level (where applicable). Based on Zoboli et al., 2016.

Indicator	Sensitivity	Evaluation Score (Coefficient of variation, %)			
		1 (%)	2 (%)	3 (%)	4 (%)
Reliability	N/A	4	10	22	50
Completeness	N/A	0	10	22	50
Composition	Highly sensitive	0	10	22	50
	Sensitive	0	5	11	22
	Not sensitive	0	2	4	8
Temporal correlation	Highly sensitive	0	10	22	50
	Sensitive	0	5	11	22
	Not sensitive	0	2	4	8
Geographical correlation	Highly sensitive	0	10	22	50
	Sensitive	0	5	11	22
	Not sensitive	0	2	4	8
Further correlation	Highly sensitive	0	10	22	50
	Sensitive	0	5	11	22
	Not sensitive	0	2	4	8
Expert judgment [a]	N/A	10	20	40	80

[a] If input values are determined through expert judgments, the uncertainty is directly assessed through the indicator Expert judgment.

5.3 Results

5.3.1 Overall phosphorus substance flow analysis

The estate P SFA (**Figure 5-1**) shows that the total import of P into the agricultural system in 2020 was 10,157 ± 858 kg (7.82 ± 0.66 kg P ha^{-1} yr^{-1}). Exports of P from the estate in this year were 9,074 ± 990 kg (6.99 ± 0.76 kg P ha^{-1} yr^{-1}). This equates to a net import of 1,080 ± 1,155 kg P yr^{-1} (0.83 ± 0.89 kg P ha^{-1} yr^{-1}) to the agricultural systems on the estate. The P efficiency of the estate has been calculated by dividing the total P exports by the total P imports. This gives a P efficiency of 89% for the agricultural enterprises on the estate.

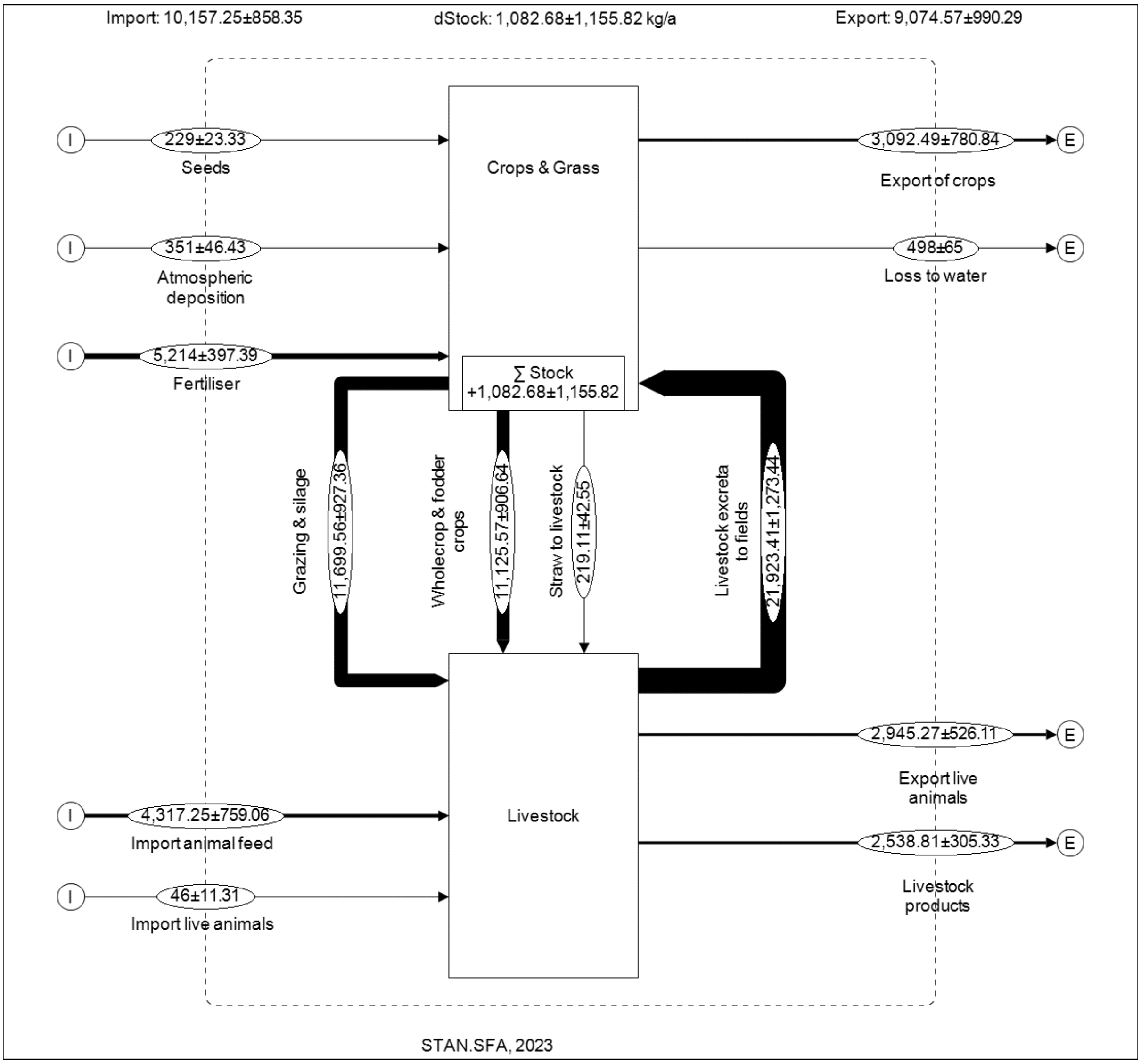

Figure 5-1: Phosphorus Substance Flow Diagram of all the Estate's agricultural enterprises for 2020, all values are shown as kg P yr^{-1} ± standard error and have been reconciled by STAN. Values within a process illustrate the annual accumulation. Line thickness of the flows are proportional to the magnitude of the flow value.

The largest import of P came from fertilisers (organically approved) that were directly applied to agricultural soils. These accounted for 5,214 ± 397 kg P in 2020, which was more than half of the annual P imports (51%). Imported animal feeds accounted for a further 4,317 ± 759 kg P (43%) with the remaining P imports to the estate coming from atmospheric deposition (3%), seeds (2%) and livestock (0.5%).

95% of P exported from the estate was contained within exported crops, livestock (primarily for meat production) and livestock products (milk and wool), accounting for 3,092 ± 781 kg, 2,945 ± 526 kg, and 2,538 ± 305 kg of P respectively. Finally, P losses from agricultural soils to water were estimated at 0.38 ± 0.05 kg P ha^{-1} yr^{-1}.

Phosphorus recycled between cropping (including grassland production) and livestock processes on the estate accounted for most P transfers. The largest single P transfer in this SFA model was via the application of manures and direct excretion to fields, accounting for 21,923 ± 1,273 kg of P in 2020, equivalent to 16.90 ± 0.98 kg P ha^{-1} yr^{-1}. A total of 22,826 kg of P was also contained within livestock feed including grazing and silage (11,700 ± 927 kg P), fodder crops (11,126 ± 907 kg P), and bedding (straw; 219 ± 43 kg P) which was utilised by the estate's livestock enterprises. A more detailed breakdown of imports and exports by livestock type and cropping type are provided in the Livestock and Crops & Grass sub-processes, detailed in the following sections (**Figure 5-2** and **Figure 5-3**).

5.3.2 Livestock sub-processes

Livestock enterprises, particularly poultry and dairy, formed an important component of the Estate's agricultural production in 2020 (**Figure 5-2**), with the majority of crops grown on the farm being used as forage. The Estate relies very little on imported livestock feeds, which in this model are assumed only used to produce the organic broiler chickens. Total home-grown forage P content was estimated as 11,700 ± 927 kg P from grazing and silage and 11,126 ± 907 kg P from fodder crops. Cattle consumed most of these grass and fodder crops, totalling 81% and 66% of total production, respectively. Cattle and poultry also dominate the export of livestock and livestock products, with P exports totalling 2,272 ± 516 kg P yr^{-1} in broiler hen production (77% of livestock P exports) and 2,539 ± 305 kg P yr^{-1} in milk production (99% of livestock product exports). The P efficiencies of the different livestock types are outlined in **Table 5-5** and are estimated based on the conversion of P intake (feed, forage, and/or grass) into P embedded in livestock products (meat, milk, and/or wool). Deer populations were excluded from these calculations as the herds are assumed to be a semi-wild population and not managed for agricultural purposes. The poultry enterprise has the highest P efficiency at 37.5%. Cattle, sheep and pigs have lower P efficiencies of 17.0%, 14.2% and 11.4% respectively.

The SFA model assumes a stable livestock population, so P not contained within live animal imports / exports or livestock products is excreted which is then recycled back into the cropping system either via excretion to land during grazing or the application of farmyard manures from housed livestock. The livestock sub-process (**Figure 5-2**) demonstrates that cattle dominate manure P output with their excreta containing 14,130 ± 1,155 kg P (64% of total). Poultry were the next largest producer of excreta P containing 3,881 ± 667 kg P (18% of total). Pig (1,979 ± 231 kg P, 9% of total), deer (1,382 ± 147 kg P, 6% of total) and sheep (552 ± 62 kg P, 3% of total) accounted for the remaining P excretion, although most of this will be directly deposited during grazing rather than applied as farmyard manure from housed livestock.

Table 5-5: Estimated livestock production phosphorus (P) efficiencies; based on the conversion of P intake (feed, forage, and/or grass) into P embedded in livestock products that are exported off the estate (such as: meat, milk, and/or wool).

Livestock group	Total P intake via feed, forage and/or grass (kg)	Total P embedded in livestock products (kg)	P efficiency (%)
Cattle	16,826	2,864	17.0
Poultry	6,058	2,272	37.5
Pigs	2,230	255	11.4
Sheep	642	91	14.2

5.3.3 Crops and grass (soil system) sub-processes

Grass and herbal leys, typically those containing legumes are a key component for organic farming rotations. In 2020, 367 ha of temporary grassland was grown on the estate alongside 362 ha and 562 ha of permanent grassland and tillage crops (**Table 5-1**). Total P inputs to soils, through applied fertilisers and manures, excreta, planted seed and atmospheric deposition, amounted to 27,717 kg P (21.3 kg P ha^{-1}) in 2020; 61% of the P inputs were applied / deposited to tillage land, with the remainder applied / deposited to grassland soils (**Figure 5-1**).

Livestock excreta was the largest contribution to P inputs on this Estate where tillage crops received 11,212 ± 1,706 kg P (20.0 ± 3.0 kg P ha^{-1}), typically through the application of farmyard manure and / or poultry manure from housed livestock. Excreta P inputs to grassland

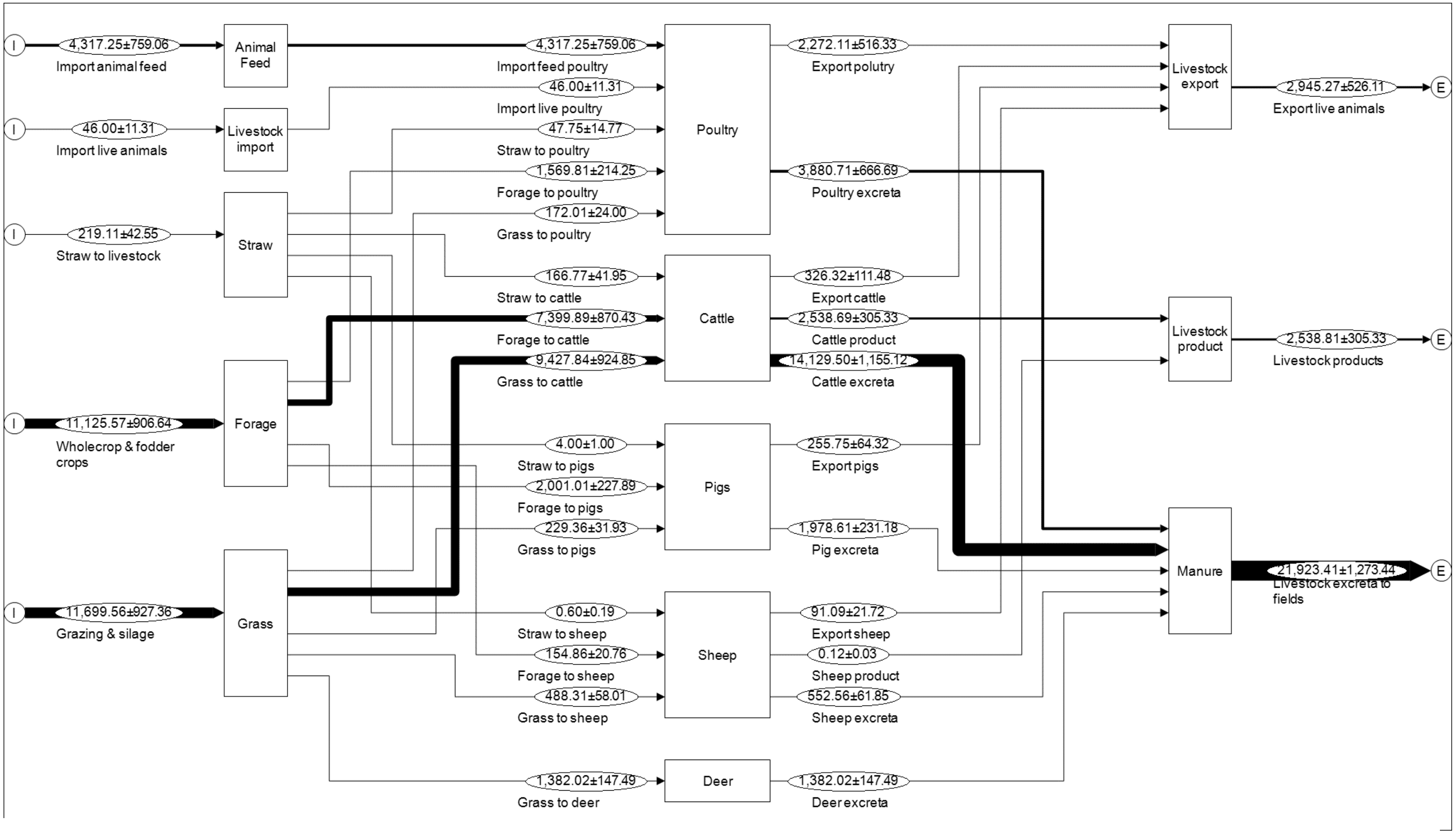

Figure 5-2: Phosphorus Substance Flow Diagram of all the Estate's Livestock sub-system for 2020, all values are shown as kg P yr^{-1} ± standard error and have been reconciled by STAN. Values within a process illustrate the annual accumulation. Line thickness of the flows are proportional to the magnitude of the flow value.

soils were slightly less than tillage crops at 10,711 ± 1,684 kg P (14.7 ± 2.3 kg P ha^{-1}) and were assumed to be directly deposited by grazing livestock. Phosphorus inputs from fertilisers were made to tillage land only at a rate of approximately 9.3 ± 0.7 kg P ha^{-1}. Data here are provided as a mean average across different land usage, however, estate records show that applications of manure and fertilisers were not made uniformly across the land (Pers. comm. June 2023). Imported P fertilisers were typically only applied to vegetable crops where soil sampling and analysis supported their application and manures from housed livestock were mainly applied to cereal and maize crops. Other P inputs in this SFA model include the P content of seeds (tillage: 216 ± 23 kg P, grassland: 13 ± 2 kg P) and atmospheric deposition (tillage: 152 ± 33 kg P, grassland: 199 ± 40 kg P).

Total P offtake from crop and grassland production was 26,137 kg P, giving a P use efficiency of 94% (**Figure 5-3**). Phosphorus offtake from agricultural soils on this estate was largely used to support the livestock enterprises on the estate (wholecrop & fodder crops: 11,125 ± 906 kg P; straw to livestock: 219 ± 43 kg P; and grazing & silage: 11,700 ± 927 kg P). Export of crops, including vegetable crops and cereal grains accounted for an estimated 3,092 ± 781 kg P and a further 498 ± 65kg P (tillage: 281 ± 56 kg P, grassland: 217 ± 46 kg P) was estimated to be lost from agricultural soil to waterbodies via diffuse pollution. These figures represent a total surplus application of P of 1,580 kg P or 1.2 kg P ha^{-1} and an accumulation of P in the agricultural soils on the estate of 1,082 ± 1,156 kg P (0.83 ± 0.89 kg P ha^{-1}) in 2020 after accounting for P losses to water.

The P surplus and P use efficiency on the estate, however, is unevenly distributed between tillage and grassland cropping systems (**Figure 5-3**). Tillage crops had a total crop offtake of 14,437 ± 1,179 kg P in food, feed and livestock bedding. Combined with a total P input of 16,794 kg P to tillage land, the P efficiency of this system is 86%. This leaves an annual surplus P application of 2,357 kg P or 4.2 kg P ha^{-1} and an accumulation of 2,076 ± 1,969 kg P (3.69 ± 3.5 kg P ha^{-1}) in tillage soils when P losses to water were accounted for.

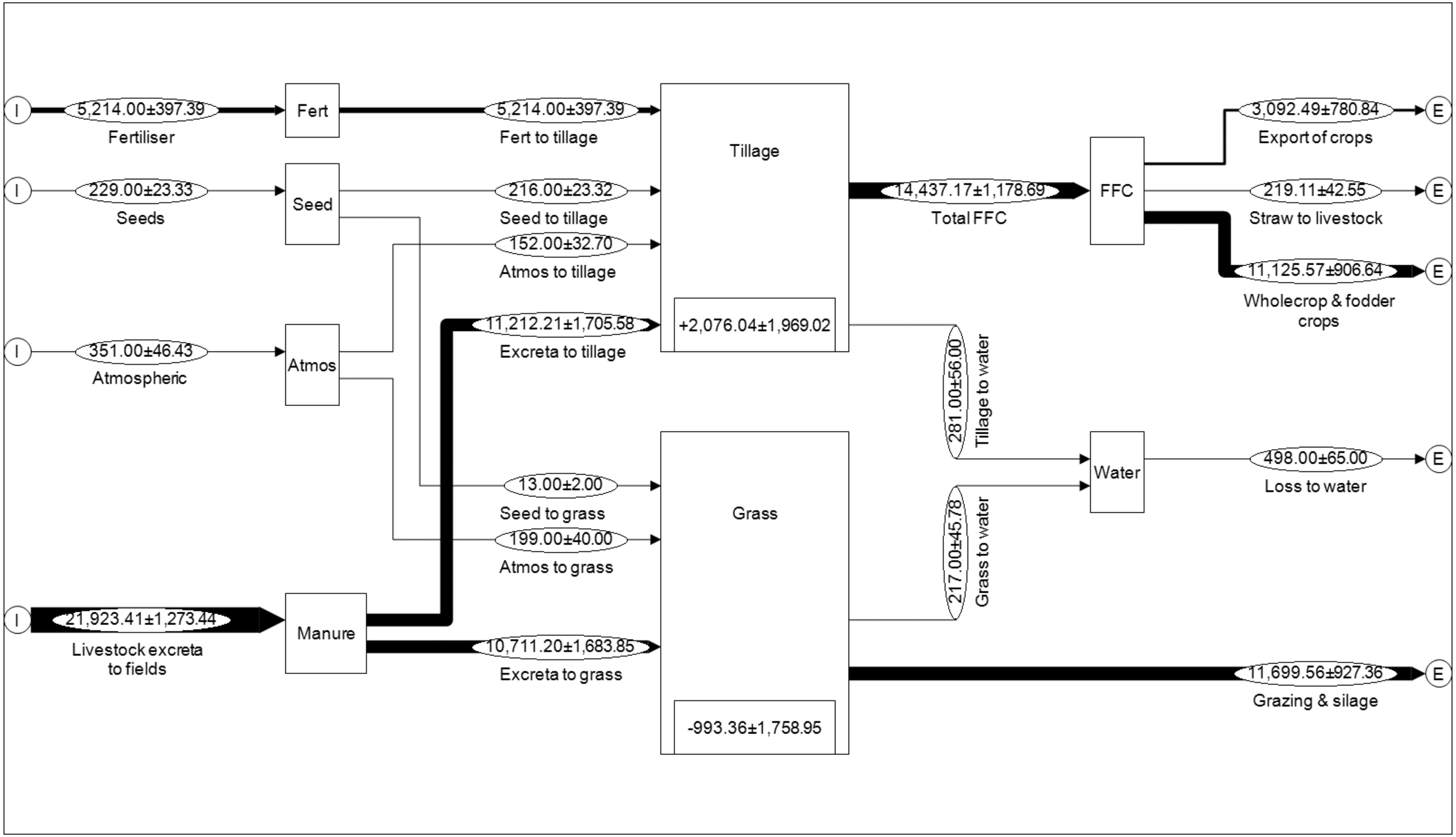

Figure 5-3: Phosphorus Substance Flow Diagram of the Estate's Crops & Grass sub-system for 2020, all values are shown as kg P yr^{-1} ± standard error and have been reconciled by STAN. Values within a process illustrate the annual accumulation. Line thickness of the flows are proportional to the magnitude of the flow value.

In contrast, grassland soils appear to be in P deficit. These systems received P inputs via grazing livestock, some seed for establishing temporary grassland leys and atmospheric deposition. The estimated P output (from direct grazing and/or cut for silage) in 2020 was 11,700 ± 927 kg P (16.0 ± 1.3 kg P ha^{-1}). This represents an annual P application deficit of 777 kg P or a P efficiency of 107%. Estimated diffuse P losses from grassland were less than tillage land at 217 ± 46 kg P ha^{-1} which means the P depletion in grassland soils for 2020 was estimated as 993 ± 1,759 kg P or 1.35 ± 2.38 kg P ha^{-1}.

5.4 Discussion

5.4.1 Hypothesis 1: long-term organic production on this estate relies on the recycling of manures from intensive livestock production to support crop production but to achieve a net P balance some inputs of P fertilisers are needed

Estimates demonstrate that in 2020, the estate imported 9,531 kg P to supplement crop productivity and livestock feed demand. With total P contained within exported crops and livestock products of 8,576 kg P, the P use efficiency from agricultural enterprises on the estate was approximately 90%. This is comparable to national P uptake efficiency estimates for arable only systems of 85% but is far greater than recent estimates for grass-based livestock systems which have a P efficiency of just 53% (Rothwell et al., 2022). The preferential use of home-grown feed and forage crops for livestock production underpins much of the practices under organic farming standards (soilassociation.org, 2024c)[59]. When combined with the recycling of manures to meet much of the P demand for crops, this likely contributed to the higher-than-average P efficiency on the estate.

Excreta is composed of organic and inorganic forms of P and the amount and type of P applied varies greatly depending on the manure source (Pagliari & Laboski, 2012). Inorganic P accounts for between 36-77% of the total P in manures (Pagliari & Laboski, 2012); much of this is in the

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[59] 59 A minimum of 60% of feed and forage crops fed to cattle or 20% fed to pigs and poultry must have been produced on the farm (soilassociation.org, 2024c)

form of orthophosphates, the main form of P that is taken up by plants and soil microbes (Darch et al., 2014). As such, most of the P in livestock excreta is supplied in a readily available, water-soluble form, which is important for the production of annual crops on the estate. However, in the absence of livestock on the estate, there would be greater pressure on meeting P requirements through the import of organic-approved fertilisers or imported manures.

With intensive livestock production as a key enterprise on the estate, there is a need to sustainably manage the manures produced. For most organic farming systems the supply of N relies on biological N fixation and application of manures. As such there is a need to balance the N inputs from manure for crop productivity against the risk of over-applying P on land with high P indices (Toth et al., 2006). Managing P drawdown on land with high index P would require coordination between different stakeholders to ensure adequate soil fertility is maintained in the future (Lalor et al., 2010; Sarvajayakesavalu et al., 2018). The high numbers of livestock and the reliance on manures for nutrient inputs for crops means that nutrient balances may be particularly vulnerable, especially if livestock numbers change substantially (Kelm & Taube, 2005).

Overall, slight reductions in P imports (from feed and/or fertilisers) would increase the P use efficiency of the estate and reduce the P surplus without compromising P supply in the system. However, if fertiliser inputs ceased, the estate balance would shift to a mean deficit of approximately 3.2 kg P ha^{-1} yr^{-1}. To balance this, livestock numbers would need to be increased (alongside P in imported feeds to meet additional livestock P demand) to increase excreta P output. For example, using current livestock numbers, livestock excreta could only support approximately 1060 ha of production (based on a mean annual P content of all harvested crops of 20.6 kg P ha^{-1}). The results from this SFA suggest that long-term organic production on this estate does rely on the recycling of excreta from intensive livestock production to support crop production. Although, without supplementation with P fertilisers, to support the level of crop production under current stocking rates, there would be a net deficit of P in the system.

5.4.2 Hypothesis 2: in a system where there are multiple stakeholders a lack of focus on whole-farm nutrient management leads to a P imbalance on some intensively managed parcels

Results demonstrate that the estate's agricultural system is close to a net P balance (P imports are equal to P exports) for the assessed year (P accumulation was less than 1 kg P ha^{-1} yr^{-1}, **Figure 5-1**). Annual P balances between different farm-scale studies often demonstrate wide variability, with organic farm balances ranging from -12 kg P ha^{-1} yr^{-1} to 48 kg P ha^{-1} yr^{-1} (Reimer et al., 2020). The whole estate balance, however, masks local losses and gains between different land uses i.e. tillage or grass or between different fields.

Land used for tillage crops on the estate received mean average manure P application rates of 20kg P ha^{-1} yr^{-1}. In 2020 this meant excess P applications amounted to 4.2 kg P ha^{-1} and an overall soil P accumulation of 3.69 ± 3.5 kg P ha^{-1} (**Figure 5-3**). This is approximately half of the UK national estimated P application surplus to agricultural soils (Defra, 2020b) and is comparable to the UK national estimated P surplus for arable only enterprises (Rothwell et al., 2022). On the other hand, land used for temporary and permanent grass production demonstrated an annual deficit of 1.35 ± 2.38 kg P ha^{-1}. The differences between soil P stocks for the tillage and grassland land uses reflect the preferential application of fertilisers and manures to tillage crops in a mixed farming system to ensure the most efficient recycling of the nutrients they contain (Möller, 2009). However, P input on grassland areas will be required (either from fertiliser or manure inputs) to avoid the long-term impacts of nutrient drawdown. Surplus P inputs to soils are common for systems involving high manure application rates or intensive livestock production, particularly dairy and poultry (Bateman et al., 2011), although, direct comparisons between studies can be a challenge due to discrepancies in methodologies and reporting parameters (Reimer et al., 2020).

The livestock enterprises are a key part of the agricultural outputs from the estate, particularly organic milk, and poultry production. The associated P efficiencies for the different livestock enterprises are shown in **Table 5-5**. The poultry enterprise has the highest P efficiency at 37.5%, whereas cattle, sheep and pigs have lower P efficiencies. The observed differences are likely attributed to the life cycle of animals. For example, a large proportion of the cattle, sheep, and pig populations are made up of mature breeding stock, which are in P homeostasis (Horst, 1986) leading to a relatively high excretion of ingested P. Conversely, much of the P consumed by the broiler hens, raised for meat, is absorbed in the animal's bones and tissues to support their continuous growth during the typical 81-day lifespan (Leinonen et al., 2012). Although most of the P is recycled within the estate and there is a minimal surplus, there may be an opportunity to reduce P inputs from feed, but this could require analysis of harvested forage crops to ensure the nutritional needs of the livestock are met.

Estimated P losses to water from the estate were estimated to be 498 ± 65 kg P yr^{-1}. Phosphorus losses from agricultural soils to water were based on national estimates calculated by Elliott (2019) using the FARMSCOPER model for land in agri-environment schemes. However, actual P losses to water can be highly variable in time and space, influenced by rainfall, slope, drainage, soil texture, soil structure, and land management practices (Heathwaite, 1997). Agricultural policy for managing P in agricultural systems is primarily targeted at reducing the transport of P from soils to watercourses and minimising the effects of diffuse pollution (e.g. the European Union Water Framework Directive (2000/60/EC)). The adoption of best management practices on the estate (such as nutrient management planning, soil testing, and well managed livestock and manure handling and storage facilities) as well as Countryside Stewardship engagement could all help to target P applications and minimise P surpluses to reduce the risk of P losses (Gooday & Anthony, 2010; Sharpley et al., 2009). Again, this will require a holistic approach with continued engagement and support from all stakeholders (Jarvie, Sharpley, Withers, et al., 2013).

This SFA model and P budget provides a snapshot of the balances for the given year (2020). However, this may mask long-term trends in P management on the estate. Farm management practices during the assessed year may have deliberately contributed to a P surplus. For example P application rates may be greater than crop nutrient requirement: 1) to raise low soil P indices to achieve optimum P indices[60] or 2) to supply the nutrient requirement for more than the assessment year (AHDB, 2020a). Similarly, P deficits on land can be introduced to lower high P indices or balance increased P inputs during other periods of the rotation. Influences of weather and disease can also influence annual P balances, impacting yields and livestock feed requirements. As such, to provide an informed and effective management response there is a need to get an understanding of the nature and magnitude of P flows through a system at different temporal scales (Chowdhury et al., 2016). Further investigations for this estate could therefore be expanded to multi-year analysis over a whole 7-year rotation.

Accurately quantifying P offtake is crucial for optimising P utilisation efficiency (Watson et al., 2002). However, field-scale yield data (and P analysis of harvested crops) were not typically provided, particularly for permanent grassland or fodder crops. As such, the SFA model presented here categorised land use (tillage and grass) and livestock practices into broad groupings to estimate P balances from different enterprises. This, however, did not capture the spatial heterogeneity of fertiliser P and manure application management strategies reported on the estate (pers. comm. June 2023), for example: manure applications were primarily made to cereal and maize crops and to those fields with lower soil P indices; fertiliser P was applied to only vegetable crops where required based on P indices; and the P deposited by grazing livestock was not fully accounted for in the records. Consequently, if poorly managed over the whole rotation, this could lead to a P imbalance on some intensively managed parcels. This highlights a potential opportunity for improving P budgeting through more complete data collection and flexibility in P balances at different spatial scales (Chowdhury et al., 2014).

Olsen P data (soils tested in 2019) were provided for some land parcels on the estate which gave an indication of the soil “available” P for crop production (**Table 5-1**). However, total soil P stocks were not quantified and added to the SFA model, as Olsen P values cannot be used

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[60] Optimum soil P index for most arable and grassland crops is 2 (Olsen P: 16-25 mg P L^{-1}) or 3 for land that is regularly used for vegetable production.

accurately predict total soil P. This is because the relationship between Olsen P and total P can be influenced greatly by individual soil properties (Recena et al., 2015; Tandy et al., 2021). Available soil P concentrations (Olsen P extraction method) were measured on 75 land parcels across the estate in 2019 (**Table 5-1**). One third of the land parcels had soil P concentrations at target Index 2 (Olsen P: 16-25 mg P L^{-1}), while 8% had P concentrations below 15 mg L^{-1}, indicating that these field parcels may not have sufficient available P for optimal crop production. On the other hand, the remaining 59% of land parcels had P measurements of more than 26 mg P L^{-1} (Index 3) with six land parcels having P concentrations of more than 70 mg P L^{-1} (Index 5). These results suggest that for most of the land parcels there would be no, or only a very small response to fresh P applications (AHDB, 2020a) and continued applications of manures or fertilisers containing P to this land could lead to increased risk of P losses or leaching (Withers et al., 2001). Understanding the total P stocks, as well as the “available” P stocks, across the estate would be valuable for long term P management. This could give insight into the timescales needed to drawdown legacy P concentrations, particularly in fields with high P indices (Menezes-Blackburn et al., 2018; modelling legacy P drawdown was also explored in Chapter 3 of this thesis).

5.4.3 Future opportunities

The SFA model presented in this study reflects a comprehensive overview of the P imports, exports and internal flows relating to the agricultural practices for an organic mixed farming estate in the UK. Substance flow analysis models in ecological systems are principally designed to support environmental decision making, although limited standardisation between different models necessitate clear system definition and the transparent quantification and interpretation of the data (van der Voet, 2002). While this study has only focused on P, the principles of SFA modelling could be applied to other nutrients. This could potentially highlight different areas of inefficiency or imbalances on the estate.

The flows of P were, where possible, quantified based on readily available farm records. The reconciliation process applied to the input data suggested a good level of confidence in the input data (mean value change from inputted flow data and the STAN reconciled data was 0.69%). Data uncertainty was assigned to input values using the methods outlined by Laner et al. (2016) and Zoboli et al. (2016) (**Table 5-3** and **Table 5-4**). Subjectivity is also introduced in determining the functions that convert the quality indicator scores into coefficients of variation. However, this enables modelers to integrate their expertise and the approach ensures consistency in estimating uncertainties within the model due to its reliance on continuous functions (Zoboli et al., 2016).

A lack of in-depth data from the estate was a considerable restraint to SFA model, impacting the uncertainty of the P balances and flows. Notable gaps in the data were largely around grass and forage yields and manure production which were extrapolated based on national data records. This was reflected in the high level of uncertainty assigned to these input values. As a result P balances estimated by the SFA model demonstrated a high degree of uncertainty, particularly for the overall P balance (± 107%, **Figure 5-1**) and the changes in the soil P stores within the model sub-system (± 95% and ± 177% for the tillage and grassland soils respectively, **Figure 5-3**). The absolute uncertainty of the change in stocks for these processes is computed by using Gauss's law of uncertainty propagation (Fellner et al., 2011). The uncertainty associated with the change in P stocks in the Grass and Tillage processes is commensurate, but with high uncertainties attributed to the flows of manure, grass and forage production. Improving the accuracy of input data through on-farm data collection could greatly reduce the degree of uncertainty.

The use of readily available data based on on-farm records means that the SFA framework presented here could be applied to other farming systems. This would provide farmers and land managers with the tools to model their own P balances and identify areas of P inefficiency on their own land, helping them to meet environmental and nutrient management sustainability targets. This framework goes beyond the simple tools for estimating the farmgate nutrient budget by providing more information on what is causing the change within the system (Watson et al., 2002). The SFA model can also be used alongside existing legislation for farmers to plan nutrient inputs to individual fields based on soil analysis results to help describe any storage or loss of nutrients in scenarios with surplus inputs (Brunner, 2010).

Pressures for the long-term sustainable management of P in agricultural systems will continue to rise (Rowe et al., 2016). As such there will be a growing need for farmers and land managers to understand the relationships between different flows of P on their land. This framework could be used to underpin the complex management decisions needed for organic and potentially conventional farming systems. Future work will explore how more accurate input, but readily-available, nutrient data can be used to support model inputs and how adaptations of the SFA framework could be implemented so that it can be used at the farm-scale by farmers and land-managers for multi-year analysis.

5.5 Conclusion

Utilising the method of SFA and the best available data sources, P balances and internal flows have been estimated for an organic mixed farming estate in the UK. This model could be used to help benchmark future management practices on the estate and provide a platform for on-going P monitoring to be integrated with soil testing and annual nutrient management planning for crop production. The recycling of manures from the livestock enterprises was fundamental to supporting crop production on the estate, thus supporting the first hypothesis. However, to achieve net P balance still required input from P fertilisers (without changes to livestock numbers). Additionally, although the estate was largely in P balance for the 2020 calendar year, manure management practices meant that P imbalances between grassland and tillage fields on the Estate were present, supporting the second hypothesis. Careful long-term management between stakeholders on the estate could address these areas of inefficiency and monitor the drawdown of P to maintain yields.

Modelling the annual flows and balances of P across a whole farming system is a valuable tool for achieving sustainable P management and making the best use of P across agricultural land. However, P balances can vary greatly between different farms, and even year-to-year necessitating the use of accurate on-farm records and multi-year analysis. This framework should also be applied to other key nutrients.

6 Understanding the main drivers and motivations for phosphorus management on farms in the UK and farmers' awareness of the term "legacy phosphorus" – a farmer questionnaire

6.1 Introduction

Phosphorus (P) is essential in food production and all parts of the UK food system are dependent on inputs of P from fertilisers and manures to support production. The widespread use of phosphate fertilizers since the mid-1900s has led to the introduction large amounts of P into agricultural soils, aiming to meet and often exceed the demands of crop production (Syers et al., 2008). This practice has, however, disrupted the natural biogeochemical storage and cycling of P, increasing the risk of P pollution in watercourses (Withers et al., 2001). Humans have effectively "opened up" the P cycle (Childers et al., 2011). Indeed, diffuse P pollution from agricultural land is the most common reason for the UK to not meet water quality targets for good ecological status in rivers and lakes (Environment Agency, 2021). Furthermore, the UK heavily relies on imported P to meet the demand for P fertilisers, making it potentially vulnerable to future P supply pressures, highlighting the need to address inefficiencies and the recycling of P throughout the food system (Cordell et al., 2022).

Current P use in many food systems is highly inefficient. For example, a recent analysis of P stores and flows across the UK food system demonstrated a P system efficiency of just 43% (Rothwell et al., 2022), and a national P surplus in agricultural soils of around 2.5 – 7.0 kg P ha^{-1} in the early 2020s (Defra, 2024c). Although the national surplus has been steadily declining since a peak of 20 kg P ha^{-1} in the 1970s (Withers et al., 2001), largely due to a decrease in the use of P fertiliser (Defra, 2024c), this level of inefficiency is still not sustainable if the UK is to meet its water quality and biodiversity targets and if it is to overcome some of the potential vulnerabilities in P supply. As such, there is considerable pressure on planning the use and application of manures and P fertilisers on farm with optimised application rates leading to more cost-effective food production, and a reduction of adverse environmental consequences (Bruulsema et al., 2019; Osmond et al., 2019). The appropriate planning and application of P has been shown to help to reduce P loss to the environment by up to 66% and improve financial returns through savings in nutrient inputs (Shepard, 2005; Vandyke et al., 1999).

In England the "Reduction and Prevention of Agricultural Diffuse Pollution (England) Regulations 2018", also known as the "Farming Rules for Water" (FRfW) were introduced in 2018 to reduce and prevent diffuse pollution from agricultural sources[61]. Similar regulatory measures were also applied to all farms across Wales under "The Water Resources (Control of Agricultural Pollution) (Wales) Regulations 2021"[62]. These policies cover aspects of nutrient management, including the planning, application and storage of fertilisers and manures as well as the management of soil and livestock. Phosphorus management is typically considered alongside all other nutrients contained in fertilisers and manures. **Table 6-1** summarises some of the legislation and how these can be interpreted for "best practice" management of P.

As outlined in the FRfW, a key part of P management is the planning of P applications, including the adoption of nutrient management plans (NMP). There are four fundamental steps to producing a NMP for P applications (AHDB, 2020a):

- Soil analysis – this is to determine the existing soil P stocks. In England and Wales this is often determined by the Olsen P test which gives and approximation of the "available" P in the soil. Typically land managers will take one, aggregated, soil sample for each field, However, precision soil sampling and analysis (such as one sample per ha) is gaining in popularity and has been shown to reduce P fertiliser

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[61] https://www.legislation.gov.uk/uksi/2018/151/contents/made

[62] https://www.gov.wales/sites/default/files/publications/2023-10/water-resources-control-agricultural-pollution-wales-regulations-2021-guidance-farmers-and-land.pdf

requirements by around 50% compared to standard soils sampling techniques (Kazlauskas et al., 2021).

- Crop requirements – depending on the crop being grown and the projected yields the P requirements of the crop will differ. This information is typically provided by agronomists or via standard crop requirement tables (such as the RB209) (AHDB, 2020a). The use of crop / grain analysis goes beyond current legislation but increasingly it is being recommended as a tool for future nutrient applications as an accurate measurement of nutrient uptake by the crop (AHDB, 2020d).

Table 6-1: A summary of the Farming Rules for Water legislation and how this can be interpreted for best practice management of phosphorus (P). Taken from "Reduction and Prevention of Agricultural Diffuse Pollution (England) Regulations 2018".

Farming Rules for Water regulation and definition	Interpretation of "best practice" for phosphorus (P) management
Applying organic manure and manufactured fertiliser to agricultural land: A land manager must ensure that, for each application of manure or fertiliser to agricultural land, the application is planned so that it does not: (i) exceed the needs of the soil and crop on that land, or (ii) give rise to a significant risk of agricultural diffuse pollution	• Take into account where the is significant risk of pollution during application (such as slope of land, proximity to watercourses, weather conditions, soil type and condition, green cover, and the presence of any agricultural land drains) • Take into account the results of soil sampling and analysis of P ○ soil testing and analysis must be carried out at least every 5 years • Land managers should be able to demonstrate that they have planned applications of manure or fertiliser. This includes for example, a nutrient management plan or other written plan. • The crop P requirement for each cultivated land parcel that should be informed by one of the following: ○ a manual such as AHDB's nutrient management guide (RB209) ○ farm software such as PLANET, MANNER-NPK or nutrient management tools such as those provided by Tried and Tested ○ a suitably qualified professional, such as an agronomist or FACTS adviser • Land managers should plan to avoid applying organic manures that raise the Soil P index above target levels for soil and crop on land over a whole crop rotation

- Understanding the contribution of manures – manures can provide a rich source of P (and other nutrients). Standard nutrient values for manures are useful for providing farmers with simple P recommendations (AHDB, 2020b). Yet, the diverse and natural range in nutrient content found in manure, affected by factors such as livestock type, diet, feeding system, bedding system, and the volume of water entering storage, underscores the need for farmers and land managers to sample and test manures before applying them (Fuentes et al., 2006; Pagliari & Laboski, 2012).

- Understanding the requirement for P fertilisers – fertilisers can be used to meet the P requirement of the crop with or without the addition of manures. Fertiliser use is sometimes preferred as they can provide nutrients at agronomic optimum ratios, which can be less easily achieved using manures (Schröder, 2005).

Environmental considerations are a key part of the FRfW regulations (**Table 6-1**), particularly with the management of manures and the implementation of manure management plans (MMP). Manure management plans involve assessing and managing the environmental risks associated with the application and storage of manures. These plans involve the creation of manure spreading risk maps, identifying areas where manures must not be applied as well as taking into consideration other field factors (such as slope, soil texture, presence of field drains, etc.) (Defra & Environment Agency, 2024). Farmers with livestock are also required to calculate the minimum area required for spreading based on stock numbers and housing periods. One disadvantage of this is that current legislation is largely centred on the management and control of N in the manures (Defra, 2009)[63] and consequently agricultural practices have meant that manures are commonly applied to meet the N demand of the crop (Sharpley et al., 2001) which can exceed the crop requirements for P leading to long-term P accumulations[64]. However, this should be addressed by following an accurate NMP on for the land making the most of all nutrients contained within manures. In addition to farming policy,

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[63] EC Nitrates Directive (91/676/EEC) and Code of Good Agricultural Practice to control nitrate loss and protect against nitrate pollution: within any 12-month period no more than 250 kg ha^{-1} of total N from organic fertilisers (of any origin) can be applied to land (Defra, 2009).

[64] For example, using standard nutrient values for manures: If cattle farmyard manure was applied at 42 t ha^{-1} (the maximum annual application rate to provide 250 kg N ha^{-1}) the total P applied to the crop would be approximately 36 kg P ha^{-1} more than the crop P requirement for a winter wheat crop grown on soils with a P index of 2. (AHDB, 2020b, 2020c; Defra, 2009)

UK agri-environment schemes have also played a part in the management of P for the prevention of diffuse water pollution. Various strategies have been proposed, from buffer strips to cover cropping, yet the positive impacts of these measures and the legislation is not always seen in the short term (Meals et al., 2010; Sharpley et al., 2009; Stackpoole et al., 2021).

The use of long-term whole-farm P budgets currently fall outside of the mandatory legislation. These budgets go beyond the annual P management requirements for a single land parcel and considers all farm P imports and exports, including P in animal feeds / seeds and the amount of P exported from livestock products (Chapter 5 of this thesis explores these budgets in more detail and provides a case study for an Organic Farming Estate in the UK). The benefits of carrying out these budgets is that they can help to identify hotspots of P inefficiency and losses of P from the farm system (Watson et al., 2002). These can then be targeted for improvements and increase the long-term P sustainability of the farm (Brunner, 2010).

According to Beegle et. al. (2000), a NMP must be practical to be effective and despite legislation being in place it is still common for farmers and land managers to not plan their P applications nor test their soils. Indeed, recent Defra (2022) studies have found that just 54% of holdings have a NMP and just 69% of holdings routinely test the nutrient content of their soils. Furthermore, although farmers may often adopt certain practices associated with NMP, such as the data collection, they then fail to fully implement these into in-field decision making, thus negating any benefits that they may bring (Buckley et al (2015).

To date, much research has focused on mitigation strategies for nutrient losses to the environment (Gu et al., 2023; Johnston & Bruulsema, 2014; Withers & Jarvis, 1998). Further studies have focused on the adoption of NMP and the factors that may influence farmers' intentions to adopt these practices (Buckley et al., 2015; Daxini et al., 2018; Daxini et al., 2019). However, very few explicitly explore P management and the barriers that land managers may face in both managing P inputs to their land and also the potentially high P stocks that have been built up in their soils. Understanding the motivation and barriers that farmers and land managers face in planning or reducing their P application rates to land could go some way into directing research, education and legislation to understanding why existing strategies to reduce the environmental impacts of P pollution from agriculture have been less successful than hoped for (Bewsell & Kaine; Daxini et al., 2018; Denny et al., 2019; Dooley et al.).

This study aims to understand some of the motivations and barriers that farmers and land managers in the UK face to manging P on their land. To address this aim there are four main research questions and hypotheses (RQ) that will be explored:

RQ1. To what extent do UK farmers follow best practice guidance for P management on their farms and to what extent do UK farmers use professional advice for their phosphate nutrient management? – UK livestock farmers will be less likely to have a NMP or seek professional advice for nutrient management compared to arable only enterprises.

RQ2. How will the motivations for P management differ between different farming enterprises? – Financial motivations will be important for all farmers in determining how much P they apply to their land; however, manure storage constraints will also be an important determining factor for livestock farmers.

RQ3. To what extent do farmers consider whole-farm P management to long-term P application? – Farmers that have taken measures to reduce the P inputs to the land will be more likely to report that their overall whole-farm P budget is "in balance" or "in deficit".

RQ4. What are the main barriers for farmers/land managers to reducing P application rates to land? – The impact of P reductions on yields will be a primary concern of most farmers growing arable crops.

The term "legacy P" has evolved in recent years to reflect the issues and challenges that have risen from the effects of long-term excess P inputs to agricultural land. There is a growing global interest in legacy P, viewed not just as a water quality threat but also as an untapped and insufficiently understood reservoir of P that holds the potential to counterbalance fertiliser P inputs (Rowe et al., 2016; Sattari et al., 2012; Stutter et al., 2012). Despite the widespread use of the term, there is still debate as to what legacy P is and how to define it, with definitions varying between disciplines (Chapter 2 of this thesis explores two contrasting views of legacy P). Awareness of legacy P is growing outside of the scientific literature into the agricultural community (Gillbard, 2022; Goodwin, 2023; Impey, 2021) and therefore it is important to understand how farmers view this term to help ensure effective communication and outreach; build on interdisciplinary collaborations; and to avoid misinterpretations between the academic, governance and farming communities.

As such, this study also aims to explore farmers' insights surrounding legacy P and investigates how they define the term. This aim will be explored by research question 5:

RQ5. How aware are farmers / land managers of the term "Legacy P" and what is their understanding of this term – based on a summary of the key phrases used, a synthesised farmer-led definition will be suggested.

6.2 Methods

To address the research questions, farmers, land managers and advisers who manage land for agricultural production in the UK were invited to complete a short questionnaire about the resources they used to plan their P applications and what their motivations are for planning. The questionnaire also explored aspects of long-term P management on their land as well as their perceptions regarding the term "legacy P".

A survey was chosen as the method for this study to enable the gathering of quantitative and qualitative data from a wide range of farmers and land managers efficiently and in their own time. Compared to interviews or focus groups, the survey also provided anonymity, potentially encouraging more honest responses from participants who might otherwise hesitate to share opinions on sensitive topics like agricultural practices and adherence with government legislation.

This research project was approved by the Lancaster University Faculty of Science and Technology Research Ethics Committee [FST-2023-3637-RECR-3] on 24th July 2023. A full copy of the Questionnaire and other supporting documents (including, participant information sheet; participant consent form; and invitations to participate) can be found in the Supplementary Information at the end of this manuscript (**SI Table 6-1** and **SI Table 6-2**).

6.2.1 Research Participants

Research participants for this project were farmers, land managers and advisers who manage land for arable and or livestock production in the UK. Participants were recruited using a snowball sampling technique. An online questionnaire (hosted via Qualtrics) was distributed to Farm Advisory companies in the UK, who were asked to voluntarily assist in recruiting participants from their client databases. The Farm Advisory companies served as Gatekeepers to the target research participants and were selected and contacted through networks know by the Research Team. Gatekeepers and participants were also encouraged to pass the survey link on to others who may be interested. There was a risk that participants may disclose information that shows that they are not following best practice guidelines and current UK legislation with regards to P management on the farm. To manage this and to encourage honesty and ensure non-traceability, responses to the survey were collected anonymously.

6.2.2 Structure of the survey

The questionnaire was split into three main sections and comprised a mixture of fixed response, multiple-choice questions, and short free-text responses. For the purposes of this study, participants were informed that the term "phosphorus" would be used to encompass all forms of P (including phosphate) in soil, fertilisers, manures, and animal feeds. This was used to overcome the differences between fertiliser contents, manure analysis and nutrient recommendations, where P is often expressed in the oxide form, phosphate (P_2O_5), and soil nutrient analysis results which are usually given as milligrams of P per litre (mg P / L) and a corresponding Soil Index value.

Section One of the survey aimed to gather background information about participants' farming enterprises including: the county/region they farm in; their role on the farm; their main farming enterprises; their main farming type (such as, conventional, organic, etc.); the total size of the area that they farm / manage; and the number of fields (or separate pots of land) that they farm / manage. This background information was used to group responses for data processing and analysis.

Section two of the survey explored participants' current P management practices and motivations for applying P to their land. Participants were firstly asked whether they applied P fertilisers and / or manures to their land and whether they imported any animal feeds containing P onto their farm. Participants were then asked whether they utilised nutrient and / or manure management plans and what resources they used to inform their P applications to the land. Participants were asked to select from a list of resources including, for example: Agronomists; soil, manure, and crop P analysis; and personal experience. Responses to these questions were used to address RQ1. To address RQ2 participants were asked to state the relative importance of various economical (such as, crop productivity and profit margin), legislative (such as: Farming Rules for Water legislation, and Countryside Stewardship scheme prescriptions) and environmental factors (such as: managing P losses to the environment) in determining how much P they applied to the land. Responses from this question were scored on a Likert scale from 1 (Not at all important) to 5 (Extremely important).

Section three of the questionnaire asked respondents to think about some of the long-term aspects of P management of their farms. Questions in this section explored whether P budgets / balances on the farms were in balance (the total amount of P entering and being removed from the farm are the same), in deficit (the total amount of P entering the farm is less than the total amount of P removed from the farm) or in surplus (the total amount of P entering the farm exceeds the total amount of P removed from the farm) and whether respondents had taken measures to reduce P inputs to their land. Responses to these questions would provide information on the extent that farmers / land managers consider whole-farm P management with long-term P applications (RQ3). To explore the barriers for farmers/land managers to reducing P application rates to land (RQ4), participants were asked to select from a range of responses (Concerns regarding impact on crop yield; Concerns regarding impacts on crop quality; Manure production / export constraints; Lack of information / evidence to support reduced P inputs), they were also given the option to add their own free-text responses.

Finally, participants were asked about their understanding of the term "Legacy P", those that had heard of the term were then asked to briefly define what they thought legacy P was (RQ5). Key words and phrases from all these responses were then extracted and grouped into four broad categories to give an overall picture of farmer / land manager perspectives on legacy P (*P availability* – these responses discuss the availability of P to crops; *P management and accumulation* – these responses discuss the impact of P management and inputs on current P stocks; *P storage and measurement* – these responses mention the role of soil and the measurement of P in understanding legacy P; and *legacy P challenges* – these responses include strategies or actions taken to address concerns about the challenges of excess P). Words and phrases with similar contexts and definitions were grouped into a single term for categorisation and to calculate the frequency of occurrence (for example: "unused", "left-over", "residual", "retained", "remain", and "not utilised" were grouped into the single term "residual"). A visual representation in the form of a word cloud was generated to depict the prevalence of words in the responses.

6.3 Results

6.3.1 Overview of the participants

In total, there were 51 online survey respondents including: 36 tenant or owner/occupier farmers); 6 land managers; and 8 advisers (**Table 6-2**). Of these respondents, farm sizes / area managed ranged from 13 ha to more than 5,000 ha with a total farmed area covering over 37,600 ha. Ninety four percent of the participants farm or manage land in England with the remainder farming in Wales. Similarly, 94% of the participants mange land using conventional farming practices, with four respondents managing their land for organic production and a further three participants adopting regenerative faming / limited tillage practices. Farming sectors covered by the survey include dairy, beef and/or sheep, pigs, poultry, forage crops, arable crops, potatoes, and horticulture (**SI Figure 6-1**). The low number of respondents in each category prevented the analysis of farming enterprises at this level of detail, and instead farming enterprises were categorised into three broad farming types: Livestock only (16 responses), Arable only (11 responses) and Mixed farming (24 responses).

Table 6-2: An overview of the participants, background information regarding their: occupation, locality, farming enterprise, farm size and farming system.

	Number of responses	**% of responses**
Number of respondents	**51**	**-**
Occupation		
Farmer (owner occupier / tenant)	36	70.6
Farm / estate manager	6	11.8
Adviser	8	15.7
Unknown / not answered	1	2.0
Farming locality		
England	48	94.1
North West	*5*	*9.8*
North East	*7*	*13.7*
West Midlands	*14*	*27.5*
East Midlands	*3*	*5.9*
South West	*11*	*21.6*
South East	*7*	*13.7*
Wales	3	5.9
Farming enterprises [a]		
Arable only	11	21.6
Livestock only	16	31.4
Mixed farming	24	47.1
Farming system		
Conventional	48	94.1
Organic	4	7.8
Upland	4	7.8
Greenhouse/polytunnels	2	3.9
Other	3	5.9
Farm area		
0 – 100 ha	13	25.5
101 – 200 ha	14	27.5
201 – 500 ha	13	25.5
> 500 ha	11	21.6
Total farmed area covered by the respondents (hectares)	**37,633**	**-**

[a] For a further breakdown of farming enterprises covered by these responses see **SI Figure 6-1.**

6.3.2 Following best practice guidance for phosphorus management on farms

Survey respondents indicated that their applications of P to land were typically informed by a variety of resources, with only a small number (four) stating that they do not plan their P applications to the land (**Figure 6-1**). The resources that farmers can use to inform P management, provided in the questionnaire, were categorised into six groups, and results of which are reported in the sub-sections that follow: governmental guidance regarding nutrient management (*"legislation (e.g. FRfW)"*; and *"agri-environment scheme prescriptions"*); sources of P that can directly influence the amount of P applied to the land (*"livestock numbers"*; *"nutrient analysis of manures"*; and *"P content of animal feed"*); P removal from the land through harvested crops (*"crop / grain analysis"*; and *"yield mapping"*); the landscape / environmental factors (*"field maps (to inform slope, proximity to watercourses, etc)"*; and *"standard soil nutrient analysis results"*); professional nutrient management advice (*"agronomist / agricultural adviser / animal nutritionist"*; and *"nutrient management guide (RB209) or other nutrient management planning software"*); and *"personal experience"*. The use of NMPs and MMPs by famers and land managers who apply fertilisers and/or manures was also explored in this study.

6.3.2.1 Government guidance to inform on-farm phosphorus management

Government guidance, such as FRfW regulations in England and/or agri-environment scheme prescriptions, influenced P applications and management for 57% of participants (**Figure 6-1**). These regulations form the basis for best practice guidance for P management. However, livestock only enterprises reported lower usage of these resources (13-25%) compared to arable only (18-73%) and mixed farming enterprises (42-67%). Legislation was also reported to influence P application and management decisions more than agri-environment scheme prescriptions.

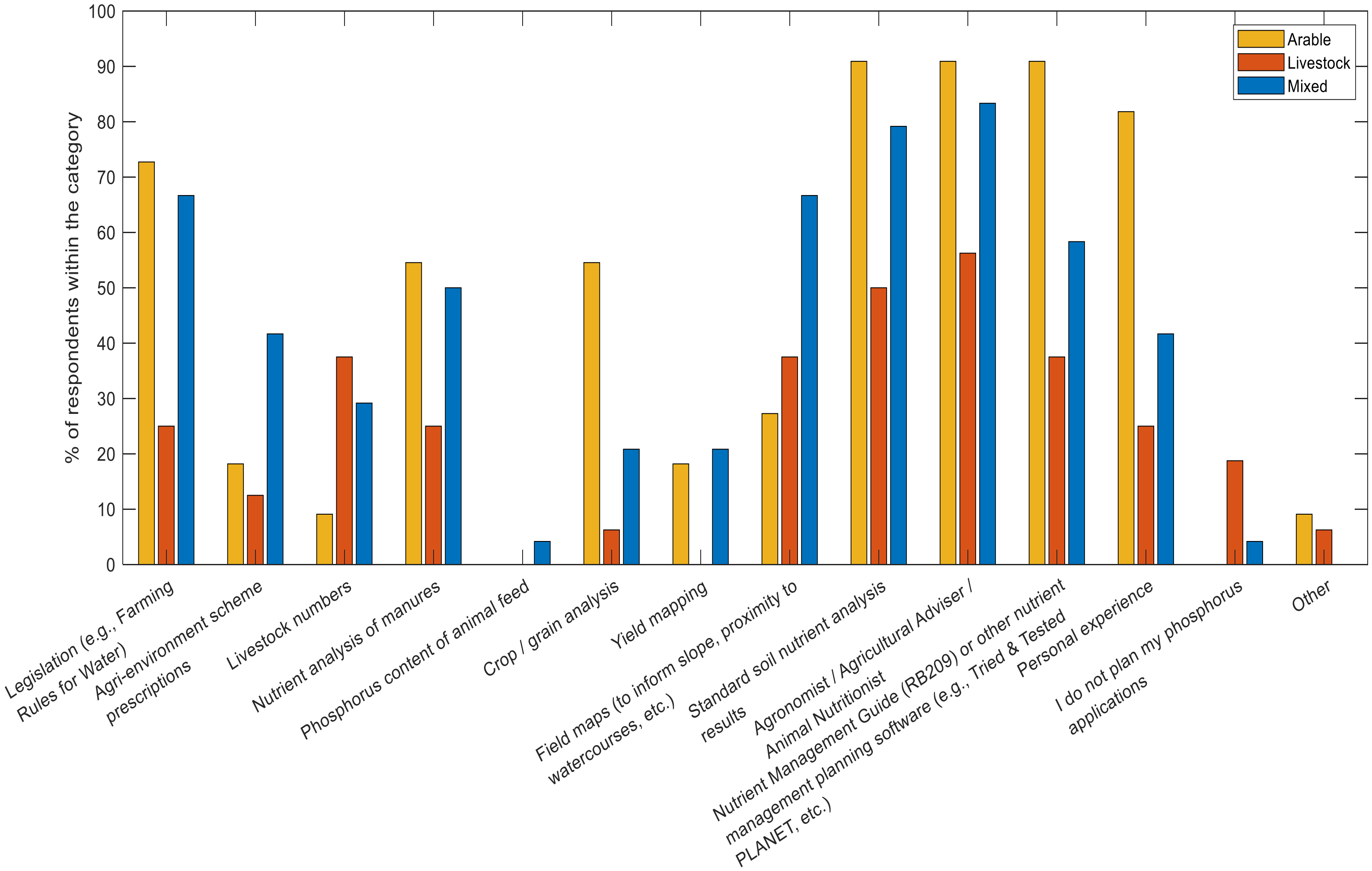

Figure 6-1: Resources that survey participants use to inform phosphorus (P) applications to their land.

6.3.2.2 Accounting for sources of phosphorus on-farm

When considering the sources of P that can directly influence the amount of P that is applied to the land, livestock numbers and nutrient analysis of manures were reportedly used by 14 and 22 of the respondents, respectively for all farm types (**Figure 6-1**). Interestingly, however, between 50-60% of arable only and mixed farming enterprises made use of manure nutrient analysis results compared to livestock only enterprises where only 25% of farmers / land managers relied on testing manure samples. Just one farmer accounted for the P content of animal feeds when planning their P applications to the land (**Figure 6-1**), despite a third of the farmers in the survey stating that they imported animal feeds containing P.

6.3.2.3 Accounting for phosphorus removal of harvested crops

Just 17 of the total 51 respondents accounted for crop/grain analysis and/or yield mapping of previous crop to inform crop P offtake and subsequent P inputs and management (**Figure 6-1**). However, the proportion of arable farmers (54%) that use crop P analysis was greater compared to other farming types.

6.3.2.4 Accounting for landscape and environmental factors

For all farming categories, soil analysis results ranked as the top one (arable only, 91%) or two (mixed farming, 79%; and livestock only; 50%) resource used to inform P applications (**Figure 6-1**). Field maps are reportedly used less than soil analysis to inform P management on farms. Field maps were used more by mixed (67%) and livestock only (38%) enterprises compared to arable only enterprises (27%). For livestock only farmers this was the joint third most common resource to inform P management to farmland.

6.3.2.5 Professional advice to inform phosphorus management

For arable only enterprises, all respondents made the use of professional advice from agronomists / agricultural advisers and/or recommendations from the RB209 or other nutrient management planning software to inform P management to their land. This compared to 83% (20) of mixed farming enterprises and to 69% (11) of livestock only enterprises that used one or more forms professional guidance to inform P management on their land.

6.3.2.6 Adoption of nutrient and/or manure management plans to inform on-farm phosphorus management

Phosphorus fertilisers and manures are applied to agricultural land by 61% and 90% of the farmers / land managers who completed the questionnaire, respectively. However, 12% of those that apply P do not have or use a NMP or MMP (**Figure 6-2**). This is increased to a quarter (25%) of participants on livestock only enterprises. For arable only enterprises all participants have and use a NMP and/or MMP, including a participant who stated that they did not apply any P fertilisers or manures and have actively been "running down" P indices on their land.

Overall, most of the farmers and land managers who completed this survey follow some of the best practice guidelines for P management on their land, with approximately 90% of the respondents using professional advice (via an agronomist or NMP software) and/or soil nutrient analysis results to inform P applications. Livestock only enterprises are less likely to seek

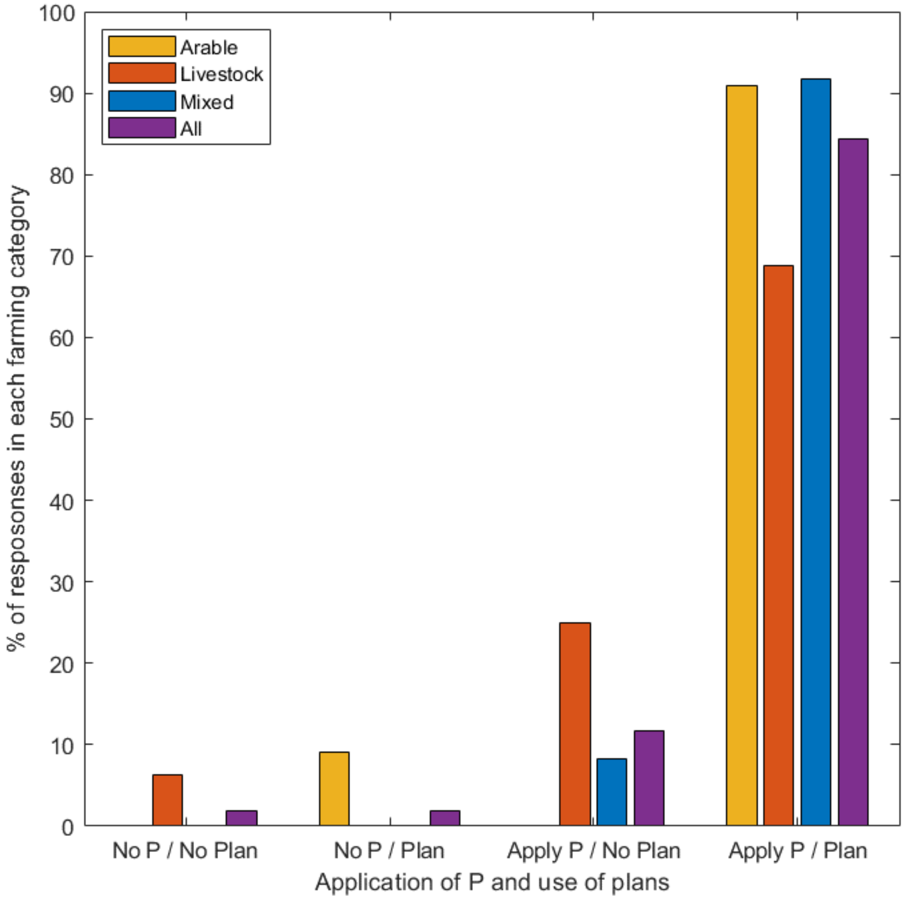

Figure 6-2: The number of participants that reportedly do or do not apply phosphorus (P) to their land in the form of fertilisers and/or manures ("Apply P" or "No P") and the number that do or do not use nutrient management plans and/or manure management plans ("Plan" or "No Plan")

professional advice compared to arable and mixed farming enterprises, but agronomists, soil analysis results, and NMP software still inform approximately 69% of P applications to these farms. Finally, it is important to note that personal experience still plays a role in many farmers' decisions to apply P, with 23 people surveyed stating that they use this as part of the P management on their land, despite detailed information about P inputs, offtakes and stores being available to them.

6.3.3 Motivations for phosphorus management

Participants of the survey were asked to rate how important various factors were to them in determining how much P they applied to their land. These responses were categorised into five broad groups: governmental / industry guidance regarding nutrient management (*"legislation (e.g. FRfW)"*; *"Farm accreditation / assurance schemes (e.g., LEAF)"*; and *"agri-environment scheme prescriptions"*); crop production (*"crop productivity"*; and *"crop quality"*); financial concerns (*"input costs"; "profit margin";* and *"application efficiency / time management"*); *"managing P losses to the environment"* and, finally, *"manure storage constraints"* (**Figure 6-3**).

6.3.3.1 Government / industry guidance

Results from the survey suggested that farm accreditation / assurance schemes and agri-environment schemes were the least important factor for most farmers and land managers when determining how much P they applied to their land. Mean response values across all farming types of 3.09 and 2.79 were reported for farm accreditation / assurance schemes and agri-environment schemes respectively (***Figure 6-3***). There was little difference between the different farming enterprises. However, farming legislation (such as the FRfW) was considered more important in determining how much P they apply to their land. 82%, 50%, and 63% of arable only, livestock only, and mixed farming enterprises respectively stating that this was an important or very important factor.

6.3.3.2 Crop production

For all farming types, crop production was a key motivation for determining how much P was applied to the land (***Figure 6-3***). For arable only enterprises, all participants claimed that crop productivity was an important or very important factor giving a mean score of 4.87 across all participants. This was similar for mixed farming enterprises where 92% of participants ranked this a four or five on the Likert scale. On the other hand, the mean Likert score across livestock only farmers was just 3.77 with only 62% of participants reporting crop productivity as important or very important. Crop productivity was the second most important factor for livestock only farmers overall. The quality of harvest was considered less important than crop yields by farmers for determining how much P is applied to the land. Yet, for arable and mixed farms, between 73% and 75% of farmers still reported this as important or very important.

6.3.3.3 Financial concerns

Overall profit margin and input costs ranked second and third as the most important motivation for farmers to determine how much P they applied to their land (***Figure 6-3***). Application efficiency / time management as a motivation for P applications was, on the other hand, less important to farmers and land managers in the study, receiving mean Likert scores of between 3.38 and 4.18 across the different farming types.

6.3.3.4 Manure storage constraints

For livestock only enterprises that apply manures to their land, the most important factor for determining the quantity of P applications to agricultural land was slurry / manure storage constraints, with 50% participants scoring this as important or very important and achieving an overall mean of 4.09 across all participants who responded (**Figure 6-3**). This was reinforced and notably summarised by one participant who stated:

> *"Our 1000 cows poop, we've discussed it with them but they won't stop. We've done our best to mitigate phosphate losses to water courses[…] However, all our fields are P index 3 or greater[....] not unexpected as [there has] been cows on the site for over 100 years".*

In the absence of livestock on the holding (arable only enterprises), the storage of manures was the least important motivation (mean score of 2.00 across all participants).

6.3.3.5 Managing phosphorus losses to the environment

The data suggest that livestock farmers were less likely to be motivated by environmental factors to manage P losses on the land compared to other factors (**Figure 6-3**). Just 31% of livestock only participants rated this as important for their planning. However, for mixed farming enterprises the mean Likert score was greater than 4.00. Arable only enterprises were moderately motivated (mean Likert score of 3.90) by managing P losses to the environment when determining how much P to apply. Although it is worth noting that six farmers have recognised that preventing excess P application to crops is important and they are actively trying to reduce soil P levels through the reduction and management of their P inputs.

6.3.3.6 Additional factors

In addition to the factors within the questionnaire, ten of the participants also stated that the results of their soil tests were an important factor in determining how much P they applied (**SI Table 6-3**). Some farmers also considered the relationship between soil P and other nutrients in soil such as calcium and iron, and the impacts this could have on P availability to the crop. Some considered how cover crops and soil health can be used to increase P availability to the main crop. Managing the P inputs, particularly from manures, to meet P requirements across the whole crop rotation was important to four participants.

Overall, crop productivity and financial considerations are typically the main motivations for determining how much P is applied to the land across all farming types compared to legislation and environmental considerations. However, manure storage constraints are the most important motivation for livestock enterprises.

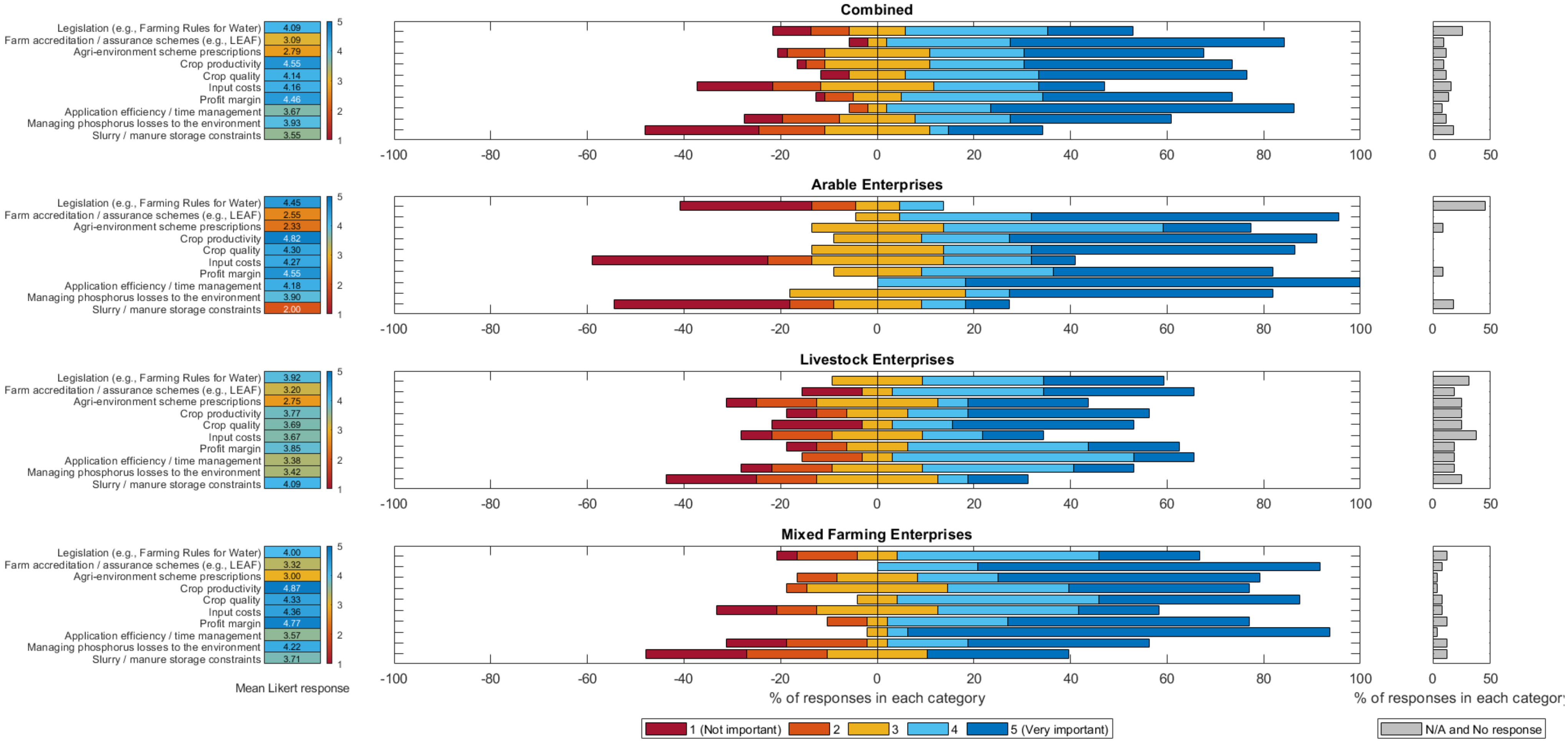

Figure 6-3: Relative importance of different factors that farmers use to determine how much phosphorus they apply to their land. Left panels: mean Likert response value. Centre panels: Percentage of responses in each category, responses with a value of "3" placed either side of centre as a "neutral" response; responses with values of "1 (Not important)" and "2" classed as a "negative" response; responses with values of "4" and "5 (Very important)" classed as a "positive" response. Right panels: Percentage of responses that specified "Not applicable" and did not give any response.

6.3.4 Whole-farm phosphorus management and long-term phosphorus applications

Respondents were asked whether they thought their whole-farm P budgets were in balance, in deficit, or in surplus and whether they had implemented measures to reduce P inputs to their land (**Figure 6-4**). Overall, approximately 43% of the participants believed that their long-term whole-farm P budget was in balance and there was little difference between the different farming enterprises. Reportedly, 50% of participants managing livestock only enterprises have taken measures to reduce their P inputs (**Figure 6-4**). However, more than one third of these participants believe that their long-term P budget is still in surplus (**Figure 6-5**). For mixed and arable enterprises, P inputs for 21% and 18% of participants' land is still in surplus

Of the 73% of arable enterprises that have taken measures to reduce their P inputs to their land, 36% of the participants believe that their long-term P balance is now in deficit (**Figure 6-4**, **Figure 6-5**). Participants' reasons for taking these measures and reducing or stopping their P inputs range from plans to "stop food production on the land" and trying to return intensive pastureland into "wildflower meadows" to simply "working to reduce indices in high index fields" in line with RB209 guidance (**SI Table 6-3**). Interestingly, the number of participants who have taken measures to reduce their P inputs to the land is very similar to those that believe their whole-farm P budget/balance is either "in balance" or "in deficit". Between 9% and 19% of participants across the different farming types did not believe they knew their long-term P balance.

6.3.5 Barriers to reducing phosphorus application rates

Overall, more than 50% of respondents felt that the potential impact of crop yield was a barrier to them reducing their P inputs to land (**Figure 6-6**). This was a greater concern for arable and mixed farming enterprises (approximately 63% of participants in these categories) compared to livestock only farms. The impact on crop quality was less of a barrier to reducing P inputs to land compared to the impact on yields. This is comparable to earlier results when participants

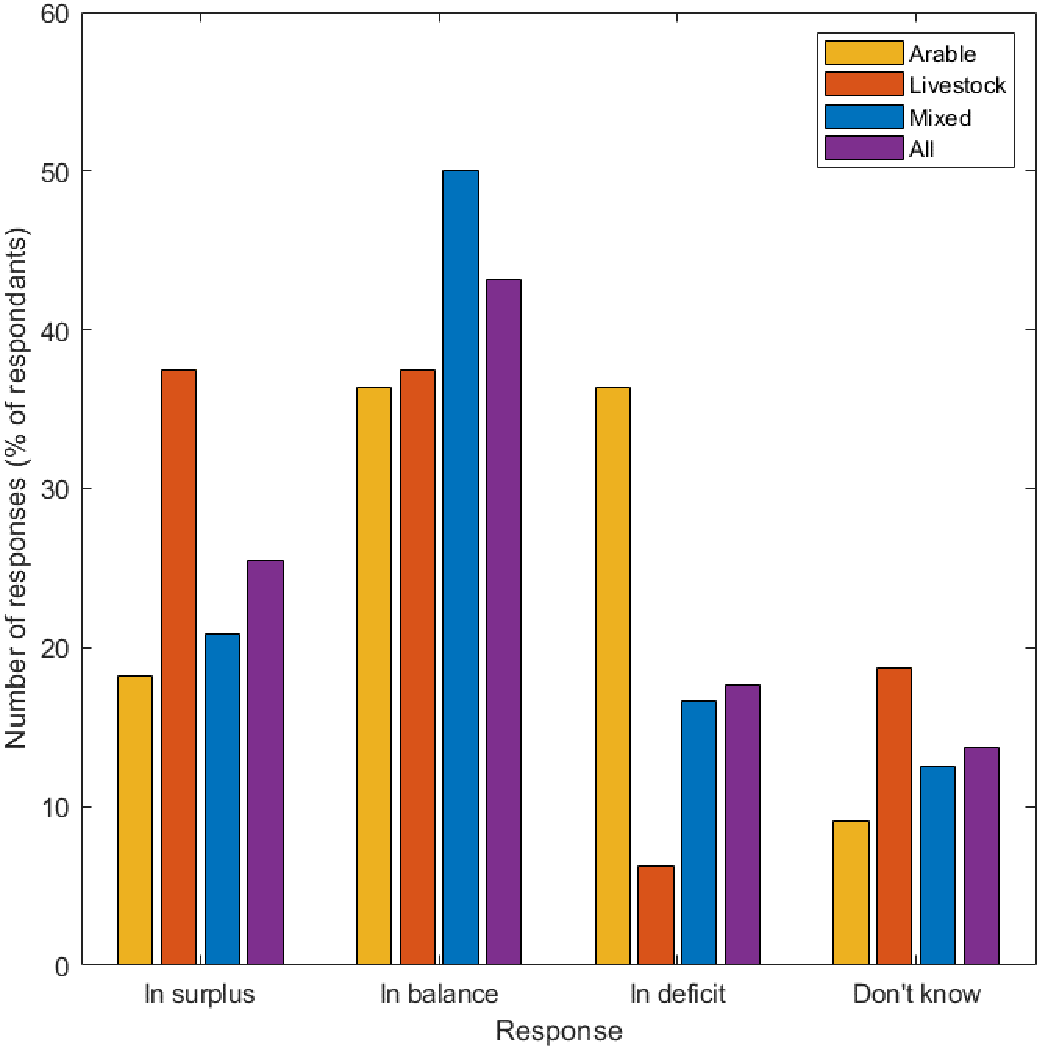

Figure 6-4: The number of participants that perceive their long-term whole-farm phosphorus balance to be either "in balance", "in deficit", or "in surplus" for each farming category.

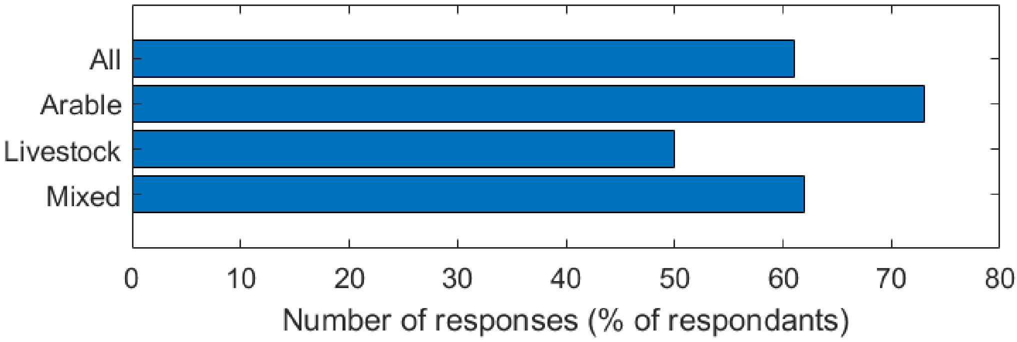

Figure 6-5: Number of participants in each farming category that stated that have taken measures to reduce phosphorus inputs to their land.

were asked about the importance of crop productivity and quality for determining how much P they applied to the land (**Figure 6-3**). Notably, four participants indicated that their land had low P indexes, hindering their ability to decrease P inputs.

Livestock and mixed farming participants expressed concern about constraints related to manure production and export. The data reveals that 38% of livestock only and mixed farming enterprises identified manure constraints as a primary obstacle to reducing their P inputs (**Figure 6-6**). This finding aligns with earlier survey responses (**Figure 6-3**). Moreover, 38% of survey participants cited a lack of information or evidence supporting reduced P inputs to land as a key barrier.

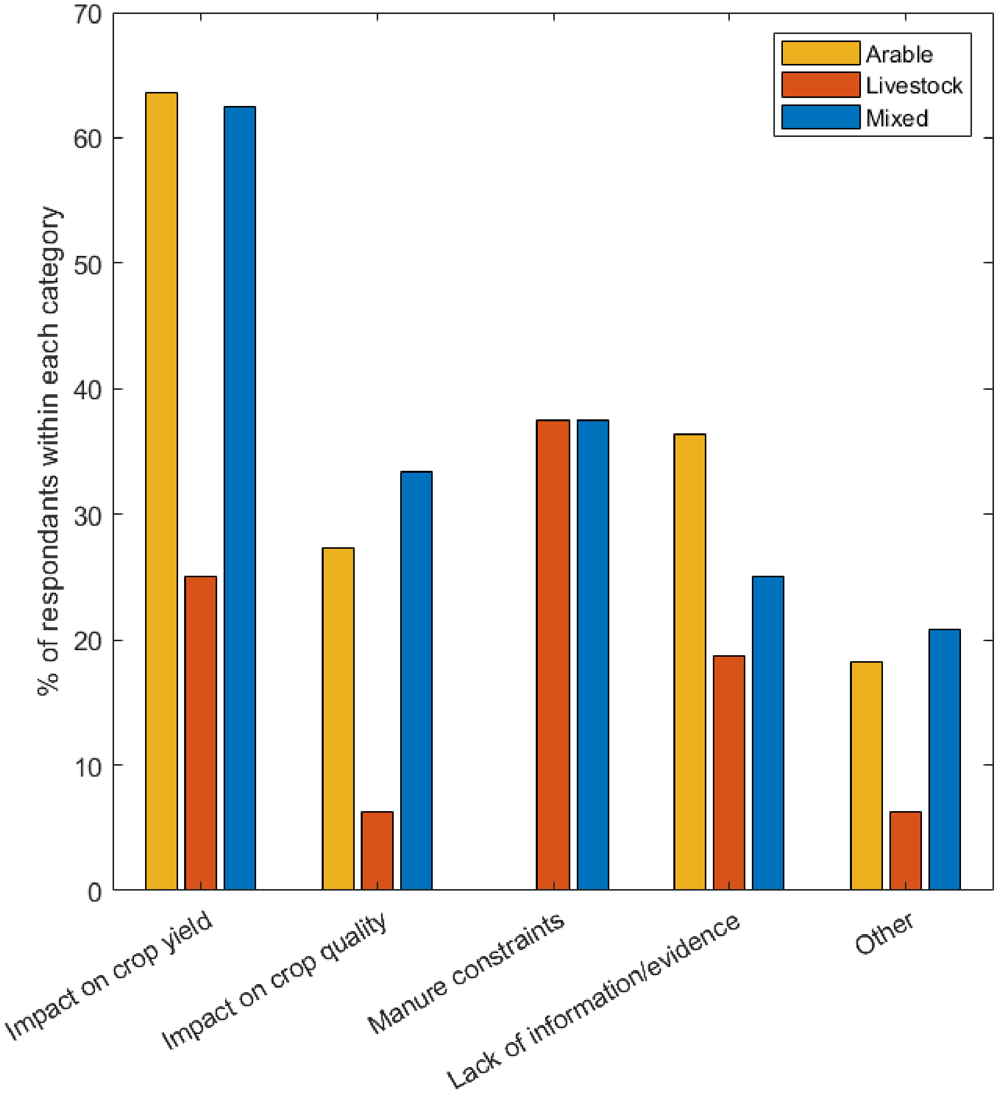

Figure 6-6: Barriers that participants may have to reducing phosphorus inputs to their land.

6.3.6 Defining "legacy phosphorus"

When participants were asked were they aware of the term "legacy P", 39% of people responded "Yes". Arable only farmers and land managers were more likely to have heard of the term compared to livestock farmers (64% and 19% respectively). Based on the definitions provided by the participants[65], it is possible to categorise the information into one of four broad themes: P storage and measurement; P availability; P management and accumulation; and legacy P challenges. A word cloud was created to visually represent the frequency of words in the responses, with larger words indicating a higher frequency across the definitions provided (**Figure 6-7**).

Analysis of the responses suggests that participants typically view legacy P as a term relating to soil (the word "soil" was included in 12 of the 17 responses) and that P is "contained" in different P "reservoirs" within the soil. Phosphorus indices (based on soil P tests such as the Olsen P test) were also identified as being important in measuring how much legacy P is contained in the soil. When considering the availability of the P stored in the soil, approximately half of the respondents believe legacy P to be "locked-up" in the soil and "not readily available" for plants. Participants appear to be concerned about how P availability would impact productivity, with 10 participants linking legacy P to the terms "crop" and "grassland".

Responses from the survey suggest that legacy P is generally considered, to have been built-up as a result of the overapplication of P, and that legacy P is the residual P caused by past management practices. Seventeen percent of the respondents indicated that they believe that current P stocks have been built up in the soil over many years and that the accumulation of legacy P is not a fast process. One participant stated that for their farm:

"legacy P is the elevated soil indices inherited following many years of grazing and manure application on a number of the fields by the previous occupiers".

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[65] Full text responses to given by participants are provided in **SI Table 6-4**.

Approximately 12% of respondents believe that legacy P poses a challenge for land management. Some proposed definitions suggested that *"the challenge is to erode [P] indices to a more appropriate level whilst maintaining productivity and making good use of...manures"*. Others suggested that they that are *"acting to improve soil health"* to help increase the availability of P stocks in the soil for crops and grassland.

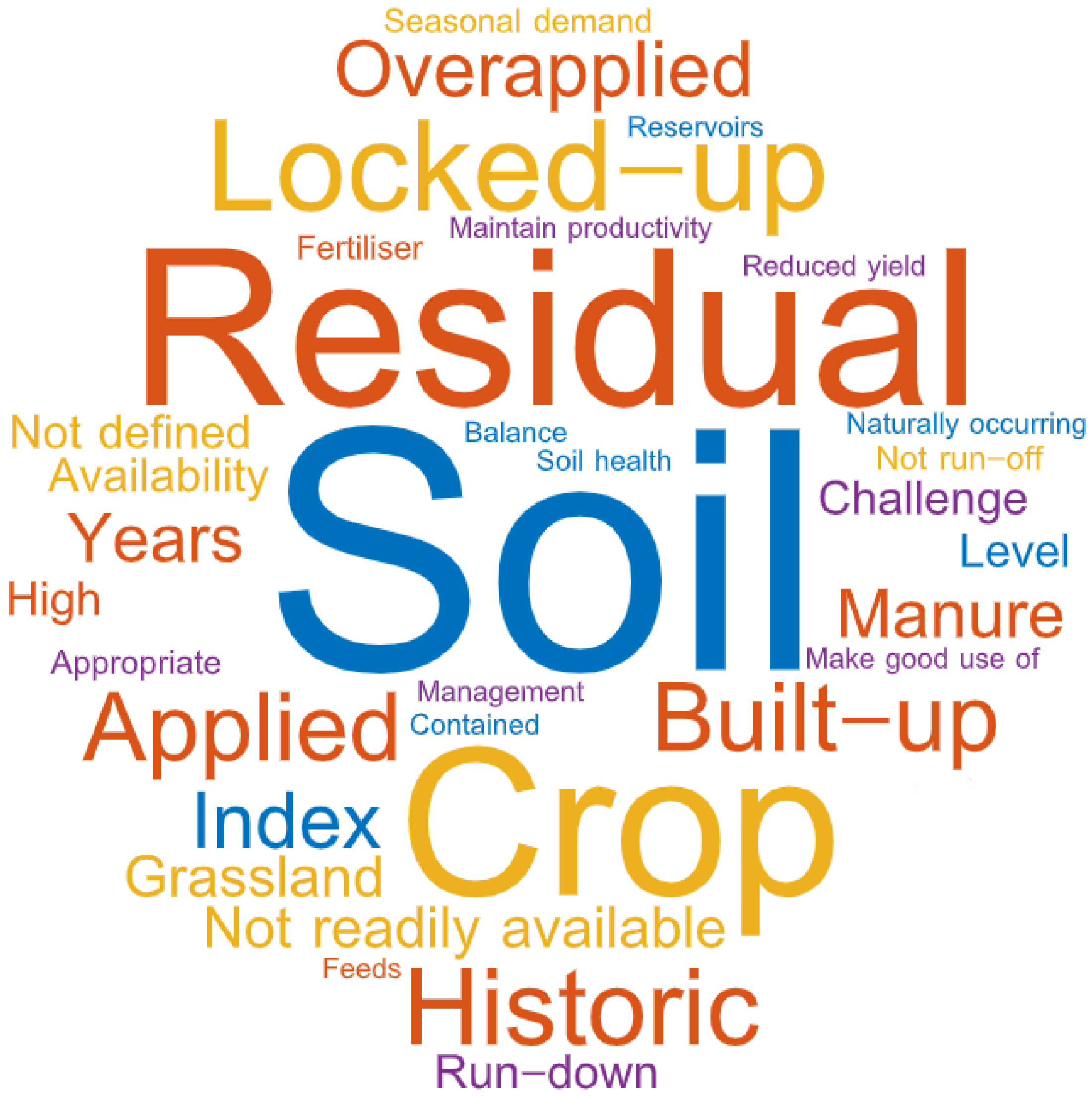

Figure 6-7: Word cloud based on participants' definitions of the term "legacy phosphorus (P)". Larger words indicating a higher frequency across the definitions provided; words and phrases with a common definition and context were grouped into a single term. Words and phrases categorised into one of four broad themes: Yellow: Phosphorus availability – these responses discuss the availability of P to crops. Orange: P management and accumulation – these responses discuss the impact of P management and inputs on current P stocks. Blue: P storage and measurement – these responses mention the role of soil and the measurement of P in understanding legacy P. Purple: Legacy P challenges – these responses include strategies or actions taken to address concerns about the challenges of excess P.

6.4 Discussion

6.4.1 Following best practice guidance for phosphorus management

Government legislation such as the FRfW in England and Water Resources (Control of Agricultural Pollution) in Wales stipulate specific guidelines for P (and other nutrient) management for UK agriculture. These regulations underpin best management guidance for P management on farms. Research question one (RQ1) of this study explored to what extent that participants followed best practice guidance for P management on their land including measures that go beyond current minimum regulation standards. This research found that almost all participants (92%) used one or more resources to inform where, when and/or how much P to apply (**Figure 6-1**). This is in line with previous, findings, which indicated that while legislation may not necessarily be used to inform P management directly, farmers typically use multiple criteria for determining P management practices, often with considerable variation between farmers in their decision-making processes (Dooley et al.)

The use of NMPs and MMPs is a requirement for all areas of cultivated land in England and Wales, yet this research demonstrates that approximately 12% of the participants did not have a dedicated NMP or MMP. The rate of non-compliance in this study is less than national farming statistics in the UK and other long-term research in the USA, which suggest that between 40-50% of holdings do not use a NMP (Defra, 2022; Shepard, 2005). Higher rates of compliance observed in this study could be due to the self-selection in the sampling of participants, and the potential influence of collection bias, wherein respondents may give positive responses based on perceived expectations (particularly regarding compliance with farming regulations). Despite the research team's efforts to address this concern through the collection of anonymous responses, it remains a factor to consider.

Standard soil analysis of P is also required on all cultivated land every 3-5 years (FRfW). Soil testing for P was scored as one of the most important resources that farmers will use to inform the P management on their land (**Figure 6-1**). However, these results demonstrate that approximately one quarter of participants are not following government legislation regarding soil testing on their land, with non-compliance higher for livestock only farmers. This suggests a potential for improvement in P management; particularly around identifying the barriers that farmers in these sectors may face towards soil testing, such as perceived value of soil testing against the cost of analysis.

This study demonstrates that a significant number of farms in the UK may be breaching farming regulations, and that low compliance could contribute to overall poor P management in the agricultural industry (Franklin et al., 2021; Ortolano et al., 2009). While carrying out soil testing and the use of NMPs forms part of UK agricultural legislation, it does not imply strict P management and efficient application (Kelly et al., 2016; Wall et al., 2018) and the full implementation of these practices may not be occurring on farms. Although this research did not explicitly explore the reasons for non-compliance with regulations, previous research suggests that low compliance with nutrient management regulations is often an issue of cost, complexity of the management requirements, compatibility with current farming systems and uncertainty surrounding the environmental benefits (Daxini et al., 2018; Monaghan et al., 2007). As such, although policy plays a crucial role in establishing P management guidelines for farms, there is a necessity to actively involve more farmers in the adoption of these practices, particularly in agricultural sectors where there is typically lower uptake. There is also a need to ensure that farmers go beyond merely fulfilling the minimum paperwork requirements to meet regulatory standards (Daxini et al., 2018).

Research question one (RQ1) of this study also questioned to what extent participants used professional advice for P management. Agricultural advisers (such as agronomists) can have a positive influence on the adoption of agricultural management practices (Daxini et al., 2018), and this advice can be critical to improve soil management decisions on farm (Ingram, 2008). Professional advice from agronomists or agricultural advisers was sought by 76% of respondents in this study, however, there was a disparity between different farming enterprises. Arable and mixed farmers were typically more likely to seek professional advice from agronomists or advisers compared to livestock only farmers (**Figure 6-1**). This disparity is also reflected in some national statistics (Defra, 2022).

Differences between farming systems were not only observed in the uptake of professional advice for P management, but also in the total number of different resources that farmers use to manage P on their land. Arable and mixed farmers in this study utilised a greater number of resources to inform the P management on the farm (arable only: mean = 6.09, mode = 5; mixed farming: mean = 5.63, mode = 9) compared to livestock only farms (mean = 3.13, mode = 0). Reasons behind this disparity between farming systems are not always clear but Rhymes et al (2021) suggest that the role of professional nutrient management advice and uptake of NMP practices for arable farmers has a more direct relationship with achieving maximum yields possible compared to livestock only farmers whose primary focus is likely to be livestock welfare. As such, there may be less perceived economic return for livestock farmers (particularly less-intensive grazing systems) from engaging with advisory support, for P management or wider nutrient management practices (Dooley et al., 2005; Mccormack et al., 2021; Rhymes et al., 2021).

In previous studies, there has been shown to be a positive relationship between the size of farm and the engagement of farms with nutrient management practices (Daxini et al., 2018; Gao & Arbuckle, 2022; Ribaudo & Johansson, 2007). This relationship was seen in some of the data from this survey, where small farms (less than 100 ha) were less likely to comply with the minimum requirements for P (nutrient) management on farms in England and Wales compared to larger farms. Reasons for this often fall upon perceived economies of scale and often larger farms have greater inputs so incentives are greater to optimise returns from P inputs (Beegle et al., 2000; Dooley et al., 2005; Rhymes et al., 2021). Free online NMP software is available to farmers (such as PLANET and the Tried & Tested software) that could be used to address this shortfall by providing low-cost guidance. However, it is important that these systems consider the characteristics of the farming system and are easy to use (Mccormack et al., 2021). The technology should be developed to give practical, tailored advice to farmers for individual land parcels, guiding them on where, when and how much P to apply, thus removing some of the complexity surrounding nutrient management (Monaghan et al., 2007; van den Berg et al., 2023).

Finally, this study asked participants to specifically consider P management on their farm. Very few studies explicitly explore P management practices on land. The findings here, however, align well with research on the use of professional nutrient management advice and the wider adoption of best management practices in the UK (Defra, 2022). Therefore, it could be considered that farmers and land managers who plan P applications will also plan for other nutrients, and that P management does not happen in isolation. Further research could explore whether farmers / land managers use different resources to plan other nutrients (e.g. N), and if this is significantly different to how they approach P management on their land. It is worth noting that sample sizes in this study were considerably smaller than those in similar (non-P-specific) research studies, that had 100-300 participants (Denny et al., 2019; Mccormack et al., 2021; Shepard, 2005) and even upwards of 1000 participants for national scale surveys (Daxini et al., 2018; Defra, 2022).

6.4.2 Motivations and barriers for phosphorus management

When exploring farmers' motivations and the relative importance of different factors in determining how much P is applied to land (RQ2), those that centred on productivity and profitability were perceived to be most important to farmers. Factors linked to managing P losses in the wider environment and the management prescriptions for land in agri-environment schemes or farm accreditation schemes were considered least important (**Figure 6-3**). For some, soil test results were also instrumental for determining how much P to apply to the land. This suggests that these farmers were likely to be implementing the NMP plans on their farms to make more efficient use of P inputs for crop production.

The potential impact on productivity was identified as the primary barrier to reducing P inputs to agricultural land (RQ5, **Figure 6-6**). To address this, it may be more effective to frame practices such as regular soil sampling and optimised P management within the context of economic and efficiency gains rather than promoting the environmental benefits (Denny et al., 2019; Mccormack et al., 2021). For some respondents, the concerns over crop productivity were linked to a need for greater information or evidence to support the reduction of P inputs to land (**Figure 6-6**). Addressing this concern remains a challenge, as the cycling of P in soils is influenced by many physical, chemical, and biological factors. Reliance on soil tests that measure the "available" P in the soil (as measured by P tests such as: Olsen-P, Mechlich-3, Morgan's-P) could contribute to this challenge as these tests do not take into account up to 90% of total P in the soil (Darch et al., 2014). Field and pot trials have shown that reduced or eliminated P inputs may only be able to support crop growth for up to 10 years without yield penalty (McDowell & Condron, 2012; Withers et al., 1994), yet other long-term modelling estimates suggest that soil P stocks could support production for more than 300 years (Menezes-Blackburn et al., 2018 and Chapter 3 of this thesis). Although these higher estimates would rely on strategies that increase the cycling of organic and more recalcitrant P forms in the soil (Doydora et al., 2020). Further research to support P inputs to land could also look to extend the standard P recommendations (as per the RB209) to include soil-specific P fertiliser and manure application recommendations, to align with the N recommendations currently available. This would take into account the different soil properties impacting crop P uptake and critical Olsen-P values to allow for more targeted approach to P management and minimise the risk of over-application on some soils (Tandy et al., 2021).

Nationally, the accumulation of P in soils is far greater in livestock-based systems (Defra, 2020a). This is largely attributed to the practices related to the production, management, and application of manures in these agricultural systems (Withers et al., 2001). Indeed, in some areas manures can be looked upon as a waste product rather than their relative nutrient value to the growing crops (Schröder, 2005). Slurry and manure storage was a key factor for many livestock and mixed farming enterprises, with average Likert scores of 4.09 and 3.71 respectively (**Figure 6-3**). Accounting for the nutrient content of manures is one the four key steps in creating a NMP, but differences in overall P fertiliser application rates with and without manures suggest that P fertiliser application rates may only be approximately 30% lower (range: 0-77% decrease) on arable fields that receive manures compared to those that do not (Defra, 2024a). For grassland areas, overall P fertiliser application rates suggest just 5% reduction on fields receiving manure applications compared to those without (Defra, 2024a). If the nutrient value of manures is not being fully accounted for, this could lead to excesses of P being applied to fields and the accumulation of P in the soil.

Manure storage and application was also identified as a barrier for reducing P inputs (**Figure 6-6**). For one farmer, the management of manures is causing "sleepless nights", despite doing their best to mitigate P losses to water courses. Improved manure management on livestock-based enterprises should therefore be a priority to ensure that the benefits of manures (in terms of their contribution to building and maintaining soil organic matter, for example) outweigh the long-term risks of P accumulation (Toth et al., 2006; Vanden Nest et al., 2014). This will require a systems approach, for example using tools such as ALOWANCE[66] (Nicholson et al., 2012), that span from the farm scale to the wider agricultural industry, national governance structures and potentially even beyond the land application of manures (Mccann et al., 2005). Because, to put it simply, *"cows poop, we've discussed it with them but they won't stop".*

6.4.3 Considering whole farm phosphorus budgets

Research question three (RQ3) of this study explored whole-farm P management. Whole-farm nutrient budgeting goes beyond calculating annual P requirements for individual crops in standard NMP guidelines and considers the flows of P into, out of, and within the whole farm system. These budgets can then be used to target areas for improvement to either help increase

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[66] The ALOWANCE (Agricultural Land and Organic 'Waste': A National Capacity Estimator) tool is used to estimate the capacity of agricultural land in England and Wales to recycle organic materials, considering physical, practical, and legislative constraints (Nicholson et al., 2012).

yields or to increase P use efficiency on the farm and minimise P losses to the environment (Brunner, 2010).

Participants were not explicitly asked if they calculated annual whole-farm P budgets for their farm. However, those that reported that they had taken measures to reduce the P inputs to their land were approximately 28% more likely to state that their whole farm P budget was in balance or in deficit. For livestock only farms in particular, surplus P applications and subsequent accumulation of P in the landscape was an issue (**Figure 6-4**). Combined with low uptake of soil/crop analysis and manure storage constraints, this suggests a potential for improvement around whole-farm P planning and targeted P application (Watson et al., 2002).

As previously stated, greater P surpluses are often associated with livestock-based systems. However, there is evidence to suggest that, unlike NMPs, grazing livestock enterprises have the largest adoption of whole-farm P budgets (70%) followed by pig & poultry units and dairy enterprises, compared to predominantly arable systems (Defra, 2022). A higher rate of adoption in these systems is likely due to the differences in P imports between livestock and arable enterprises. Much of the P that is imported for livestock-based systems comes from animal feeds (Haygarth et al., 2005) and subsequently recycled as manures. Whole-farm P budgets, rather than individual field plans, can therefore be used in these instances to help identify where livestock diets can be changed to influence P flows on the farm (Brunner, 2010).

Approximately 14% of the participants were unaware of their whole-farm P budget. However, national data suggests that 43% of farms have never calculated a whole farm nutrient balance for P (Defra, 2022). This suggests that there is scope for further guidance on the long-term aspects of P management on farms. Increasing the use of P budgets and associated P management planning will be essential if the long-term P use efficiency of the UK food system is to be improved (Rothwell et al., 2022).

6.4.4 Farmer-led definition of legacy phosphorus

The term "legacy P" has gained prominence in academic literature to characterise the accumulation of P in agricultural soils, and broader surface water catchment areas, due to excessive anthropogenic inputs from fertilizers and/or manures. However, the precise nature of legacy P in chemical or biological terms remains a subject of debate (Doydora et al., 2020). Although there are strategies to manage excess soil P, having a consistent definition of the term legacy P between scientific literature, policy makers, and land managers is important because it ensures effective communication and understanding across diverse stakeholders. This alignment is crucial for informed policymaking, preventing misunderstandings that could lead to the implementation of inadequate or misinformed strategies. A cohesive approach will also support interdisciplinary collaboration for managing legacy P that ultimately will enhance the overall effectiveness of strategies aimed at addressing the environmental challenges.

In response to RQ5 of this study, farmers perceive legacy P as a factor requiring management in the soil, with an emphasis on managing inputs and reducing it to more "appropriate" levels. The synthesised farmer-led definition based on all responses was given as:

> *"The historical build-up of P in the soil, often resulting from past applications or practices, which may be locked-up in the soil and not be readily available to current crops."*

Notably, the connection between legacy P and water or the broader catchment areas, as communicated within the P academic community (Haygarth et al., 2014; Jarvie, Sharpley, Spears, et al., 2013; Sharpley et al., 2013), is overlooked in the definitions given by farmers in this study. It is worth noting that this questionnaire primarily centred on investigating P management on land and in the soil. As such, this might have inadvertently shaped participants' responses, directing their attention towards soil legacy P and excluding the broader catchment and potential impacts on water quality.

Disconnects between academic research and farmer practice are commonplace and can be a significant barrier to achieving sustainable farming goals (Dwivedi et al., 2024). There are many barriers to achieving effective adoption of new practices, but farmer intuition (Nuthall & Old, 2018) and nuances in local farmer practices are often overlooked and disregarded (Salembier et al., 2018). As part of this, it is important that the terminology used by the academic literature, policy makers, and the wider industry is consistent. For legacy P, a disparity between P scientists and farmers in their understanding of legacy P could contribute to the mismanagement of P resources. For example, the definitions given in the study suggest that farmers view legacy P as a store of P in the soil that is "locked-up" and cannot necessarily be accessed by crops for growth. This would likely feed into the common insurance-based approach to P management that aims to address the inherently low availability of P in soils, low rates of fertiliser P recovery by crops (attributed to soil-P "fixation"), and significant seasonal variations in crop response to added P, both across different fields and within individual fields (Withers et al., 2014).

Farmers also indicated that legacy P is the build-up of soil P that is linked to the historic management of the land, particularly from the application of manures. As industry and public attention increasingly gravitates towards legacy P, significant changes in best practices and management strategies have been put forward to the agricultural industry. Notable examples include practices such as the 4Rs of fertiliser management (Roberts, 2007) and concepts such as "feed the crop, not the soil" (Withers et al., 2014) as well as adherence to FRfW in England. The long-term nature of P build-up adds to the challenge of managing legacy P in the future as it can take many harvests for P decrease to levels that minimise the risk to the environment (Dodd & Mallarino, 2005; Dodd et al., 2012; Haygarth et al., 2014). The selection and uptake of measures to manage legacy P could therefore depend on the levels of public versus private net benefit (Rowe et al., 2016). Such as in instances where private net benefits, such as savings in fertiliser costs, are substantial, farmers are likely to adopt the new practice through efforts to increase awareness and education. However, when private net benefits are negative, such as yield reductions, and public net benefits, such as improved water quality, are high, financial incentives through agri-environment schemes become more important to compensate farmers for the adoption of such practices (Rowe et al., 2016).

Some farmers are aware of the term legacy P and the definitions provided here highlight that research and communication with farmers about the potential of legacy P stocks is important. Indeed, rather than communicating legacy P to be an environmental problem, farmer outreach efforts could re-address the issue as one that has the potential for improving P use efficiency on farms. However, breaking the barriers of the perceived negative views of legacy P and understanding the motivations and barriers farmers have towards managing P on their land will require flexibility that takes into account the heterogeneity of UK farming systems.

6.5 Conclusion

UK farmers and land managers largely follow best practice guidance for P management and seek professional advice for managing P inputs. However, across the livestock sectors this requires significant improvement, and there are likely many farms in the UK that are breaching farming regulations. Farmer motivations for applying P remain largely focused on crop productivity and financial considerations rather than the environmental concerns. The risk of reduced crop yields is also the primary barrier in reducing P inputs to land. Effective education, and promotion of the benefits for carrying out P management could help to address this.

Most farmers in this study have taken measures to reduce the P inputs to their land and have reported that they believe their overall whole-farm P budget is in balance or in deficit. However, for livestock-based systems manure storage constraints are an important factor for determining how much P is applied to land, and the primary barrier for these farmers in reducing their P application rates. Whole-farm P balances could help to identify hotspots of inefficiency and support livestock systems in reducing P inputs and surpluses on land.

Finally, farmers' understanding of the term legacy P does not consider it's role as a potential source for agronomic purposes as it is largely perceived as "locked-up" and "unavailable" to plants. This creates an opportunity for further research and communication to address these concerns. Ongoing research should continue to explore the nature of legacy P and its management to increase understanding of this complex problem whether through long-term P modelling, field trials or improved P fertiliser recommendations. Nevertheless, any gap in understanding between P scientists, policy makers and farmers regarding legacy P needs to be carefully managed to maximise uptake of P management measures and minimise the risk of the mismanagement of P resources.

7 Final Discussion - Bridging science and practice: legacy phosphorus management utilising models and farmer engagement

7.1 Introduction

This thesis has explored the potential of legacy phosphorus (P) to support agricultural production, focusing on different modelling approaches and the drivers and motivations for farming practices. The research aimed to bridge the gap between viewing legacy P as either an opportunity or an environmental challenge, emphasising how modelling could integrate these perspectives. Through an analysis of various modelling techniques, including a process-based model and P flow analysis, this thesis investigated their role in understanding and "unlocking" legacy P in crop production. Additionally, the study examined how farmers' perceptions and management practices can influence the utilisation of legacy P, highlighting the importance of aligning scientific research with real-world farming needs. **Figure 7-1** outlines some of the key findings which are then addressed in more detail.

7.2 Addressing thesis objectives

7.2.1 Objective 1: To explore the two contrasting views of legacy phosphorus within the scientific literature and how models can be used to address the blind spots in our understanding of legacy phosphorus

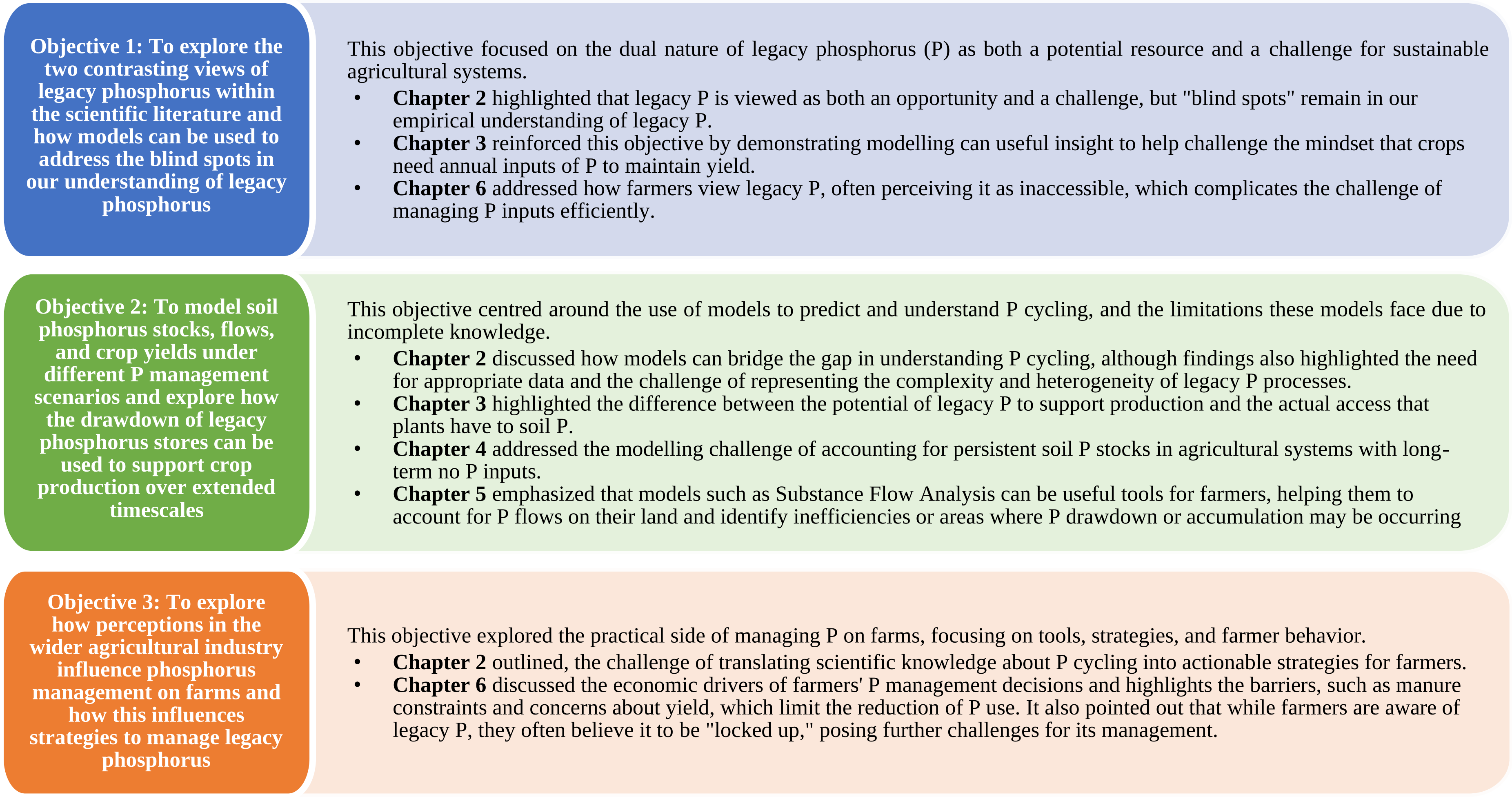
Legacy P has been used to describe the accumulation of P with terrestrial and aquatic environments as a result of anthropogenic activities, in particular the addition of P in fertilisers and manures to support crop growth (Sharpley et al., 2013). The potential for legacy P to support long-term crop production was central to this thesis. However, understanding the dual nature of the legacy P debate is vital for sustainable nutrient management, especially in the context of reducing dependency on external P inputs and addressing the environmental risks associated with P accumulation.

Chapter 2 of this thesis outlined the key factors contributing the legacy P debate and the multi-scaled nature of P management. At the catchment scale, the dissolution of legacy P from aquatic sediments and the transfer of P from intermediate stores, can hinder the effectiveness of water quality improvement strategies on agricultural land (Meals et al., 2010). The biogeochemical processes involved in the uptake, storage, and transformation of P throughout the catchment also play a critical role (Haygarth et al., 2005). Together, these factors highlight the inherent challenges of managing legacy P in the environment to reduce impacts on water quality.

On the other hand, much of the excess P that was applied in the past to support crop production, remains in the soil. These legacy P stocks have the potential to contribute towards P sustainability, and in the absence of new P inputs has been shown to sustain crop yields for multiple cropping seasons (Dodd et al., 2012; Johnston et al., 2016).

Chapter 3 further reinforces the agronomic potential of legacy P by modelling the number of years that legacy P could support crop production without yield penalty. The chapter’s findings show that, in soils with a history of P inputs exceeding crop offtake, legacy P has the potential to support production at current levels for 50-83 years and 155-217 years on a cereal and permanent grassland plot, respectively with no applications of P fertiliser. This modelling study provided useful insight to help challenge the mindset that crops need annual inputs of P to maintain yield.

While scientific literature and models suggest that legacy P could be a valuable resource, many farmers and land managers view it as something that is “locked up” and inaccessible to crops (Chapter 6 of this thesis). This perception reveals a significant disconnect between scientific understanding and wider industry perceptions. Farmers’ belief that legacy P cannot be accessed by plants poses a challenge for encouraging sustainable P management practices, such as reduced or no-P inputs. These findings underscore the need for better communication between



Objective 1: To explore the two contrasting views of legacy phosphorus within the scientific literature and how models can be used to address the blind spots in our understanding of legacy phosphorus

This objective focused on the dual nature of legacy phosphorus (P) as both a potential resource and a challenge for sustainable agricultural systems.

- **Chapter 2** highlighted that legacy P is viewed as both an opportunity and a challenge, but "blind spots" remain in our empirical understanding of legacy P.
- **Chapter 3** reinforced this objective by demonstrating modelling can useful insight to help challenge the mindset that crops need annual inputs of P to maintain yield.
- **Chapter 6** addressed how farmers view legacy P, often perceiving it as inaccessible, which complicates the challenge of managing P inputs efficiently.

Objective 2: To model soil phosphorus stocks, flows, and crop yields under different P management scenarios and explore how the drawdown of legacy phosphorus stores can be used to support crop production over extended timescales

This objective centred around the use of models to predict and understand P cycling, and the limitations these models face due to incomplete knowledge.

- **Chapter 2** discussed how models can bridge the gap in understanding P cycling, although findings also highlighted the need for appropriate data and the challenge of representing the complexity and heterogeneity of legacy P processes.
- **Chapter 3** highlighted the difference between the potential of legacy P to support production and the actual access that plants have to soil P.
- **Chapter 4** addressed the modelling challenge of accounting for persistent soil P stocks in agricultural systems with long-term no P inputs.
- **Chapter 5** emphasized that models such as Substance Flow Analysis can be useful tools for farmers, helping them to account for P flows on their land and identify inefficiencies or areas where P drawdown or accumulation may be occurring

Objective 3: To explore how perceptions in the wider agricultural industry influence phosphorus management on farms and how this influences strategies to manage legacy phosphorus

This objective explored the practical side of managing P on farms, focusing on tools, strategies, and farmer behavior.

- **Chapter 2** outlined, the challenge of translating scientific knowledge about P cycling into actionable strategies for farmers.
- **Chapter 6** discussed the economic drivers of farmers' P management decisions and highlights the barriers, such as manure constraints and concerns about yield, which limit the reduction of P use. It also pointed out that while farmers are aware of legacy P, they often believe it to be "locked up," posing further challenges for its management.

Figure 7-1: An outline of the three main objectives of this thesis and some of the key findings from the work carried out.

scientists and farmers, as well as the development of tools and strategies that align with farmers' practical needs and economic realities (Dwivedi et al., 2024).

The assumption that legacy P could be uniformly beneficial across agricultural systems is challenged by the varied responses of different soils and crops to P availability. The data from Chapters 3 and 6 indicate that site-specific factors, such as the history of P inputs and the type of crops grown, play a critical role in determining whether legacy P can effectively support long-term production. Furthermore, "blind spots" still exist in our understanding of P cycling, namely the (bio)availability or speciation of P (particularly the role of organic P in crop production and water quality) (Janes-Bassett et al., 2019), and the variability in connectivity and lag times between P sources and P impact (Haygarth et al., 2005). This illustrates the complexity of managing legacy P and while it presents an opportunity, fully realising its potential requires overcoming both scientific, and socio-economic barriers.

7.2.2 Objective 2: To model soil phosphorus stocks, flows, and crop yields under different P management scenarios and explore how the drawdown of legacy phosphorus stores can be used to support crop production over extended timescales.

Modelling P cycling allows users to predict P availability, identify inefficiencies in its use, and evaluate the long-term sustainability of various land management strategies. However, P cycling is influenced by a wide range of factors, and it is often difficult to capture this complexity in models (Achat et al., 2016). How P dynamics are represented in models plays a critical role in scientific understanding but also has practical applications for industry and policy. The findings from this thesis emphasise the limitations of models, and the potential value of combining empirical research with model development to address these gaps.

Chapter 2 underscores the importance of using models to bridge the gap between the agronomic opportunity and environmental challenge posed by legacy P in soils. Findings also highlight the need for appropriate data to develop and validate modelled P flows and stores in the environment and the challenge of representing the complexity and heterogeneity of legacy P processes.

Long-term experiments, such as the Broadbalk and Park Grass experiments at Rothamsted Research, UK, have shown that crop yields can persist for over 100 years without fertiliser or manure inputs (Macdonald et al., 2018). To explore the biogeochemical cycling of legacy P to support crop production, the N14CP model was combined with data from long-term experiments at, Rothamsted Research, Harpenden, UK (Chapter 3). Key findings from this work demonstrate that N14CP can estimate crop yields and soil nutrient stocks reasonably well under scenarios with annual nitrogen and P inputs. However, determining how long legacy P stocks can sustain crop production is challenging due to the uncertainties in modelling and the vast number of biogeochemical factors that influence P behaviour in soil (Doydora et al., 2020). This often results in significant variability in data from P drawdown experiments in the field (Dodd & Mallarino, 2005; Dodd et al., 2012; Johnston et al., 2016). This highlights the difference between the potential of legacy P to support production (as represented by long-term biogeochemical models such as N14CP) and the actual access that plants have to soil P.

Previous long-term biogeochemical modelling of agricultural systems using N14CP has struggled to explain the sustained yields and observed soil nutrient levels in no-input systems (Janes-Bassett et al., 2020). This suggests that there is a greater amount of P in the soil and available to plants than the model is able to predict. While many biogeochemical P models for agronomic systems account for P inputs annual fertiliser and manure applications (Metherell et al., 1993; Muhammed et al., 2018; Wu et al., 2007); other factors, such as atmospheric deposition of P, P weathering, animal deposits, water-driven pathways (e.g., leaching and runoff), and variable plant stoichiometry are often underrepresented. However, despite considering these alternative P sources, N14CP still could not to fully explain the persistent soil P stocks in the Park Grass system (Chapter 4). This suggests a gap in our understanding of how agricultural systems manage P without anthropogenic P inputs, pointing to a need for further research on legacy P and its role in long-term crop sustainability. It could also raise questions about the development of models that rely on long-term experimental data from small plot trials, which may not fully represent the complexity of real-world agricultural systems. Further N14CP testing across similar sites, such as the Morrow Plots, USA could help to address this in addition to increased testing for soil total and organic P in long-term field experiments (Recena & et al., 2019; Sattari et al., 2012) which can be a limiting factor for model testing and validation.

System budget models can be useful tools for farmers, helping them to account for P flows on their land and identify inefficiencies or areas where P drawdown or accumulation may be occurring (Chapter 5). However, while these models can help identify P flows and inefficiencies (Brunner, 2010), they rely on the availability and accuracy of P coefficients from inputs and outputs. This is especially important for systems that aim to maintain production through the recycling of manures without relying on fertilisers. Furthermore, to provide more meaningful insights, system budget models should be carried out over multiple cropping seasons or across a whole rotation (Chowdhury et al., 2016).

Understanding P cycling is essential for developing sustainable agricultural practices, yet significant gaps remain in how models represent some of these processes. One major gap, as noted in Chapters 2, 3, and 4, is the limited understanding of microbial interactions and their role in mobilising legacy P stocks. While it is known that microbial communities can influence P availability, quantifying this process and incorporating it into models remains a challenge (Janes-Bassett et al., 2019). Addressing these gaps will require improved models that integrate a more comprehensive understanding of soil-plant interactions, as well as access to representative empirical data for testing. Future research should focus on effectively using models to formalise our understanding of P processes and identifying key knowledge or data gaps in empirical legacy P research (Vadas et al., 2013).

7.2.3 Objective 3: To explore how perceptions in the wider agricultural industry influence phosphorus management on farms and how this influences strategies to manage legacy phosphorus

Practical management strategies and farmer perspectives are crucial to understanding how legacy P can be effectively managed in agricultural systems. While scientific advancements and models offer valuable insights into P cycling, they can fall short if they don't align with the practical needs of farmers (Buckley et al., 2015). The final objective of this research was to highlight the practical application of P management strategies at the farm level, addressing how farmer perceptions and socio-economic barriers influence utilising legacy P as part of sustainable management practices.

Managing P efficiently at the farm level is essential for reducing reliance on external P inputs, such as fertilisers, and mitigating the environmental risks associated with P runoff and leaching. However, as Chapter 1 outlines, the challenge lies in translating scientific knowledge about P cycling into actionable strategies for farmers.

Chapter 6 delved into farmers' perspectives on legacy P and their management practices, revealing several barriers to reducing P use. Economic factors, such as concerns about yield reduction, remain a primary driver in farmers' decision-making rather than environmental considerations. Within the livestock sector, manure management posed the biggest barrier to reducing P inputs. This is reflected in UK national estimated P application surpluses which demonstrates that intensive livestock production is often associated with greater soil P surplus, compared to stockless arable systems (Rothwell et al., 2022; Withers et al., 2001). While many farmers have adopted P management strategies on their land (e.g. nutrient management planning and routine soil testing) a significant number of farmers fail to meet the minimum standards for nutrient management. Education and promotion of the wider benefits of employing sustainable P management strategies could help to address this (Rowe et al., 2016).

While Chapter 1 highlights the potential of legacy P to support long-term crop production, many farmers view legacy P as "locked up" (Chapter 6). This suggests that despite the availability of system budgets and nutrient management planning support, their potential complexity and inherent data uncertainties may still mean that farmers will hesitate to adopt new practices (Daxini et al., 2018; Monaghan et al., 2007). Further research is needed to identify strategies for mobilising legacy P in a way that is both practical and economically viable for farmers, such as crop breeding, cover crops, or promoting soil microbial communities (Doydora et al., 2020).

Tools like system budgets offer valuable insights, but more work is needed to address the economic drivers and perceptions that influence farmers' decisions. Bridging the gap between research and practice will be essential for developing effective legacy P management strategies that support both agricultural productivity and environmental sustainability.

7.3 Looking forward

No one solution will solve the legacy P environmental challenge nor realise the full potential of legacy P for sustainable agriculture. However, the three “keys” highlighted in this thesis form a valuable but, sometimes overlooked, set of resources that contribute to the wider understanding of P management in agricultural systems.

For the process-based model N14CP, a key question remains are the inherent model limitations preventing it from explaining sustained yields and observed soil nutrient levels in no-input systems or is there a need for a fundamental shift in our understanding of phosphorus cycling in low P systems? The inclusion of microbial processes and a different representation of organic P cycling will enable a better understanding of what legacy P is and what it becomes. Although a key limitation of this work with N14CP was a lack of total P data for model testing and validation, the inclusion of this data in Chapter 3 and analysis of more historical data in Chapter 4 of this thesis would strengthen this work. More comprehensive soil analysis (to include organic P and total P concentrations, alongside more conventional soil test P analysis) carried out as standard on long-term field trials will allow model testing and development across a wider range of environments and agricultural management scenarios to help address this question.

Limited availability of detailed data from the estate was challenge for accurately modelling the P system budget for the organic estate in the UK (Chapter 5). Key data gaps were primarily related to grass and forage yields, as well as manure production, which had to be extrapolated from national data records. This reliance on external data contributed to the high uncertainty associated with these input values and consequently, on the P balances estimated by the system budget. In system budget models, the emphasis should be on improving their usability for on-farm decision-making, ensuring that accurate and readily-available data can be used to build the models. Extending the model to consider other nutrients and different temporal scales will further identify where inefficiencies are occurring and where discrepancies exist between managing land for different nutrient requirements. This would allow for more targeted P management and better alignment with sustainable practices.

Chapter 6 explored farmers' perspectives on legacy P and their management practices, revealing several barriers to reducing P use. However, a key limitation of this work was the low survey response rate, with only 51 responses received. This constrained data availability and reduced the depth of analysis and meaningful conclusions that could be drawn, particularly surrounding farmer awareness and understanding of the term "legacy P". However, this work has shown that engaging farmers and land managers will require developing clear, economically viable strategies that demonstrate the benefits of utilising legacy P while maintaining yields. The next step is to bridge the knowledge gap through tailored outreach programs that could focus on practical applications of both process-based and SFA models. Collaborating with farmers to co-develop tools and approaches that address their specific needs will foster greater trust and adoption of these strategies, ultimately enhancing the management of legacy P.

Cross-disciplinary collaboration has been consistently cited as a key requirement for addressing the legacy P debate, as highlighted in research spanning from the 1990s (Withers & Jarvis, 1998), 2000s (Haygarth et al., 2005), 2010s (Sharpley et al., 2013), to the 2020s (Doydora et al., 2020). It is clear that this interdisciplinary collaboration is still as important now in order to realise the potential of legacy P stores in many agricultural soils.

As data availability and processing capacity continue to grow, so does the opportunity for integrated P research, across academic and industry sectors to address the gaps in our understanding of P cycling in the environment. However, these challenges will persist unless there is widespread adoption of land management strategies aimed at preventing further P accumulation in soils and effectively managing existing legacy P stocks.

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9 Supplementary Information

Abstract word count: 298

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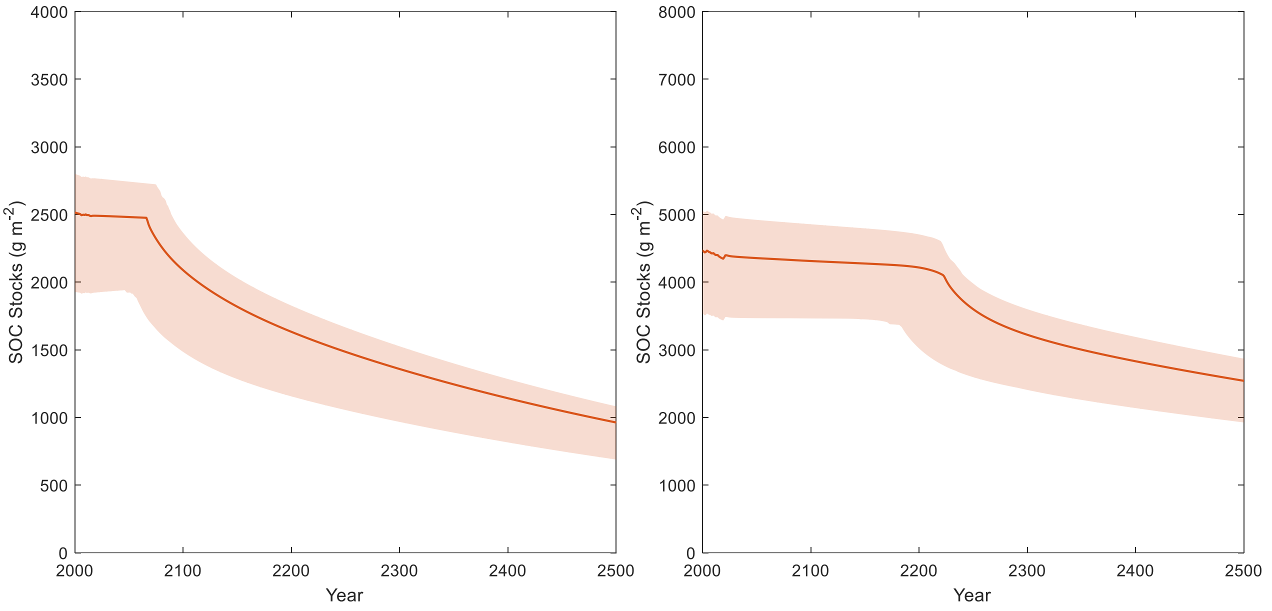
9.1 Supplementary Information: Chapter 3

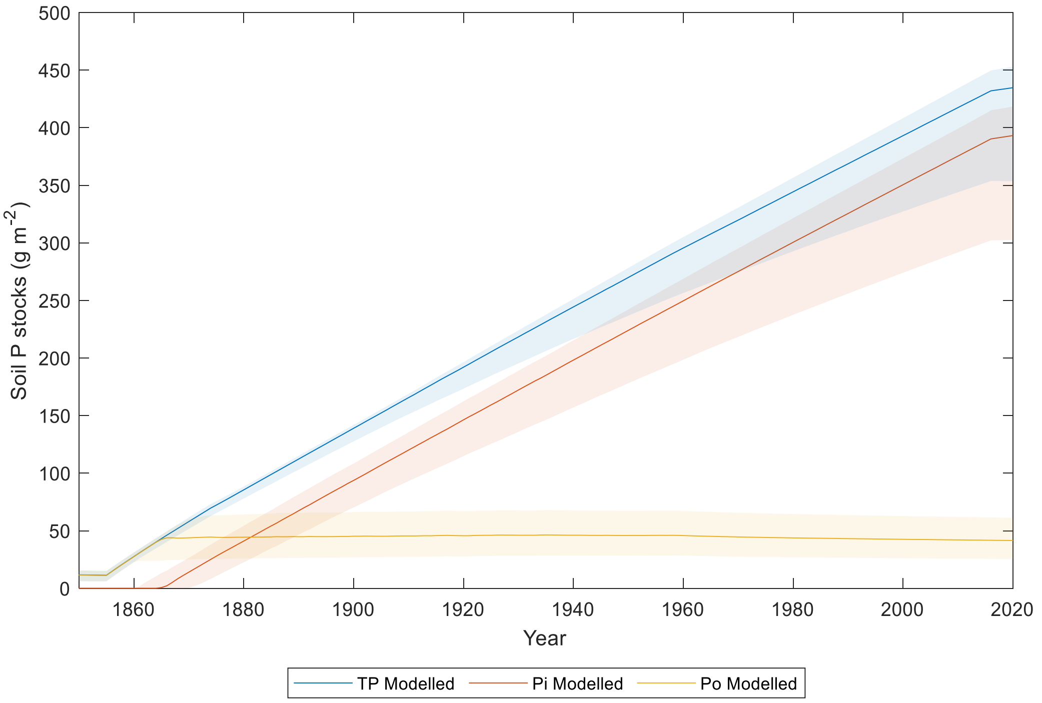


SI Figure 3-1: Modelled timeseries for soil organic carbon stocks (SOC) from the start of the simulation period for the arable (2001, left) and permanent grassland (2017, right) under four different fertiliser treatment scenarios. Prior to the start of the simulation period N14CP inputs for land use and management were based on historical data for the sites. Shaded areas indicate 5th and 95th percentiles based on the uncertainty analysis.

9.2 Supplementary Information: Chapter 4

SI Table 4-1: Annual N14CP total dissolved phosphorus (P) leaching outputs from adjacent Park Grass

Year	P input to Plot 4/1d from Plot 4/2d	P input to Plot 3d from Plot 4/1d
1856	0.006	0.006
1857	0.007	0.006
1858	0.007	0.006
1859	0.007	0.007
1860	0.007	0.007
1861	0.008	0.007
1862	0.008	0.007
1863	0.008	0.007
1864	0.008	0.007
1865	0.009	0.009
1866	0.009	0.012
1867	0.009	0.015
1868	0.009	0.017
1869	0.009	0.019
1870	0.009	0.020
1871	0.010	0.022
1872	0.011	0.024
1873	0.014	0.026
1874	0.016	0.028
1875	0.017	0.029
1876	0.017	0.030
1877	0.017	0.032
1878	0.018	0.033
1879	0.019	0.035
1880	0.020	0.037
1881	0.021	0.038
1882	0.022	0.040
1883	0.023	0.042
1884	0.024	0.043
1885	0.025	0.045
1886	0.026	0.047
1887	0.027	0.048
1888	0.028	0.050
1889	0.029	0.052
1890	0.031	0.054
1891	0.032	0.055
1892	0.033	0.057
1893	0.034	0.059
1894	0.035	0.060
1895	0.036	0.062
1896	0.037	0.064
1897	0.038	0.066
1898	0.039	0.067
1899	0.040	0.069
1900	0.041	0.070
1901	0.043	0.072
1902	0.045	0.074
1903	0.046	0.076
1904	0.047	0.078
1905	0.048	0.079
1906	0.049	0.081
1907	0.050	0.083
1908	0.052	0.084
1909	0.052	0.086
1910	0.054	0.088
1911	0.055	0.090
1912	0.056	0.091
1913	0.058	0.093
1914	0.058	0.095
1915	0.059	0.096
1916	0.060	0.098
1917	0.061	0.099
1918	0.063	0.101
1919	0.063	0.103
1920	0.065	0.105
1921	0.067	0.106
1922	0.068	0.108
1923	0.069	0.109
1924	0.070	0.111
1925	0.070	0.112
1926	0.072	0.114
1927	0.073	0.116
1928	0.074	0.118
1929	0.075	0.119
1930	0.076	0.121
1931	0.077	0.123
1932	0.079	0.124
1933	0.080	0.126
1934	0.081	0.127
1935	0.082	0.129
1936	0.083	0.131
1937	0.084	0.132
1938	0.086	0.134
1939	0.087	0.136
1940	0.087	0.137
1941	0.088	0.139
1942	0.090	0.140
1943	0.093	0.143
1944	0.093	0.144
1945	0.096	0.146
1946	0.095	0.147
1947	0.097	0.149
1948	0.098	0.151
1949	0.100	0.152
1950	0.100	0.154
1951	0.101	0.155
1952	0.102	0.157
1953	0.104	0.159
1954	0.105	0.160
1955	0.106	0.162
1956	0.107	0.163
1957	0.108	0.165
1958	0.109	0.167
1959	0.111	0.168
1960	0.112	0.170
1961	0.113	0.172
1962	0.113	0.173
1963	0.114	0.175
1964	0.116	0.176
1965	0.116	0.178
1966	0.118	0.179
1967	0.118	0.181
1968	0.119	0.182
1969	0.120	0.184
1970	0.121	0.185
1971	0.123	0.187
1972	0.124	0.189
1973	0.125	0.190
1974	0.126	0.192
1975	0.127	0.193
1976	0.128	0.195
1977	0.129	0.197
1978	0.130	0.198
1979	0.131	0.200
1980	0.132	0.201
1981	0.133	0.203
1982	0.134	0.204
1983	0.135	0.206
1984	0.136	0.207
1985	0.137	0.209
1986	0.138	0.211
1987	0.139	0.212
1988	0.140	0.214
1989	0.141	0.215
1990	0.142	0.217
1991	0.143	0.218
1992	0.144	0.220
1993	0.145	0.221
1994	0.146	0.223
1995	0.147	0.224
1996	0.148	0.226
1997	0.149	0.228
1998	0.150	0.229
1999	0.151	0.231
2000	0.152	0.232
2001	0.153	0.234
2002	0.154	0.235
2003	0.155	0.237
2004	0.156	0.238
2005	0.157	0.240
2006	0.158	0.241
2007	0.159	0.243
2008	0.160	0.245
2009	0.161	0.246
2010	0.162	0.248
2011	0.164	0.249
2012	0.164	0.251
2013	0.165	0.252
2014	0.166	0.254
2015	0.168	0.255
2016	0.168	0.257
2017	0.169	0.256
2018	0.170	0.256
2019	0.171	0.257
2020	0.172	0.257
Average	**0.090**	**0.130**
Min	**0.010**	**0.010**
Max	**0.170**	**0.260**



SI Figure 4-1: N14CP modelled Park Grass Plot 4/1d (phosphorus (P) fertiliser only plot) soil total P (TP), inorganic P (Pi) and organic P (Po) stocks since the start of the long-term experiment (1856). Shaded areas indicate 5th and 95th percentiles based on the uncertainty analysis.

9.3 Supplementary information: Chapter 5

SI Table 5-1: Details of flow descriptions and the data sources used for material mass flow and phosphorus (P) contents for the Estate P substance flow analysis, inputted P flow data values ± SD, and STAN reconciled flow data ± SD with the percentage difference between input and reconciled values.

Flow	Flow Name	Flow Description (flow is the elemental P contained in those materials)	Input data (Kg P yr-1)		STAN calculated output data (Kg P yr-1)		% difference STAN calculated / input data	Data sources and method
			Mass Flow	SD	Mass Flow	SD		
F1.01	Import live animals	Live animals imported into the Estate	46	15	46	11	0.00	Livestock numbers and assumptions based on Estate records (pers. comm. June 2023). P coefficient of livestock from Defra (pers. comm. May 2020).
F1.01a	*Import live poultry*	Imported livestock from F1.01 that are poultry	46	15	46	11	0.00	Assumed breeding stock kept for cattle, pigs, sheep, and deer so no stock imported into the Estate. All poultry stock imported (age at import ~ 1 day). Mass of imported chicks from Tona et al. (2004).
F1.02	Export live animals	Live animals exported out of the Estate system	2941	1176	2945	526	0.14	Livestock numbers and assumptions based on Estate records (pers. comm. June 2023). P coefficient of livestock from Defra (pers. comm. May 2020). Assumed no exports of deer (semi-wild population)
F1.02a	*Export live cattle*	Exported livestock from F1.02 that are cattle	326	112	326	111	0.10	Dairy cattle: assumed to only include number moved off farm as recorded. Beef cattle: assumed to include number moved off farm as recorded as well as all young stock. Mass at export based on Munksgaard et al. (2020) and AHDB (2024a).

Flow	**Flow Name**	**Flow Description (flow is the elemental P contained in those materials)**	**Input data (Kg P yr-1)**		**STAN calculated output data (Kg P yr-1)**		**% difference STAN calculated / input data**	**Data sources and method**
			Mass Flow	**SD**	**Mass Flow**	**SD**		
F1.02b	*Export live pigs*	Exported livestock from F1.02 that are pigs	253	65	256	64	1.08	Assumed all litter exported at weaning (7kg / head). Number exported based on Wilkins (2021).
F1.02c	*Export live poultry*	Exported livestock from F1.02 that are poultry	2270	624	2272	516	0.09	Assumed all exported (age at export ~ 81 days old) Mass at export based on Defra (2016)
F1.02d	*Export live sheep*	Exported livestock from F1.02 that are sheep	92	22	91	22	1.00	Assumed to include number moved off farm as recorded as well as all lambs. Mass at export based on AHDB (2024b) and Stout (2024).
F1.03	Livestock products	Products of the livestock sector, includes milk, and wool	2536	647	2539	305	0.11	Livestock numbers and assumptions based on Estate records (pers. comm. June 2023). P coefficient of livestock products from Defra (pers. comm. May 2020)
F1.03a	*Cattle product*	Cattle products from F1.03 (Milk)	2536	350	2539	305	0.11	Milk yields based on 10-year average milk yields including a 20% yield reduction for organic farming practices (NBDC, 2024; soilassociation.org, 2024b)
F1.03b	*Sheep product*	Sheep products from F1.03 (Wool)	0.12	0.03	0.12	0.03	0.00	Fleece weight from britishwool.org (2010).
F1.04	Excreta to fields	Livestock excreta that is either directly deposited during grazing or available as manure for spreading to agricultural land, includes P from straw used as livestock bedding	21791	4445	21923	1273	0.60	Housed livestock numbers and manure applications to fields informed by Estate records (pers. comm. June 2023). Livestock P excretion coefficients from Defra (pers. comm. May 2020) - excretion coefficients scaled down for livestock less than 1 year old.

Flow	Flow Name	Flow Description (flow is the elemental P contained in those materials)	Input data (Kg P yr-1) Mass Flow	SD	STAN calculated output data (Kg P yr-1) Mass Flow	SD	% difference STAN calculated / input data	Data sources and method
F1.04a	*Cattle excreta to fields*	Excreta from F1.04 that comes from cattle	14059	2867	14130	1155	0.50	Dairy cattle: assumed over winter housed for 3 months of the year (12 weeks), plus 8 hours per day (based on overnight housing and housing pre/post milking). Remainder is deposited directly to grassland fields. Beef cattle - assumed over winter housed for 3 months of the year (12 weeks), remainder is deposited directly to grassland fields.
F1.04b	*Pig excreta to fields*	Excreta from F1.04 that comes from pigs	1885	384	1979	231	4.73	Outdoor pig rearing units. Assumed all manure left on fields.
F1.04c	*Poultry excreta to fields*	Excreta from F1.04 that comes from poultry	3888	793	3881	667	0.19	Assumed 80-day growth period and 80% of manure is deposited in housing (based on overnight housing). Remainder is deposited directly to grassland fields.
F1.04d	*Sheep excreta to fields*	Excreta from F1.04 that comes from sheep	579	118	553	62	4.79	Sheep - assumed to be housed during lambing (4 weeks), remainder is deposited directly to grassland fields.
F1.04e	*Deer excreta to fields*	Excreta from F1.04 that comes from deer	1380	234	1382	147	0.15	Deer - not housed all excreta deposited to grassland. P excretion coefficient from eISB (2022) weighted mean of P excreted by fallow and red deer.
F1.04f	*Excreta to tillage fields*	Excreta from F1.04 spread on land used for tillage crops	11143	2273	11212	1706	0.62	All calculated housed livestock manures from F1.04 applied to tillage crops.
F1.04g	*Excreta to grass fields*	Excreta from F1.04 deposited during grazing or spread on permanent grassland.	10648	2172	10711	1684	0.59	All calculated grazing livestock excreta from F1.04 deposited to grassland.

Flow	**Flow Name**	**Flow Description (flow is the elemental P contained in those materials)**	**Input data (Kg P yr-1)**		**STAN calculated output data (Kg P yr-1)**		**% difference STAN calculated / input data**	**Data sources and method**
			Mass Flow	**SD**	**Mass Flow**	**SD**		
F2.01	Seeds	Seeds used for growing crops and grass	229	34	229	23	0.00	Mass of seed sown based on industry publications (see **SI Table 5-3** for individual sources), seed P coefficients from Defra (pers. comm. May 2020).
F2.01a	*Tillage seed*	Seeds from F2.01 used for growing crops on tillage land	216	32	216	23	0.00	
F2.01b	*Grass seed*	Seeds from F2.01 used for growing grass	13	2	13	2	0.00	
F2.02	Food & feed crops (FFC)	All tillage crops grown on the Estate (excluding grass)	14860	4799	14437	1179	2.93	Quantity of crops harvested from Estate records (pers. comm. June 2023) and typical crop yields (see **SI Table 5-3** for individual sources), crop P coefficients from Defra (pers. comm. May 2020) and AHDB (2020c, 2020d, 2020e).
F2.02a	*Exported FFC*	Those crops from F2.02 exported from the Estate	3081	791	3092	781	0.37	Proportion of harvested crops that are exported from the Estate are informed by Estate records (pers. comm. June 2023). Crop P coefficients from Defra (pers. comm. May 2020) and AHDB (2020c, 2020d, 2020e).
F2.02b	*FFC to feed*	Those crops from F2.02 used for animal feed	11565	2969	11126	907	3.95	Proportion of harvested crops that are used for livestock forage are informed by Estate records (pers. comm. June 2023). Crop P coefficients from Defra (pers. comm. May 2020) and AHDB (2020c, 2020d, 2020e).
F2.02c	*FFC to bedding*	Those crops from F2.02 used for animal bedding	214	67	219	43	2.33	Proportion of harvested crops that are used for livestock bedding are informed by Estate records (pers. comm. June 2023). Crop P coefficients from Defra (pers. comm. May 2020) and AHDB (2020c, 2020d, 2020e).

Flow	**Flow Name**	**Flow Description (flow is the elemental P contained in those materials)**	**Input data (Kg P yr-1)** **Mass Flow**	**SD**	**STAN calculated output data (Kg P yr-1)** **Mass Flow**	**SD**	**% difference STAN calculated / input data**	**Data sources and method**
F2.03	Grazing & grass crops	Grass produced on the Estate that is grazed or cut for silage and hay	11780	1628	11700	927	0.69	Areas for temporary and permanent grass informed by Estate records (pers. comm. June 2023). Grass dry matter production for temporary and permanent grassland was calculated from benchmark yield data (GrassCheckGB, 2020) and grass P content from AHDB (2020c)
F2.03a	*Grass to cattle*	Grass from F2.03 eaten by cattle	9425	1303	9428	925	0.03	Distribution of grass to grazing livestock estimated from the balance between daily DM intake requirements (soilassociation.org, 2024c), livestock weight, livestock age and housing period.
F2.03b	*Grass to pig*	Grass from F2.03 eaten by pigs	230	32	229	32	0.28	
F2.03c	*Grass to poultry*	Grass from F2.03 eaten by poultry	172	24	172	24	0.01	
F2.03d	*Grass to sheep*	Grass from F2.03 eaten by sheep	480	66	488	58	1.70	
F2.03e	*Grass to other*	Grass from F2.03 eaten by other livestock	1383	191	1382	147	0.07	
F2.04	Agriculture to water bodies	Loss of P to waterbodies from diffuse agricultural pollution	498	112	498	65	0.00	Agricultural P losses to water for England are from Elliott (2019) which uses the FARMSCOPER model (Gooday & Anthony, 2010) to account for uptake of diffuse P loss mitigation measures.
F2.04a	*Tillage to water*	Diffuse P loss from F2.04 from land used for tillage crops	281	63	281	56	0.00	
F2.04b	*Grass to water*	Diffuse P loss from F2.04 from land used for grass	217	49	217	46	0.00	
F2.05	Atmospheric deposition	P naturally deposited on agricultural land from the atmosphere	351	80	351	46	0.00	Atmospheric P deposition rates are taken from Tipping et al. (2014) scaled up to agricultural areas from Estate records (pers. comm. June 2023).
F2.05a	*Atmospheric to tillage*	Atmospheric P from F2.05 deposited on tillage land	152	35	152	33	0.00	

Flow	**Flow Name**	**Flow Description (flow is the elemental P contained in those materials)**	**Input data (Kg P yr-1)**		**STAN calculated output data (Kg P yr-1)**		**% difference STAN calculated / input data**	**Data sources and method**
			Mass Flow	**SD**	**Mass Flow**	**SD**		
F2.05b	*Atmospheric to grass*	Atmospheric P from F2.05 deposited on grass land	199	45	199	40	0.00	
F2.06a	*Straw to cattle*	Straw from F2.06 used for cattle	170	53	167	42	1.94	Distribution of straw to livestock estimated from the balance between housed livestock manure production and typical straw content of farmyard manures (gov.scot, 2024).
F2.06b	*Straw to pigs*	Straw from F2.06 used for pigs	4	1	4	1	0.00	
F2.06c	*Straw to poultry*	Straw from F2.06 used for poultry	48	15	48	15	0.52	
F2.06d	*Straw to sheep*	Straw from F2.06 used for sheep	0.6	0	0.6	0.19	0.00	
F2.07a	*Forage to cattle*	Forage from F2.03 eaten by cattle	7359	1017	7400	870	0.55	Distribution of grass to grazing livestock estimated from the balance between daily DM intake requirements (eISB, 2022; soilassociation.org, 2024c), livestock weight, livestock age and housing period.
F2.07b	*Forage to pig*	Forage from F2.03 eaten by pigs	2048	283	2001	228	2.35	
F2.07c	*Forage to poultry*	Forage from F2.03 eaten by poultry	1567	217	1570	214	0.18	
F2.07d	*Forage to sheep*	Forage from F2.03 eaten by sheep	154	21	155	21	0.56	
F3.01	Fertiliser to fields	Mineral P fertiliser applied to agricultural land	5214	562	5214	397	0.00	Quantity of imported P fertiliser, P content and application rate informed by Estate records (pers. comm. June 2023)
F3.01a	*Fertiliser to tillage*	Fertiliser from F3.03 that is applied to land used for tillage crops	5214	562	5214	397	0.00	
F4.01	Import feeds	Compound feeds imported for livestock	4330	1732	4317	759	0.30	Quantity of imported livestock feed informed by Estate records (pers. comm. June 2023) and industry production guidelines (soilassociation.org, 2024c).

Flow	**Flow Name**	**Flow Description (flow is the elemental P contained in those materials)**	**Input data (Kg P yr-1)**		**STAN calculated output data (Kg P yr-1)**		**% difference STAN calculated / input data**	**Data sources and method**
			Mass Flow	**SD**	**Mass Flow**	**SD**		
F4.01a	*Import feed poultry*	Compound feeds imported for poultry	4330	1732	4317	759	0.30	Quantity of imported livestock feed assumed to be 70% of the total daily rations. This reflects the production of home-grown forage crops that could be used for poultry systems on the estate (Crawley, 2015) and the export of all cereal grain from the Estate (pers. comm. June 2023). Baseline industry maximum of 80% of daily rations from imported feed (soilassociation.org, 2024c). Crop P coefficients from Defra (pers. comm. May 2020)

SI Table 5-2: Data uncertainty for phosphorus (P) flows on the Estate. Values were assigned following the systematic approach outlined by Laner et al. (2016) and Zoboli et al. (2016).

Flow	**Flow Name**	**Flow Description (flow is the elemental P contained in those materials)**	**Mass Flow (P kg yr^{-1})**	**Data uncertainty**							
				Reliability	**Completeness**	**Composition**	**Temporal correlation**	**Geographical correlation**	**Further correlation**	**Expert Judgement**	**CV(%)**
F1.01	Import live animals	Live animals imported into the Estate	46.0	10	22	5	22	5	0	0	**33**
F1.01a	*Import live poultry*	Imported livestock from F1.01 that are poultry	46.0	10	22	5	22	5	0	0	**33**
F1.02	Export live animals	Live animals exported out of the Estate system	2941.0	22	22	5	22	11	0	0	**40**
F1.02a	*Export live cattle*	Exported livestock from F1.02 that are cattle	326.0	10	22	0	22	11	0	0	**34**
F1.02b	*Export live pigs*	Exported livestock from F1.02 that are pigs	253.0	10	22	5	5	5	0	0	**26**
F1.02c	*Export live poultry*	Exported livestock from F1.02 that are poultry	2270.0	22	10	5	11	5	0	0	**27**
F1.02d	*Export live sheep*	Exported livestock from F1.02 that are sheep	92.0	4	22	0	5	5	0	0	**23**
F1.03	Livestock products	Products of the livestock sector, includes milk, and wool	2536.1	4	10	5	22	5	0	0	**25**
F1.03a	*Cattle product*	Cattle products from F1.03 (Milk)	2536.0	4	10	5	5	5	0	0	**14**
F1.03d	*Sheep product*	Sheep products from F1.03 (Wool)	0.1	4	10	0	22	5	0	0	**25**

Flow	**Flow Name**	**Flow Description (flow is the elemental P contained in those materials)**		**Data uncertainty**							
			Mass Flow (P kg yr^{-1})	**Reliability**	**Completeness**	**Composition**	**Temporal correlation**	**Geographical correlation**	**Further correlation**	**Expert Judgement**	**CV(%)**
F1.04	Excreta to fields	Livestock excreta that is either directly deposited during grazing or available as manure for spreading to agricultural land, includes P from straw used as livestock bedding	21791.0	4	10	10	10	10	0	0	**20**
F1.04a	*Cattle excreta to fields*	Excreta from F1.04 that comes from cattle	14059.0	4	10	10	10	10	0	0	**20**
F1.04b	*Pig excreta to fields*	Excreta from F1.04 that comes from pigs	1885.0	4	10	10	10	10	0	0	**20**
F1.04c	*Poultry excreta to fields*	Excreta from F1.04 that comes from poultry	3888.0	4	10	10	10	10	0	0	**20**
F1.04d	*Sheep excreta to fields*	Excreta from F1.04 that comes from sheep	579.0	4	10	10	10	10	0	0	**20**
F1.04e	*Deer excreta to fields*	Excreta from F1.04 that comes from deer	1380.0	4	10	5	5	11	0	0	**17**
F1.04f	*Excreta to tillage fields*	Excreta from F1.04 spread on land used for tillage crops	11143.0	4	10	10	10	10	0	0	**20**
F1.04g	*Excreta to grass fields*	Excreta from F1.04 deposited during grazing or spread on permanent grassland.	10648.0	4	10	10	10	10	0	0	**20**
F2.01	Seeds	Seeds used for growing crops and grass	229.0	10	10	2	4	2	0	0	**15**

Flow	**Flow Name**	**Flow Description (flow is the elemental P contained in those materials)**	**Mass Flow (P kg yr^{-1})**	**Data uncertainty**							
				Reliability	**Completeness**	**Composition**	**Temporal correlation**	**Geographical correlation**	**Further correlation**	**Expert Judgement**	**CV(%)**
F2.01a	*Tillage seed*	Seeds from F2.01 used for growing crops on tillage land	216.0	10	10	2	4	2	0	0	**15**
F2.01b	*Grass seed*	Seeds from F2.01 used for growing grass	13.0	10	10	2	4	2	0	0	**15**
F2.02	Food & feed crops (FFC)	All tillage crops grown on the Estate (excluding grass)	14860.0	22	22	5	5	5	0	0	**32**
F2.02a	*Exported FFC*	Those crops from F2.02 exported from the Estate	3081.0	22	10	5	5	5	0	0	**26**
F2.02b	*FFC to feed*	Those crops from F2.02 used for animal feed	11565.0	22	10	5	5	5	0	0	**26**
F2.02c	*FFC to bedding*	Those crops from F2.02 used for animal bedding	214.0	22	22	2	2	2	0	0	**31**
F2.03	Grazing & grass crops	Grass produced on the Estate that is grazed or cut for silage and hay	11780.0	4	10	5	5	5	0	0	**14**
F2.03a	*Grass to cattle*	Grass from F2.03 eaten by cattle	9425.0	4	10	5	5	5	0	0	**14**
F2.03b	*Grass to pig*	Grass from F2.03 eaten by pigs	230.0	4	10	5	5	5	0	0	**14**
F2.03c	*Grass to poultry*	Grass from F2.03 eaten by poultry	172.0	4	10	5	5	5	0	0	**14**
F2.03d	*Grass to sheep*	Grass from F2.03 eaten by sheep	480.0	4	10	5	5	5	0	0	**14**
F2.03e	*Grass to other*	Grass from F2.03 eaten by other livestock	1383.0	4	10	5	5	5	0	0	**14**
F2.04	Agriculture to water bodies	Loss of P to waterbodies from diffuse agricultural pollution	498.0	4	22	0	2	2	0	0	**23**

Flow	**Flow Name**	**Flow Description (flow is the elemental P contained in those materials)**		**Data uncertainty**							
			Mass Flow (P kg yr^{-1})	**Reliability**	**Completeness**	**Composition**	**Temporal correlation**	**Geographical correlation**	**Further correlation**	**Expert Judgement**	**CV(%)**
F2.04a	*Tillage to water*	Diffuse P loss from F2.04 from land used for tillage crops	281.0	4	22	0	2	2	0	0	**23**
F2.04b	*Grass to water*	Diffuse P loss from F2.04 from land used for grass	217.0	4	22	0	2	2	0	0	**23**
F2.05	Atmospheric deposition	P naturally deposited on agricultural land from the atmosphere	351.0	4	22	0	4	2	0	0	**23**
F2.05a	*Atmospheric to tillage*	Atmospheric P from F2.05 deposited on tillage land	152.0	4	22	0	4	2	0	0	**23**
F2.05b	*Atmospheric to grass*	Atmospheric P from F2.05 deposited on grass land	199.0	4	22	0	4	2	0	0	**23**
F2.06a	*Straw to cattle*	Straw from F2.06 used for cattle	170.0	22	22	2	2	2	0	0	**31**
F2.06a	*Straw to pigs*	Straw from F2.06 used for pigs	4.0	22	22	2	2	2	0	0	**31**
F2.06a	*Straw to poultry*	Straw from F2.06 used for poultry	48.0	22	22	2	2	2	0	0	**31**
F2.06b	*Straw to sheep*	Straw from F2.06 used for sheep	0.6	22	22	2	2	2	0	0	**32**
F2.07a	*Forage to cattle*	Forage from F2.03 eaten by cattle	7359.0	4	10	5	5	5	0	0	**14**
F2.07b	*Forage to pig*	Forage from F2.03 eaten by pigs	2048.0	4	10	5	5	5	0	0	**14**
F2.07c	*Forage to poultry*	Forage from F2.03 eaten by poultry	1567.0	4	10	5	5	5	0	0	**14**
F2.07d	*Forage to sheep*	Forage from F2.03 eaten by sheep	154.0	4	10	5	5	5	0	0	**14**
F3.01	Fertiliser to fields	Mineral P fertiliser applied to agricultural land	5214.0	4	10	0	0	0	0	0	**11**

Flow	**Flow Name**	**Flow Description (flow is the elemental P contained in those materials)**	**Mass Flow (P kg yr^{-1})**	**Data uncertainty**							
				Reliability	**Completeness**	**Composition**	**Temporal correlation**	**Geographical correlation**	**Further correlation**	**Expert Judgement**	**CV(%)**
F3.01a	*Fertiliser to tillage*	Fertiliser from F3.03 that is applied to land used for tillage crops	5214.0	4	10	0	0	0	0	0	**11**
F4.01	Import feeds	Compound feeds imported for livestock	4330.0	0	0	0	0	0	0	40	**40**
F4.01a	*Import feed poultry*	Compound feeds imported for poultry	4330.0	0	0	0	0	0	0	40	**40**

SI Table 5-3: Phosphorus (P) flows for crops grown on the Estate that are exported used for or animal feed, includes all cereals, vegetables and forage crops.

Crop type	Area grown - based on estate maps (ha) [a]	Seed sown (kg/ha)	Seed P content (kg P / kg seed)	Total P import as seed (kg)	Annual yield (t/ha)	Total annual yield (t)	P content of harvested Crop (kg/t)	Total P of harvested crop (kg)
Barley - Grain	52.88	200.0 [b]	0.0034 [e]	**36.4**	2.69 [a]	142.2	3.4 [e]	**484**
Barley - Straw					1.35 [g]	71.4	1.0 [e]	**71**
Wheat - Grain	15.83	200.0 [b]	0.0035 [e]	**11.1**	1.93 [a]	30.6	3.4 [e]	**104**
Wheat - Straw					0.97 [g]	15.4	1.0 [e]	**15**
Oats - Grain	90.41	200.0 [b]	0.0036 [e]	**64.9**	2.81 [a]	254.1	3.4 [e]	**864**
Oats - Straw					1.41 [g]	127.5	1.0 [e]	**127**
Carrots	68.96	2.3 [c]	0.0035 [e]	**0.6**	25.00 [j]	1724.0	0.3 [e]	**534**
Leeks	12.89	2.0 [f]	0.0035 [e]	**0.1**	14.00 [j]	180.5	0.3 [e]	**56**
Onions	28.84	2.0 [f]	0.0035 [e]	**0.2**	40.00 [a]	1153.6	0.3 [e]	**358**
Potatoes	57.40	2500.0 [b]	0.0005 [e]	**77.5**	27.00 [a]	1549.8	0.4 [g]	**682**
Grass - Temporary	367.78	10.0 [b]	0.0035 [e]	**12.7**	26.80 [h]	9856.5	0.6 [g]	**5914**
Grass - Permanent	364.79	N/A	N/A	**N/A**	26.80 [h]	9776.4	0.6 [g]	**5866**
Lucerne	55.05	23.0	0.0035 [e]	**4.4**	32.00 [i]	1761.6	3.3 [g]	**5813**
Beet - fodder	11.91	4.0 [b]	0.0035 [e]	**0.2**	76.00 [b]	905.2	0.8 [e]	**751**
Maize - fodder	132.27	26.0 [b]	0.0035 [e]	**11.9**	22.80 [a]	3015.8	0.6 [g]	**1843**
Mixed forage	15.61	140.0 [b]	0.0035 [e]	**7.6**	22.00 [b]	343.4	3.8 [e]	**1305**
Turnips - fodder	62.76	3.6 [b]	0.0035 [e]	**0.8**	35.56 [b]	2231.7	0.8 [e]	**1852**

[a] Estate data (pers. comm. June 2023)
[b] SRUC (2023)
[c] Napier (2022)
[d] Oliver-Seeds (2023)
[e] Defra (pers. comm. May 2020)
[f] Ortola (2013)
[g] AHDB (2020c, 2020d, 2020e)
[h] GrassCheckGB (2020)
[i] AHDB (2015)
[j] Lampkin (2023)

9.4 Supplementary Information: Chapter 6

SI Table 6-1: Copy of participant information sheet, consent form, and questionnaire.

Participant Information Sheet

This research is conducted as part of a PhD studentship awarded by the Waitrose Collaborative Training Partnership and Lancaster University. The aim of the study is to gain an understanding of the main drivers and motivations for phosphorus management on farms in the UK.

Please read the following information to help you to decide whether to take part in the study.

What is the study about?

This brief survey will help me to understand the main drivers and motivations for phosphorus management on farms in the UK, specifically the planning of phosphate/phosphorus applications.

This questionnaire is split into three sections, Section 1 gathers some background information about your farming enterprise(s). Section 2 explores your current phosphorus management practices and your motivations for applying phosphorus to your crops. Section 3 explores some of the long-term aspects of phosphorus management on your farm.

The survey will take approximately 15 minutes to complete and consists of a mixture of multiple choice and short answer questions.

Do I have to participate?

You are not obliged to complete the survey and can stop at any time. The responses to this survey are fully anonymous, as such answers cannot be withdrawn as they cannot be identified. If you wish to provide your email address for future contact, this will be collected separately from your survey answers, you may request for your email address to be deleted by contacting j.davies24@lancaster.ac.uk.

Will my data be identifiable?

No, any identifying data, such as email addresses, will be collected separately and stored securely and separately to the other data. It is your choice to provide an email address, which will only be used to send you a summary report of our key findings from the study. Email addresses will be deleted from all records at the completion of the project and will not be shared with anyone outside the research group. The responses to this survey are fully anonymous and will be collated before they are shared with anyone outside the research group. All data will be stored securely in encrypted files in line with Lancaster University guidelines, and the UK Data Protection Act 2018.

How will we use the information you have shared with us and what will happen to the result of the research study?

I will use the information you provide for academic purposes only; this will include my PhD thesis and journal articles. I may present the findings of this study at academic and industry conferences. When writing up the findings of this study, I would like to share some of the views you state in your survey. I will only use anonymised quotes so that you cannot be identified. Should you wish to supply your email address, I will send you a summary report of our key findings at the end of the project.

Who has reviewed this project?

This project has been approved by the Lancaster University Faculty of Science and Technology Research Ethics Committee. The deadline for the completion and submission of the survey is 29th September 2023.

What if I have a question or concern?

If you have any questions about the survey please email me at j.davies24@lancaster.ac.uk or contact the project supervisor Professor Phil Haygarth at p.haygarth@lancaster.ac.uk.

If you have any concerns or complaints that you wish to discuss with a person who is not directly involved in the research, you can also contact: the Director of Lancaster Environment Centre, Professor Kirk Semple at k.semple@lancaster.ac.uk, Address: Lancaster Environment Centre, Lancaster University, Lancaster, United Kingdom, LA1 4YQ, Tel: 01524 510554.

For further information about how Lancaster University processes personal data for research purposes and your data rights, please visit our webpage: www.lancaster.ac.uk/reserach/data-protection.

Thank you for considering to participate in this project.

Consent form

By taking part in this survey:

- I confirm that I have read the information in the participant information sheet and fully understand what is expected of me within this study. I have had the opportunity to ask questions and to have them answered.

- I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason.
- I understand that the information I provide will be pooled with other participants' responses, anonymised and may be published. I understand that once my data have been anonymised and sorted, it may not be possible for it to be withdrawn, though direct quotes can be removed if required, up to the point of publication.
- I consent to information and quotations from my responses being used in reports, conferences, and PhD thesis.
- I understand that the researcher will discuss data with their supervisor as needed.
- I understand that any information I give will remain confidential and anonymous unless it is thought that there is a risk of harm to myself or others, in which case the principal investigator may need to share this information with their research supervisor.
- I consent to Lancaster University keeping the anonymised data for a period of 10 years after the study has finished.

I consent to take part in this study (this answer is required to continue)

No ☐

Yes ☐

Questionnaire

Phosphorus is an essential nutrient for plant growth. For fertiliser contents, manure analysis and nutrient recommendations phosphorus is often expressed in the oxide form, phosphate (P_2O_5). Soil nutrient analysis results are usually given as milligrams of phosphorus per litre of soil (mg P / L) and a corresponding Soil Index value.

For the purposes of this study, I will be using "phosphorus" to encompass all forms of phosphorus (including phosphate) in soil, fertilisers and manures.

Section 1: Background information about your farming enterprise(s).

1. Background information

1.1. In which area do you farm?
  1.1.1. Country:
    1.1.1.1. England ☐
    1.1.1.2. Scotland ☐
    1.1.1.3. Wales ☐
    1.1.1.4. Northern Ireland ☐
  1.1.2. County / region: ______________________

1.2. What is your role on the farm:
  1.2.1. Owner occupier ☐
  1.2.2. Tenant farmer ☐
  1.2.3. Farm manager ☐
  1.2.4. Other. Please specify: ______________________

1.3. What is/are your main farming enterprise(s)? (Tick all that apply)
  1.3.1. Dairy ☐
  1.3.2. Beef and/or Sheep ☐
  1.3.3. Pigs ☐
  1.3.4. Poultry ☐
  1.3.5. Arable crops ☐
  1.3.6. Potatoes ☐
  1.3.7. Horticulture ☐
  1.3.8. Other. Please specify: ______________________

1.4. Which of the following apply to your farming system (Tick all that apply)
  1.4.1. Conventional ☐
  1.4.2. Organic ☐
  1.4.3. Upland ☐
  1.4.4. Greenhouse / polytunnels ☐
  1.4.5. Other. Please specify: ______________________
  1.4.6. None ☐

1.5. What is the total size of your farm? ___________ ha OR __________ac

1.6. How many fields (or separate plots of land located in different areas) do you manage?

____

Section 2 Explores your current phosphorus management practices and your motivations for applying phosphorus to your crops.

2. Current phosphorus application practices

2.1. Do you apply any fertilisers containing phosphorus (straight and/or compound) to some or all of your land?
    2.1.1. No ☐
    2.1.2. Yes ☐
        2.1.2.1. If yes, what type do you apply? ______________________________

2.2. Do you apply manures to some or all of your land?
    2.2.1. No ☐
    2.2.2. Yes ☐
        2.2.2.1. If yes, what type do you apply? ______________________________
        2.2.2.2. If yes, are these produced on your farm or imported?
            2.2.2.2.1. Home-produced ☐
            2.2.2.2.2. Imported ☐
            2.2.2.2.3. Both ☐

2.3. Do you import any animal feeds containing phosphorus onto your farm
    2.3.1. No ☐
    2.3.2. Yes ☐
        2.3.2.1. If yes, what type? ____

2.4. Do you have and use a nutrient and/or manure management plan on your farm?
    2.4.1. No ☐
    2.4.2. Yes – I use a nutrient management plan only ☐
    2.4.3. Yes – I use a manure management plan only ☐
    2.4.4. Yes – I use both a nutrient and manure management plan ☐

2.5. What sources of information do you use to inform your phosphorus applications to your land (Tick all that apply) – this includes any phosphorus contained within manures
    2.5.1. Agri-environment scheme prescriptions ☐
    2.5.2. Agronomist / Agricultural Adviser / Animal Nutritionist ☐
    2.5.3. Crop / grain analysis ☐
    2.5.4. Field maps (to inform slope, proximity to watercourses, etc.) ☐
    2.5.5. Legislation (e.g., Farming Rules for Water) ☐
    2.5.6. Livestock numbers ☐
    2.5.7. Nutrient analysis of manures ☐
    2.5.8. Nutrient Management Guide (RB209) or other nutrient management planning software (e.g., Tried & Tested, PLANET, etc.) ☐
    2.5.9. Personal experience ☐
    2.5.10. Phosphorus content of animal feed ☐
    2.5.11. Standard soil nutrient analysis results ☐
    2.5.12. Yield mapping ☐
    2.5.13. Other. Please specify ____________________________________
    2.5.14. I do not plan my phosphorus applications ☐

2.6. On a scale of 1 to 5, how important to you are the following for determining **how much** phosphorus you apply to your land– this includes any phosphorus contained within manures
1 = Not at all important, 5 = Extremely important, N/A = Not applicable

		1	**2**	**3**	**4**	**5**	**N/A**
2.6.1	Agri-environment scheme prescriptions						
2.6.2	Application efficiency / time management						
2.6.3	Crop productivity						
2.6.4	Crop quality						
2.6.5	Farm accreditation / assurance schemes (e.g., LEAF)						
2.6.6	Input costs						
2.6.7	Legislation (e.g., Farming Rules for Water)						
2.6.8	Managing phosphorus losses to the environment						
2.6.9	Profit margin						
2.6.10	Slurry / manure storage constraints						
2.6.11	Application efficiency / time management						

2.7. Please list any other factors you use to determine **how much** phosphorus you apply to your land? ____ ____________

Section 3 Explores some aspects of long-term phosphorus management on your farm.

3. Thinking about long-term phosphorus management on your farm

3.1. Do you think that your long-term whole-farm phosphorus balance/budget is:
3.1.1. In balance – the total amount of phosphorus entering and being removed from the farm are the same ☐
3.1.2. In deficit – the total amount of phosphorus entering the farm is less than the total amount of phosphorus removed from the farm ☐
3.1.3. In surplus – the total amount of phosphorus entering the farm exceeds the total amount of phosphorus removed from the farm ☐
3.1.4. Don’t know ☐

3.2. Have you taken measures to reduce phosphorus inputs to your land?
3.2.1. No ☐
3.2.2. Yes ☐

3.3. What are the main barriers to you reducing your phosphorus inputs to your land? (tick all that apply)
3.3.1. Concerns regarding impact on crop yield ☐
3.3.2. Concerns regarding impacts on crop quality ☐
3.3.3. Manure production / export constraints ☐
3.3.4. Lack of information / evidence to support reduced phosphorus inputs ☐
3.3.5. Other. Please specify ____

3.4. Are you aware of the term “Legacy Phosphorus”?
3.4.1. No ☐
3.4.2. Yes ☐
3.4.2.1. If yes, what is “Legacy Phosphorus” in your understanding? How would you define it? ____

Thank you for taking part in this survey. If you would like to be contacted in the future about this study and to receive a short report giving the key findings from this project, please provide your email address.

If you have any questions about the survey please email j.davies24@lancaster.ac.uk or contact the project supervisor Professor Phil Haygarth at p.haygarth@lancaster.ac.uk.If you have concerns about the survey please contact the Director of Lancaster Environment Centre Professor Kirk Semple at k.semple@lancaster.ac.uk.

For further information about how Lancaster University processes personal data for research purposes and your data rights, please visit www.lancaster.ac.uk/reserach/data-protection.

SI Table 6-2: Copy of participant invitations.

Invitation for Farm Advisory Companies / Gatekeepers asking to distribute the questionnaire.

Dear _____

I am conducting a research project as part of my PhD studentship awarded by the Waitrose Collaborative Training Partnership and Lancaster University.

The aim of the study is to gain an understanding of the main drivers and motivations for phosphorus management on farms in the UK. This work is targeted towards all farmers / land managers in the UK and will involve a short questionnaire to be completed by the farmer / land manager.

I am writing to ask if you would be willing to promote and distribute the questionnaire to your client database and any other interested parties, inviting them to participate in this research project.

The questionnaire is purely voluntary and is available online at [link] and a printable pdf version is also available (see attached). The survey should take approximately 15 minutes to complete and the response window will close on 29th September 2023. Please can you return any hard copies of the questionnaire that are completed to the address below.

Please could you email me at j.davies24@lancaster.ac.uk to confirm that you are willing to distribute this questionnaire to your clients inviting them to take part. Please note that by agreeing to distribute this questionnaire to your clients, you will ensure that you will remain impartial, and you will not use the knowledge of participant responses to treat participants differently.

Thank you for your time and I hope to hear from you soon.

Jennifer Davies

Invitation direct to participants

Dear _____

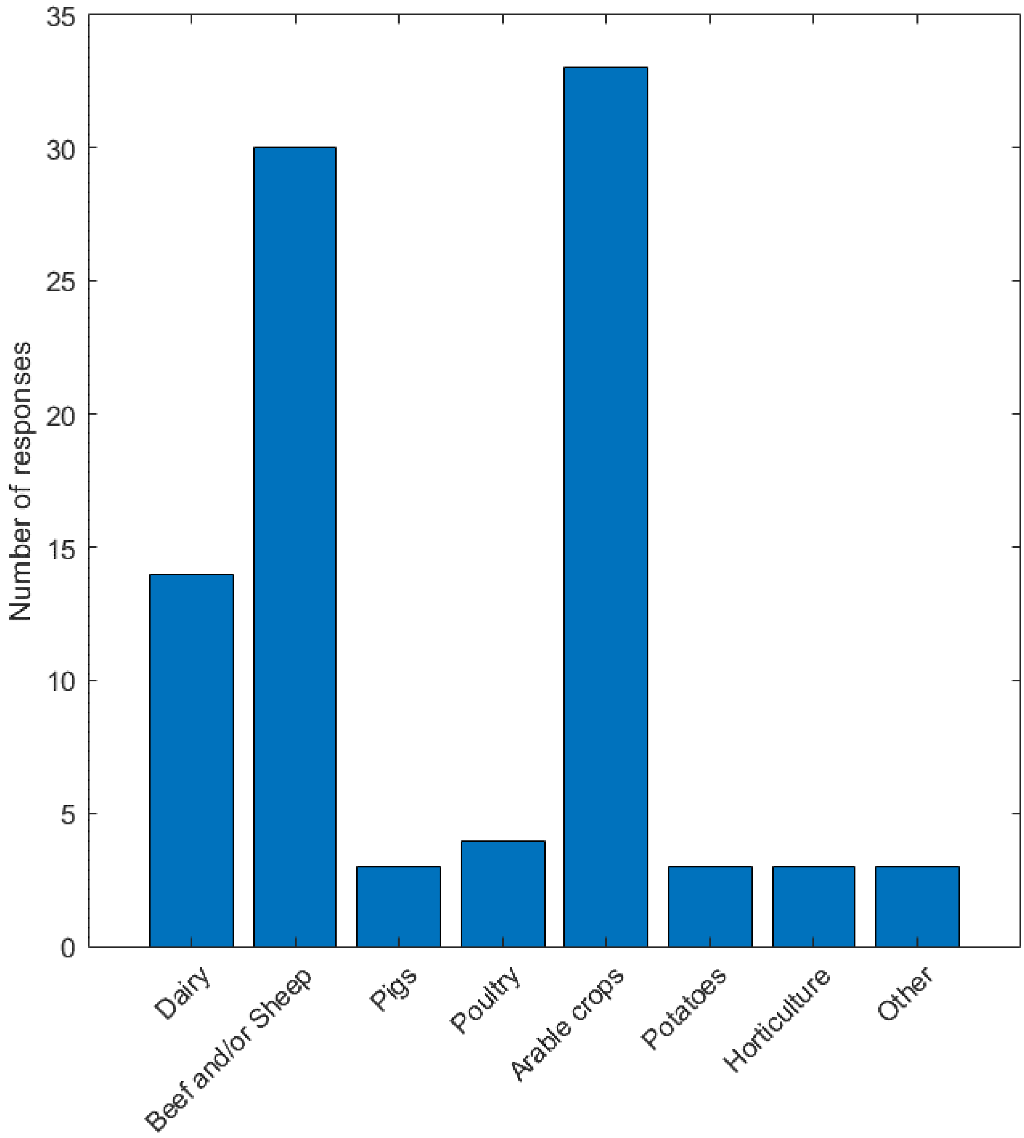
My name is Jennifer Davies and I am kindly requesting your participation in a research study that I am conducting as part of my PhD studentship awarded by the Waitrose Collaborative Training Partnership and Lancaster University.

The aim of the study is to gain an understanding of the main drivers and motivations for phosphorus management on farms in the UK. This work is targeted towards all farmers / land managers in the UK and will involve a short questionnaire.

Participation is completely voluntary, and you may withdraw from the study at any time. If you would like to participate in the study, please read the Participant Information Sheet. To begin the study, click the survey link at the end.

Thank you for your time and participation

Jennifer Davies



SI Figure 6-1: A breakdown of the different farming enterprises managed by the participants of this questionnaire. Participants could select one or more categories as part of their response.

SI Table 6-3: Free-text responses to the question "Please list any other factors you use to determine how much phosphorus you apply to your land?"

Free-text responses
Soil test results = availability and crop need
I sample all fields on a 3 yearly rotation. Biosolids have been applied to all land over the last three years. Indices are all 2 or 3. RB209 used to make recommendations for TSP if Biosolids not applied in the last 12 months, may apply 20-30kg/ha if at index 3 just so there is some available to the crop. The aim is to maintain soil indices consistently over the rotation and reduce TSP use through biosolid applications.
We will be stopping food production and using land for different uses so have been running down P, K indices. We only apply foliar sprays if we can detect problems in leaf tissue tests.
Crop yield, crop response, fertiliser & manure availability & price
Crop phosphate demand through growing season. Detailed soil analyses that may indicate Phosphorus lock up such as Ca/Fe levels
We are trying to return what had been pasture on an intensive Dairy farm into wildflower meadows.
Use manures to meet crop requirement for P based on soil analysis and RB209, working to reduce indices on high index fields. Note - FACTS qualified farmer / adviser.
We apply various organic industrial wastes to our land, so all NP K&S are accounted for and in line with crop need/soil nutrient levels and agreed with the EA
Rarely is any purchased. Cattle manure is spread, within constraints of how far you can move it, weather & soil conditions
Our 1000 cows poop, we've discussed it with them but they won't stop. We've done our best to mitigate phosphate losses to water courses. No bare land over winter, no application Nov - Feb, slurry spread as thinly as possible from where it came (cut fields) with application no more than crop offtake. All application by dribble bar. Soil wash to ditch avoided ... no muddy gateways or cow tracks. Don't see how i can practically do more. However, all our fields are P index 3 or greater .... not unexpected as been cows on the site for over 100 yrs. So, no way are we compliant. My nutrient management plan and farm records are carefully drafted to make sure we appear compliant. That why i maintain a FACTS certificate. A detailed inspection with somebody that knows what they are doing, and all will unravel. This gives me sleepless nights. Getting a bit fed up with the well-meaning environmentalists huffing and puffing about what we are doing as they pour milk over their Weetabix and make cheese and pickle sandwiches for lunch. The vegans and animal rights activists absolutely are entitled to their point of view, but they have no right to impose their views on others. Tolerance and respect. We believe that producing commodity food staples is a public good. "
Crops to be grown
I'm going to start tissue testing plants and looking at calcium balance
Soil sampling
Soil health working on this to reduce need to important through better nutrient cycling
I am filling this in thinking about a specific farm I work with. I am constantly battling with the owner about improving phosphate applications through soil analysis and NMP, and they are

continuing doing what they have always done. I am hoping SFI will drive an improvement in the NMP on this farm
Soil analysis results.   We also apply sewage sludge/biosolids this is a waste product that is regulated, and applications are undertaken in accordance with best practice guidance and overseen by the supplier.
Prescription by soil analysis, crop need and expected yield.
The crop rotation is planned, and phosphate applied within the rotation using a balance sheet so that all crops have requirements met without excessive application as manure levels and crop requirements vary by nutrient you can never be accurate to an individual crop with manure applications.
I am trying to lower my phosphorous levels, so by growing buckwheat as a cover crop i hope to make the phosphorous more available for the cash crop.
We zone GPS soil test on a routine basis (3-5 yearly). This provides the basis of our application planning.
Crop off take and future cropping plans.

SI Table 6-4: Free-text responses to the question "what is "Legacy Phosphorus" in your understanding? How would you define it?"

Free-text responses
Phosphorus that has built up in the soil over many years, it may not necessarily be easily released or readily availability to a current crop.
Yes we are running it down
what is left in the soil from years past but locked up
P applied historically and retained in the soil.
Phosphate locked up in the soil, currently unavailable to plants
High levels of P in soils from overapplication of OMs/fertiliser
Amount of phosphorus in soil as determined by Olsens test. It's availability to crops is not defined by this test and whether it will meet crop seasonal demands is not fully understood.
In the case of our farm legacy P is the elevated soil indices inherited following many years of grazing and manure application on a number of the fields by the previous occupier. The challenge is to erode those indices to a more appropriate level whilst maintaining productivity and making good use of the N & K fraction of the manures - have slurry, need N,K and S, don't really want the P.
It is the Phosphate that builds up in the soil due to over application, as phosphate is contained in several reservoirs in the soil, legacy phosphate is generally in the less available reservoirs
Balance of unused phos becoming locked up and unusable
Putting manure and bought in feeds
arises from over application in response to crop offtake or reduced yields. we are aware of issues relating to phosphate lock up so we are acting to improve soil health to promote phosphate availability to our crops and grassland
The phosphorus that is not used from applications which becomes unavailable to plants and builds the total soil phosphorus level/index.
Residual phosphate remaining in soils from previous/historic applications
Excess P left over from historic management
Naturally occurring phosphate
Accumulation of P in the soil not able to be utilised by the crop, nor lost in run-off