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ANALYSIS OF THE NEW ZEALAND AGRICULTURAL PHOSPHORUS BUDGET

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Abstract

The New Zealand agricultural industry utilises a significant amount of phosphorus (P) in the form of fertiliser to support sustainable and economically viable agricultural production, in particular, to support pasture and crop growth for the pastoral farming sectors. Phosphorus can however have significant negative environmental effects, meaning that sustainable management of P resources are required to reduce the risk of eutrophication of freshwater bodies.

To plan for the sustainable management and future use of P within New Zealand's agricultural industry, there needs to be an understanding of the current P use, the current P requirements for maintenance of production, and potential future P demands. There is limited research into the maintenance P requirements of soils under the pastoral farming sectors (dairy and sheep and beef) and even less research into the soil P requirements under the arable and horticultural sectors, and particularly, how these values vary regionally and nationally.

In order to provide insight into the current maintenance P requirements of New Zealand agricultural soils and current surplus or deficit of P using a P budget, this research developed regionally representative case studies for the dairy and sheep and beef sectors using data from industry sources. These data were modelled in the Overseer nutrient budgeting model (v 6.5.9) for the 2021/2022 season as this season had the most comprehensive data available. For the dairy and sheep and beef sectors, regionally representative case study farms were developed for each of the production regions and respective sectors, with data being sourced from industry specific annual production reports, including the Dairy NZ Dairybase (2024) dataset, and Beef + Lamb NZ (2022) benchmarking data. Due to a lack of regionally detailed production data for the arable and horticultural industries, these sectors underwent a much more rudimentary analysis with the annual P applied in the 2021/2022 season used as a proxy for maintenance P requirements. Given that the pastoral industries apply approximately 91% of the total P fertiliser applied in New Zealand, the main focus of this study was on the dairy and sheep and beef industries.

Overall, the estimated national maintenance P requirement of the pastoral farming sectors (dairy and sheep and beef) was 146,546 tonnes P for the 2021/2022 season. The dairy sectors maintenance P requirement was estimated to be 35 kg P/ha or a total of 59,579 tonnes P for the 2021/2022 season, and the sheep and beef sectors (excluding production class 1 farms)

maintenance P requirement was estimated to be 18 kg P/ha or a total of 86,877 tonnes for the same season. When compared to fertiliser P application, it was found that overall, the average application of fertiliser P to the pastoral sector, of 129,974 tonnes P (according to Stats NZ (2024) and FANZ (2022d) was 16,482 tonnes less than the estimated maintenance P requirement for the 2021/2022 season.

Combining the arable and horticulture P use (maintenance proxy) with the pastoral sector's maintenance requirement, the total agricultural maintenance P requirements for the 2021/2022 season was estimated to be 157,259 tonnes P. The estimated national maintenance P requirement and the total fertiliser P applied in the 2021/2022 season are similar, with the national maintenance P being only 14,430 tonnes P greater than the total P applied (142,829 tonnes P), which suggests that in general, soil plant available P values (Olsen P values) are likely to remain near static at a national scale. At the sector level, it is likely that dairy soil Olsen P values were maintained, while sheep and beef Olsen P values are likely to have decreased.

Across the dairy sector, the average fertiliser P application rate tended to be lower than the estimated maintenance P requirements, with only the 'Canterbury' and 'Otago + Southland' regions having a higher average fertiliser P application rate, of 38 kg P/ha and 27 kg P/ha respectively, than the estimated maintenance P requirements of 32 kg P/ha/yr and 26 kg P/ha/yr respectively. The inclusion of P from imported supplementary feeds and effluent additions in the current research are likely contributors to the decrease in dairy maintenance P requirements in comparison to past estimations. The highest average P imports in supplementary feed were determined in the 'Waikato + Bay of Plenty' region, importing 13 kg P/ha, with the lowest average recorded in the 'West Coast + Marlborough' region, importing only 7 kg P/ha in supplementary feeds.

Across the sheep and beef sector the average fertiliser P application rate was lower than the estimated maintenance P requirement for all regions and farm production classes. The largest difference between fertiliser P applied and estimated maintenance P requirements was recorded in the 'Marlborough + Canterbury' region class 8 farms, where the estimated maintenance requirement was 12 kg P/ha higher than the average fertiliser P application rate. Although soil Olsen P values may decrease long term (if fertiliser P application continues to be less than maintenance), it is unlikely that there would be any short-term effects on production.

The P budgets revealed that the largest P surpluses were in land under dairy production in the 'Canterbury' and 'Otago + Southland' regions, which were estimated to be accumulating 6 kg P/ha/yr and 7 kg P/ha/yr, respectively. A large P deficit was also estimated from soils under dairy production in the 'West Coast + Marlborough' region, which was estimated to be -4 kg P/ha.

In the sheep and beef sector, the P balance was mostly in a deficit, with the 'Marlborough + Canterbury' region estimated to have the largest P deficit at both the average regional level (-7 kg P/ha/yr) and farm production class level (-21 kg P/ha for the average class 8 farm, and -8 kg P/ha/yr for the average class 2 farm). At a regional level, minimal P surpluses were recorded for the 'Northland + Waikato + Bay of Plenty' and 'Taranaki + Manawatū' regions, of 0.4 kg P/ha/yr and 1 kg P/ha/yr, respectively.

The P budgets of the dairy and sheep and beef sectors suggested that the dairy sector was accumulating P at the rate of 3 kg P/ha/yr across all regions and soil types, whereas the sheep and beef industry indicated a P deficit of -2 kg P/ha/yr, across all regions, farm production classes, and soil types, for the 2021/2022 season. These P balances are sensitive to variability in P fertiliser application data and so need to be interpreted with caution. The general agreement between the national estimated maintenance P requirements and the total fertiliser P applied across the New Zealand pastoral industries is a testament to the strong focus on nutrient management within the pastoral sectors in this country.

However, there is still room for improvement in the sustainable use of P in the agricultural sector, as the apparent under application of fertiliser P to the soils under sheep and beef production risks mining soil P, resulting in a decrease in soil Olsen P values and pasture, forage crop and cash crop production over time, which in turn would have a negative impact on meat and wool production. The possible over application of fertiliser P to soils under dairy production risks a slow buildup in soil legacy P, which increases the risk of P loss to water. The current New Zealand dairy soil Olsen P values also increase the risk of P loss, as six out of the seven dairy regions assessed in the current research had soil Olsen P values above the upper target Olsen P value of 30 mg P/L (target range being 20-30 mg P/L), which indicates a surplus of P in the soil solution which can be readily lost via surface runoff or possibly leaching.

This study represents the most comprehensive analysis of P maintenance requirements across New Zealand agriculture and for the first time, presents a national agricultural P balance for the country. This information is critical to not only ensure best practice P fertiliser use within New Zealand, but to allow us to benchmark both our industry and national scale P balances internationally. These insights are useful to project future trends in P fertiliser requirements, highlighting industries and regions which may require higher inputs of P to maintain economic productivity.

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Chapter 1 Introduction

Phosphorus (P) is a vital element for the function of life sustaining bio-chemical reactions in all living organisms, from plants and micro-organisms to animals and humans (Heckenmüller et al., 2014; Khan et al., 2023; Muindi, 2019; Roberts & Johnston, 2015; Smit et al., 2009). However, due to soils often having low concentrations of P in solution, and P generally being poorly soluble (Smit et al., 2009), it is often the main nutrient limiting agricultural production (Ringeval et al., 2017). In order to maintain high levels of agricultural production, P is applied in the form of chemical fertilisers or as organic animal manure. (Heckenmüller et al., 2014; Ringeval et al., 2017). Unfortunately, phosphate rock (PR) (the mineral substance from which chemical P fertilisers are manufactured) is a non-renewable resource that is geographically restricted (Chowdhury et al., 2017). With increasing global demand for agricultural products, and high levels of P discharge to the environment, sustainable management of P has become increasingly important (Chowdhury et al., 2017; Van Vuuren et al., 2010). Freshwater systems are sensitive towards P inputs, with eutrophication of freshwater [caused by P discharged from human activities and in particular, agricultural use of P fertilisers (McDowell et al., 2001a; Ortiz-Reyes & Anex, 2018; Withers et al., 2014; Withers et al., 2001)], and increased likelihood of algal blooms affecting approximately 1.8 billion people (76% of catchments globally) (McDowell & Haygarth, 2024).

Historically, P fertilisers have played a vital role in the agricultural production in New Zealand, with phosphate rock making up 24-37% of total fertiliser imports from 2021 to 2022, with an import value of \$227 million dollars in 2022 (Hall, 2023). The majority of the P fertilisers sold are applied to/consumed by the pastoral grazing industries (dairy and sheep and beef farming) which cover approximately 80% of New Zealand agricultural land area [approximately 10.5 million ha covered by dairy and sheep and beef (including small holdings) according to B+LNZ (2023a)]. As such, the P lost to the wider environment and freshwater bodies in New Zealand comes predominantly from agricultural sources, with 64% of monitored rivers in New Zealand having elevated dissolved reactive P (DRP) concentrations, making them more susceptible to eutrophication (Stats NZ, 2022b).

In order to manage P in a sustainable manner, we must know the current use in relation to the soil and pasture/crop requirements and potential future demands for P. Current use data [available from Stats NZ (2024) and FANZ (2022g)] report an average of 154,000 tonnes of P sold

in 2019, decreasing to an average of 142,829 tonnes sold in 2022. These data are useful for understanding how P is distributed within the agricultural industry, and estimating the amounts potentially sold/applied to farms in the future, however they are unable to shed light on how current and future P use relates the maintenance requirements of agricultural soils, and thus how the agricultural industry is tracking in terms of maintaining optimum soil P levels to support current and future production. Calculation of the current maintenance P requirements for the range of New Zealand agricultural soils is difficult as requirements are influenced by varying soil types, land types, regional climates and intensities of farming which create a wide range in maintenance values.

As such, modelling is the most practical way of estimating the soil maintenance P requirements across farm, regional and national scales. In order to provide useful maintenance P requirements, a model has to take into account not only the P inputs and outputs of a farm, but also the changes in soil P pools and animal transfers. The Overseer Nutrient Budgeting model is a New Zealand model, tailored to pastoral grazing systems, that uses readily available farm level information and draws on national soil type (Wheeler, 2018a) and climate databases (Wheeler, 2018b) to estimate both soil maintenance P requirements and P nutrient budgets (Shepherd & Wheeler, 2012; Wheeler et al., 2006). The use of this model allowed for a more detailed analysis of P maintenance requirements than has been possible previously, by creating regional sector specific case studies to accurately represent different soil types, climates and farm system intensities.

Chapter 2 Literature review

2.0 Introduction

This chapter reviews the importance of phosphorus (P) in New Zealand agriculture and the need for careful management of P due to the cost of this fertiliser product, its status as a non-renewable resource, and the environmental implications of poor management. As such, knowing the current use and potential future demands of P is important to help plan for the sustainable use of P. This chapter also reviews the methods and models available for obtaining farm P requirement data, in order to determine the best model available for use in New Zealand's agricultural industry.

2.1 The role of phosphorus in food production

Phosphorus is an essential nutrient for the growth and development of all living organisms [including both plants and animals (Roberts & Johnston, 2015)], for a range of metabolic and physiological processes involving energy metabolism, cell division, and DNA synthesis (Khan et al., 2023). To support these life sustaining functions plants must take up a significant amount of P from the soil solution [plant P concentrations range from 0.05%-0.50% of dry matter (DM) (Vance et al., 2003)]. However, labile P in soils can be limiting to plant growth as soil concentrations vary widely, ranging from 0.001 to about 1.0 mg P L⁻¹ (<1% of total P) (Muindi, 2019; Pierzynski et al., 2005), requiring additional P to be applied in order to ensure sufficient levels of labile and plant available P.

Historically, crop and livestock production relied on the natural levels of soil P recycled P from litter and green waste, and locally produced manure (and city waste) to replace nutrients exported from farm, up until the second half of the 19th century, where external inputs of P fertiliser became more readily available, with the mining and export of phosphate rock (Smit et al., 2009). Dawson and Hilton (2011) drew attention to the fact that without the commercial manufacturing process for P fertilisers, agriculture and in turn life in many industrialised countries would have become unsustainable, due to the increasing pressure on agricultural soils and the inability to supply the required levels of P via naturally recycled forms. With the global population expected to reach a peak of 10.3 billion people by 2080 (United nations 2024), the global demand on P via food production and distribution will only continue to increase. Helin and Weikard (2019) estimated the total P replenishment requirements to be 13.5 MT (million metric

tonnes) in 2011, increasing to an estimated 23-52 Mt by the end of the century, depending on income growth and shifting consumer patterns.

2.1.1 Phosphate rock: Sources and limitations

The world's main source of P for fertiliser use is phosphate rock (PR), a resource that is becoming increasingly more limited and costly (Cordell et al., 2009), with approximately 75% of the total PR produced in China, Morocco, the United States and Russia in 2022 (Manschadi et al., 2014; U. S. Geological Survey, 2024). After the 2007/2008 price spike of phosphate rock, the question of phosphate rock scarcity arose, resulting in an increase in literature predicting when peak P production would occur (after which P production would decrease) (Cordell et al., 2009; Cordell & White, 2011) and debate surrounding the true levels of the global PR reserves. Over time, the PR reserve estimates have changed with the emergence of new information and the use of updated estimation methods and definitions. As of 2024, the U. S Geological Survey estimated the global PR reserves to be around 74,000 MT, a 4-fold increase from the 2009 estimates [with the definition of 'reserves' being "That part of the reserve base that could be economically extracted or produced at the time of determination" (U. S. Geological Survey, 2024; United States Geological Survey, 2009)]. While there has been changes to the "peak P" timeline, and other research arguing that P will be in supply for centuries to come (Edixhoven et al., 2014), it is widely accepted that phosphate rock is a limited and depleting resource (Cooper et al., 2011).

With the industrialisation and on-going development of many areas around the world, continuous applications of P fertilisers have often been recommended and applied to maintain or increase labile P concentrations and replace the plant nutrients removed during harvest (Roberts & Johnston, 2015). However, P deficiency continues to affect large areas of cropland and grasslands with approximately 73% of the global grassland and cropland operating below the agronomic optimum soil test P concentration for optimum pasture and crop yield (42% and 30-32%, respectively) (Lun et al., 2018; Macdonald et al., 2011; McDowell et al., 2024). McDowell et al. (2024) found that the largest areas operating above the agronomic soil test P threshold (no P deficit) were Europe and North America, whereas the greatest deficit was seen in Asia, and in general, developing countries also experienced P deficits (Macdonald et al., 2011). As such, there is the need to more efficiently use P fertilisers in areas operating in a P deficit, while not applying fertilisers and "mining" the accumulated P in areas operating in a P surplus (McDowell & Haygarth, 2025). McDowell and Haygarth (2025) go on to suggest that there is a significant amount of total P stock in grassland and cropland soils (which reflects a long legacy of P fertiliser application) sitting un-used in the top 20-30cm of the soil (approximately 3.32 - 4.26 Gt). Their

research suggests that 32-41% of the 2020 estimated geologic P reserves are present in grassland and cropland soils as non-plant available forms of P (approximately 3.0 - 3.38 Gt), and it is estimated that if this P was accessed by more efficient agricultural crops, the P stocks could represent 146-186 years of the 2020 mass of P fertiliser applied annually.

2.1.2 Sources of phosphorus to the soil

Phosphorus can be introduced to agricultural systems in many ways; the most significant being inorganic P fertilisers, imported feeds and recycled/imported organic P (farm effluent or solid manure). The most commonly applied P fertilisers in New Zealand are single superphosphate (SSP) and diammonium phosphate (DAP), containing 9% and 20% P respectively, as they contain highly soluble forms of P which become readily plant available in the soil solution upon application (Nash et al., 2019). Application of these highly soluble forms of P not only increase the amount of labile P (available for plant uptake), but also the amount of P available for adsorption and precipitation within the soil (Schnug & Haneklaus, 2016). Application of fertiliser P in excess of plant/crop requirements can lead to significant P enrichment of the soil (elevated soil test P values) (Liu et al., 2023; McDowell et al., 2008), and wider environmental impacts if lost from the soil into freshwater environments. Less reactive forms of P fertiliser such as reactive phosphate rock (RPR) can be used to slow the P released into the soil solution (Quin & Rajendram, 2019) and can be a useful fertiliser where risk of P loss to the environment is high (Rowarth et al., 2019).

Imported feeds are another form of introduced P, predominantly to intensive dairy farm systems where large quantities of supplementary feeds are required to support high levels of production (Roche et al., 2017). The commonly imported supplementary feeds on New Zealand dairy farms include palm kernel extract (PKE), maize silage, barley, wheat, and oats (DairyNZ Economics Group, 2019) with PKE representing 54% of the 3.7 million tonnes of total grain and feed imported in 2022 (Densley et al., 2023). Imported feeds are not that common in sheep and beef systems, however the intensive finishing/breeding systems will bring in feeds like sheep nuts, and silage grown on other farms to support production (Sise et al., 2017, 2018). It has been estimated that in three mixed farming catchments in New Zealand, P from imported supplementary feeds contributed negligible amounts of P in a dairy farm P budgets (1-5 kg P/ha/yr) (Power et al., 2002). These P budgets were constructed with data from 5-21 dairy farms in each catchment, however, Ledgard et al. (2016) estimated that system 4 and 5 dairy farms in the Waikato (which are high intensity farms), import around 21-30% and $\geq 31\%$ respectively of the feed used throughout the

lactation period. This calculates to an annual average of 4,030 kg feed/ha which is typically made up of palm kernel extract (PKE), maize silage, barley grain, molasses and brewers' grain. With these feeds containing approximately 0.65%, 0.26%, 0.36%, 0.21% and 0.67% P (Gourley et al., 2010), respectively, the system 4 and 5 farms in the Waikato could be importing as much as 19 kg P/ha/yr in the form of supplementary feed. As such, imported supplementary feeds could be contributing large amounts of P to a dairy farm's P budget, depending on the intensity of the farm system.

The recycling of nutrients from decomposing crop/plant residues (left over from harvest or plant senescence), animal manure and effluent, and composted agricultural waste are all sources of organic P in the farm system that can build soil organic matter and improve soil structure (Abdel-Fattah, 2020; Robinson, 2000). Organic P represents between 20-80% of the total P (TP) in the soil depending on the soil type and land use (McLaren et al., 2020). For these organic forms to become plant available, organic P needs to be mineralised via soil microbes and micro-organisms, and released into the soil solution following cell death (Schnug & Haneklaus, 2016; Turner et al., 2013). Effluent and manure are generated from a range of livestock operations including dairy, pig, and poultry farms (Izmaylov et al., 2022; Longhurst et al., 2017; Sommer et al., 2013) where there is infrastructure to collect, scrape and wash down the manure produced by the livestock. Because New Zealand's dairy operations are predominantly pasture based and graze year-round, the main source of organic P is from farm dairy effluent (FDE), generated from the milking shed, feed pad, and animal shelters (Longhurst et al., 2017). Effluent from these areas is either washed out with water (creating liquid effluent) into a holding pond or sump, or scraped or deposited directly into a concrete bunker as a slurry or drained as solid manure (Longhurst et al., 2017). The concentration of P in effluent varies with the type of effluent, ranging from an average of 60 g/m³ from Dairy shed effluent, to 1,500 g/m³ from winter barn solids (Waikato Regional Council, 2025). Longhurst et al. (2017) also noted a seasonal change in the mean effluent P content of pond effluent with the lowest concentration recorded in July at 20 g/m³, and the highest concentration recorded in October and December at 50 g/m³, likely due to changes in pasture quality and the type and amount of imported feed fed during the lactation period.

Uneven dung deposition on hill country paddocks due to animal grazing behaviour, location of shelter, topography and stocking rate led to 60% of the dung being deposited on the flatter areas of paddocks (which make up only 17% of the paddock) (Rowarth et al., 1992). This results in a large amount of P deposited on a small proportion of the farm area, resulting in an accumulation

of nutrients in the flatter areas, and a depletion of nutrients from the grazed hills. Aarons et al. (2004) determined that P returns to the surface soil (0-5cm) of grazed dairy pasture soils can amount to 248 kg P/ha/year under dung pads, resulting in a 2-fold increase in soil test P (STP) values under dung (increasing approximately from an STP value of 30 mg P/L to 60mg P/L) after 60 days. Systems where dung and effluent are efficiently collected allow for a more even dung and nutrient redistribution to paddocks via a slurry mixture.

2.1.3 Loss of phosphorus

The loss of P from agricultural soils via runoff and leaching can have significant, negative environmental effects if that enriched water were to enter freshwater bodies.. Phosphorus loss is often categorised into two types, the first is *background* (soil) P loss and the second is *incidental* (fertiliser) P loss (Haygarth & Jarvis, 1999; McDowell et al., 2005). Background P loss has been defined as the P lost associated with land-use, management (i.e. irrigation type, mole/tile drainage), and transport factors (i.e. topography and rainfall) which affect P loss long term (Gray et al., 2016b; McDowell et al., 2005). Incidental P losses are influenced by additional management factors such as rate and timing of fertiliser or farm dairy effluent (FDE) application, application depth of FDE, and type of P fertiliser applied (Gray et al., 2016a). Commonly, only 13% of a dairy farm is irrigated with FDE, therefore the risk of incidental P loss is calculated proportionally to area (McDowell et al., 2005). The form in which P is lost from the soil (via incidental and/or background losses) can be as dissolved P (DP) and particulate P (PP) (Barlow et al., 1999).

Dissolved P

Dissolved P describes P that is dissolved into solution and includes particulate P <0.45µm in size, which pass through most filters (Withers et al., 2001). This form of P is generally assumed to be the dominant form lost from grazed pasture and forest systems where soil tends to be less exposed (Bargh, 1977; Daniel et al., 1998; McDowell et al., 2004; Sharpley et al., 1994). The amount of P lost as DP is controlled by the concentration of P in soil solution (STP) and the buffering capacity of the soil (McDowell et al., 2008). Nash and Murdoch (1997) and (Nash et al., 2000) found that DP made up over 90% of the total P (TP) lost from a highly fertile dairy pasture soil with good ground cover.

Particulate P

The loss of PP is generally associated with over grazing resulting in treading damage (McDowell et al., 2008), cultivating at the wrong time of year (Du et al., 2021), or leaving land fallow between cropping rotations, with PP concentrations in runoff increasing as the level of exposed soil increases. McDowell et al. (2007) found that 24% and 33% of TP was in the form of PP under grazing treatments with bare soil, and grazing treatments that resulted in treading damage (respectively). At a global level, Alewell et al. (2020) found that continental and national erosion P losses accounted for between 40-85% of the TP lost from agricultural systems.

2.1.4 Phosphorus loss transport pathways

Phosphorus cycles through agricultural systems via the plant-animal-manure-crop loop (Helin & Weikard, 2019), meaning that P fertiliser applied to plants (both arable crops and pasture) is consumed by grazing livestock, and recycled back to the soil/plants via dung. While a closed loop system is often targeted, P is exported from the system via animal products (meat, wool, and milk), harvested crops, lost to water, or sorbed by soil, meaning fertiliser P applications are required to replace the nutrients exported or made unavailable. The majority of the P fertilisers manufactured are soluble-salt forms of P, that are readily soluble in the soil solution upon application and are immediately available for plant uptake (Altamira-Algarra et al., 2022). The two main transport pathways from which significant amount of P can be lost from soil solution are surface runoff and leaching.

Surface runoff

Surface runoff is generated when rainfall intensity and/or frequency exceeds the soil's infiltration rate (McDowell et al., 2008; Ramke, 2019), causing the water to move across the surface rather than down the soil profile (Figure 2.1). The loss of P via this transport pathway is of concern especially from agricultural/cropping soils where there has been regular cultivation of the soil, and/or treading damage due to highly stocked paddocks or winter grazing (McDowell et al., 2003a; Silburn et al., 2011). Treading damage caused by grazing livestock contributes to decreased infiltration rate and soil porosity, and thus increases the risk of surface runoff (McDowell et al., 2003a). Combined with the application of soluble P fertilisers and effluent, runoff can be a significant pathway of P loss from grassland and cropping soils. In a study of potential P losses in overland flow under superphosphate and reactive phosphate rock treatments, McDowell et al. (2003b) found that up to 5.4 mg P L⁻¹ was lost in surface runoff after

a recent application of 376 kg/ha single superphosphate. The proximity of the P source to freshwater bodies significantly influences the risk that surface runoff will deposit P into freshwater systems. Under moderate to heavy rainfall, McColl and Gibson (1979) and Gillingham and Gray (2006) found that surface runoff moved between 3-5m downslope on sheep and beef pastures, with McDowell et al. (2001b) finding that 90% of surface runoff occurred within 30 m of the stream in a predominant cropped catchment.

Leaching/subsurface flow

The occurrence of P leaching in New Zealand tends to be concentrated in areas with very high stocking rates and low soil P retention (Dymond et al., 2013), however it is relatively uncommon due to the generally higher anion storage capacities (ASC) and P sorption capacities of most of the countries soils. In their report, Dymond et al. (2013) found that areas like Southern Hawkes Bay and the West Coast had elevated leaching of dissolved P, due to a combination of high stocking rates and low P sorbing soils. Leaching or subsurface drainage is most likely to occur in areas with free draining, shallow sandy or stony soils (Carrick et al., 2013; McDowell et al., 2019a) which contain preferential flow paths, especially in areas with long term P fertilisation and/or recent P application (Nash et al., 2019). In their study of direct exports of P fertilisers from grazed pasture, Nash et al. (2019) found that under poor management, 30-80% of total farm P exports in drainage (subsurface flow) can be attributed to recently applied P fertiliser. In a study comparing the effects of fertiliser and FDE application to irrigated shallow stony soils of the Canterbury area, McDowell et al. (2019a) found that even when following industry best practice when applying synthetic fertilisers and FDE (either 40 kg P/ha/yr as fertiliser, or 30 kg P/ha/yr as fertiliser plus 10 kg P/ha/yr as FDE) the particulate and dissolved P concentrations increased annually. It was found that over the 14-year application period, the shallow stony soil receiving FDE applications had a mean annual DRP load of 0.316 kg P/ha/yr and a TP load of 1.46 kg P/ha/yr.

Leaching of P via drainage water can occur on high clay content soil with artificial drains installed, as these soils can develop large macro pores that facilitate preferential flow. These large macropores drain quickly and reduce the amount of time water sits in the soil (Radcliffe et al., 2015), thus reducing the likelihood of plant uptake and soil P sorption and increasing the likelihood that the soluble P is transported through the soil profile in the drainage water. The loss of P to artificial drains is of greatest concern in soils with low ASC values (poor retention of P), or where P concentrations are in excess of plant requirements (McDowell et al., 2001c). Artificial drainage (particularly tile drains), has been identified as a major contributor to the loss of P from

land under agricultural production in many of the major global agricultural countries (Husk et al., 2024; Kokulan, 2017; Macrae et al., 2007; Tedeschi et al., 2024)

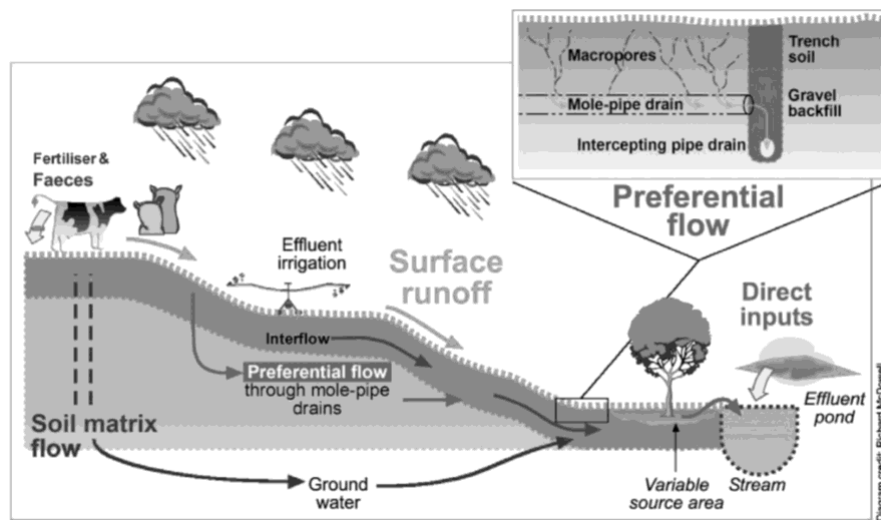


Figure 2.1. Conceptual diagram of potential sources and processes that transport P from the dairy pastures to surface water (Taken from McDowell & Nash, 2012).

2.1.5 Water quality effects of phosphorus loss

Utilising the P reserves already present in agricultural soil is exceedingly important as P contributes significantly to the non-point pollution of freshwater (Carpenter et al., 1998; Gillingham & Thorrold, 2000), with P pollution being one of the most serious issues facing freshwater in many parts of the world (Devlin & Brodie, 2023). The loss of excess P from agricultural soils into surface freshwater leads to the eutrophication of these waterways, which can trigger sudden and excessive algal blooms and the growth of other aquatic plants (Baldwin, 2013). This enrichment of freshwater affects approximately 40% of the world's population (McDowell et al., 2025), with the algal blooms leading to taste and odour problems, depletion of dissolved oxygen, interference with recreational use, as well as being potentially toxic (Dodds, 2006; Fetscher et al., 2015; Wood et al., 2017).

In New Zealand, there are a number of freshwater bodies that are P limited, which means that in relation to other nutrients, P is the nutrient restricting algal growth. Additional P inputs into these freshwater bodies could in turn, un-limit the P and cause undesirable growth of periphyton algae. McDowell et al. (2020b) found that of 1100 freshwater sites in New Zealand, 76% of the sites were P-limited, with areas like shallow Waikato lakes, the Taupo River, and the larger Tukituki catchment often being P-limited over the summer (Ausseil, 2008; NIWA, 2020). The extent of P loss to these P-limited waterways is influenced by several management practices such as on-

farm deforestation, grazing management (stocking rates and grazing of stream banks/flow paths), and the timing and rate of fertiliser P application.

2.1.6 Factors influencing phosphorus loss

Most of the P lost to the environment comes from agricultural production (McDowell & Haygarth, 2024), with a range of factors having an influence on the loss of P to the environment. The main factors influencing P loss from the farm system are the farm topography, soil P retention and drainage properties, STP values, fertiliser additions, crop residues, livestock excreta and the hydrological connectivity to freshwater sources, with the management of these factors determining their level of contribution to environmental P loads (McDowell & Haygarth, 2024).

In New Zealand, the highest risk of P loss comes from hill country farms that cover a large portion of the agricultural land, due to the steeper topography and higher rates of erosion. The steeper slopes are at greater risk of generating runoff, due to the low soil permeability/infiltration rate (Huang et al., 2017), which could result in large amounts of P lost if the runoff were to enter nearby freshwater sources.

Fertiliser P and the application of livestock excreta are two significant sources of P, due to the solubility of many of the forms of P fertiliser used, and the propensity of these sources to be lost in runoff. The 4Rs of nutrient stewardship are often followed when applying fertiliser and effluent, calling for the consideration of the right time, right place, right form, and right rate of application (McDowell & Haygarth, 2024). In terms of rate and timing of fertiliser P application, Dougherty et al. (2011) found that on Australian dairy farm soils (from New South Wales and Tasmania) with a range of P sorption capacities, a single application of 40 kg P/ha increased the CaCl₂ extractable P concentration from 4 mg/kg to 207 mg/kg, whereas the first application of the split treatment (consisting of 3 applications of 13.3 kg P/ha) only increased the extractable P concentration from 4 mg/kg to 25 mg/kg. In a similar study, on a low P buffering soil from the North-West of Tasmania, Burkitt et al. (2011) also found that the single application of 40kg P/ha resulted in higher P concentrations in runoff (TP = 44 mg/L), than the combined total from three split applications (9.5 mg P/L). Although the split applications resulted in lower soil extractable P and TP in runoff, both Burkitt et al. (2011) and Dougherty et al. (2011) found that multiple P fertiliser applications increase the likelihood of an application coinciding with a runoff event. Thus, special care should be taken to avoid applying P fertiliser when surface runoff is likely to occur.

The loss of P from fertiliser and effluent applications is however influenced by the soil's ability to sorb P, this is known as the ASC and is a soil characteristic that cannot easily be changed. The ASC value is strongly influenced by the weathering of a soil and the parent materials contained within (Saunders, 1964). Saunders, (1964) found that ASC was lowest in the weakly weathered brown-grey soils (9%) and highest in the strongly weathered andesitic and rhyolitic volcanic ash (>90%) soils in New Zealand. This is due to increased aluminium and iron oxides and clay minerals in the more weathered soils, which sorbs P (Pierzynski et al., 2005). Using soils sampled across northern Ireland, Yang et al. (2024) found that soils with low P sorption capacities were at greater risk of P loss than the high sorption soils. It should be noted that their definition of high and low P sorption was based on the amount of extractable M3-Al (Mehlich-3 extractable aluminium) as the amount of M3-Al in the soil samples had the greatest influence on P-sorption behaviours in the soil. Using the ASC values of New Zealand soils, Taylor et al. (2016) documented the relationship between soil ASC and Olsen P values (a measure of P in the soil solution), and found, similarly, that soils with higher ASC values (for example, allophanic soils) tended to have lower risk of P loss regardless of the Olsen P values, and that low ASC soils (organic and recent soils) tended to have a higher risk of P loss at relatively low Olsen P values.

In high ASC soils, a greater percentage of P applied is sorbed from the soil solution and often occluded, resulting in less plant available P. These soils therefore require increased rates of P fertiliser to overcome the soil's P sorption capacity and supply sufficient P to pasture or crops (Balemi & Negisho, 2012). Most soils continue to sorb P each year, resulting in the need to apply maintenance levels of P to replace that which is removed by plants and sorbed.

Although not a direct factor in the loss of P, STP values are a measure of the amount of plant available P in the soil solution, and thus provide an indication of the amount of P at risk of being lost in runoff or subsurface flow events. In New Zealand, the Olsen P test [developed by Olsen et al. (1954)] is used extensively as a way of monitoring soil quality and fertility and to assess how land use and management factors of agricultural land may be affecting the soil and surrounding environment (Taylor et al., 2016). A study done by Taylor et al. (2016) also showed a strong relationship between the Olsen P value of a soil and its potential risk of P loss, with increasing Olsen P values resulting in increasing risk of P loss. The study detailed that the risk of P loss was influenced not only by soil ASC, but both Olsen P and slope.

A study by Morton et al. (2003) documented the relationship between P loss, Olsen P, and ASC in an attempt to balance P requirements for milk production and water quality. The trial was run across 3 New Zealand soils (most commonly used for dairy) with differing ASC values and compared the dissolved reactive P (DRP) concentrations lost against the national surface water quality guidelines of 0.03 mg/L. The trial found that in low ASC Waikoikoi soils (ASC of 15%) and medium ASC Waikiwi soils (ASC of 49%) the DRP concentration in the overland flow water exceeded the guidelines when the soil had an Olsen P value of 30 and 50 mg/L, respectively. However, on the high ASC soil (Egmont Allophanic, an ASC of 83%) the DRP concentration only exceeded the surface water quality guidelines when the soil had an Olsen P value of 110 mg/L or above. These results are similar to those by McDowell et al. (2003c) who found the Waikoikoi soil exceeded the DRP limit of 0.02 mg/L when the soil had an Olsen P of 20 mg/L or above. The medium ASC Waikiwi soils exceeded the DRP limit when the soil had an Olsen P of 24 mg/L.

The loss of P from the farm system to the wider environment can result in significant damage due to eutrophication and the facilitation of algal blooms which disrupt the status quo of many freshwater environments. Not only is the loss of P damaging to the environment, it can also be very costly for farmers, as the low P use efficiency (low conversion of P into useful crop or animal product) means that more P has to be purchased and applied to replace what was lost to the environment and not utilised by the pasture or crops. While it is hard to determine the full extent of the cost of freshwater eutrophication, Dodds et al. (2009) estimated that the cost of freshwater eutrophication in the USA was approximately \$2.2 billion dollars annually. This included the estimated cost of recovering drinking water and threatened species, as well as the estimated decrease in value from water-front real estate and recreational water usage.

2.2 Phosphate fertiliser sources, uses and trends in New Zealand

New Zealand's agricultural industry relies heavily on P fertilisers, importing significant amounts of PR (predominantly for the manufacturing of superphosphate), and compound fertilisers annually to support its largely pastoral based agricultural industry (Hall, 2023). The PR imported to New Zealand are sourced predominantly from Morocco, with Morocco supplying 58% of the total P imported since 2014, followed by China (8%), South Africa (7%) and Togo (7%). The compound fertilisers are predominantly sourced from China, with China supplying 70% of all compound fertilisers imported since 2014 (Hall, 2023).

As of the 2021/2022 production season, approximately 13.2 million hectares of land was used for agricultural production in New Zealand, with pastoral grazing covering three quarters of that land, followed by the forestry, arable and horticultural sectors (McDowell et al., 2019b; Stats NZ, 2021). As such, is not surprising to find that pastoral farming in New Zealand consumes 90-92% of all fertiliser P applied (43%-55% to sheep and beef land, and 35%-45% to dairy land), with the remaining 8-10% being consumed/applied to arable, horticultural, deer and forestry land (FANZ, 2022d; Stats NZ, 2024). To show just how valuable P is to the New Zealand agricultural industry and wider economy, Journeaux (2024) undertook research looking into the effect that stopping P use (allowing soil Olsen P levels to reduce significantly below the target ranges) would have on the farm-gate operating profit of the dairy, sheep and beef, horticultural, and arable sectors in New Zealand. The research found that if soil Olsen P values were to decrease to extremely low levels of 5 mg/L through the removal of fertiliser P over an extended period of time, the farm-gate operating profit of the national agricultural industry would be reduced by \$8.0 billion, with the pastoral sector seeing the most significant reduction of \$5.9 billion (\$0.9 billion in the sheep and beef and \$5.0 billion in the dairy sector). The drop in farm-gate operating profit for the arable and horticultural sectors was estimated to be \$1.4 billion and \$0.7 billion, respectively.

With the sheep and beef sector account for a large proportion of P consumed, the sale of P in fertilisers in New Zealand is often closely related to farm profit and annual revenue, with dry stock profitability, and in particular, lamb sales, having a significant influence on the amount of P purchased (Hedley et al., 2011). Since 1991, the amount of P sold (in fertilisers) has increased 133% from 94,000 tonnes, to a record high of 219,000 tonnes in 2005 (Figure 2.2). As mentioned by Hedley et al. (2011), this increase in P sales is mirrored by an increase in lamb profitability of the 1992-2005 period, but from 2006 to 2009, a significant decrease in P fertiliser was determined (48% decrease), reflecting both the low returns experienced by sheep and beef farmers and a 700-900% increase in phosphate rock price, driven by the crash of the global stock market (Cordell et al., 2009; Cordell & White, 2011; Heckenmüller et al., 2014). From 2008/2009 to 2021/2022, the amount of P fertiliser consumed/applied has recovered slowly to an average 142,829 tonnes in the 2021/2022 season (FANZ, 2022g; Stats NZ, 2024).

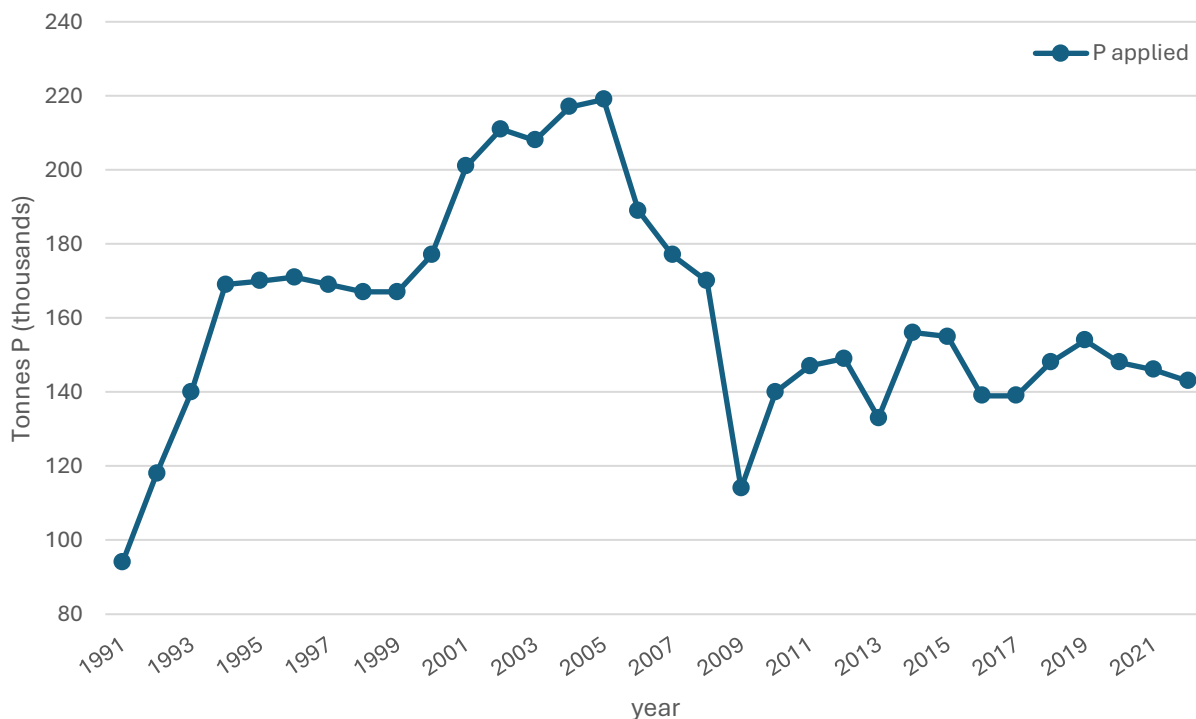


Figure 2.2: Amount of phosphorus (P) in fertiliser sold in New Zealand (000's tonnes) from 1991-2019. Adapted from (with permission): Stats NZ (2022a).

2.2.1 Phosphorus requirements in New Zealand

While it is important to understand how much P is currently being applied to the agricultural industry from fertilisers, that information does not give insight on how sustainable the P applications are in terms of meeting or exceeding the soil's maintenance P requirements.

The term “maintenance P requirement” refers to the amount of P required to sustain the current soil test values (balancing the nutrients removed by pasture and exported in crop or animal products) (McDowell et al., 2024; White et al., 2017), and changes depending on the soil type, current STP values, land type, and the type/intensity of the current land use (Morton et al., 1996). In a study of the maintenance P requirements of Northland sedimentary soils under dairy and sheep and beef production (approximately 600,000 ha), Roberts et al. (1996) estimated the required maintenance P application rates for dairy production (with a stocking rate of 2 cows per hectare) to be 22-26 kg P/ha, increasing to 52-56 kg P/ha for a stocking rate of 4 cows/ha, and for sheep and beef production to be 6-12 kg P/ha (with a stocking rate of 7 SU/ha), increasing to 21-28 kg P/ha when the stocking rate increased to 16 SU/ha. Similar maintenance requirements were reported previously by Ledgard et al. (1991), where it was found that the average

maintenance P requirements were 25 kg P/ha and 16 kg P/ha for dairy and sheep and beef, respectively, across all soil types in the Bay of Plenty region. The maintenance P requirements presented by Ledgard et al. (1991) were estimated using Ministry for Agriculture and Fisheries (MAF) fertiliser recommendation models, with the STP values sourced from 4,785 soil samples taken from across 1,527 dairy and sheep and beef farms. Although variations with stocking rates weren't reported by Ledgard et al. (1991), the maintenance P requirements estimated are similar to the 2 cows/ha and 10 SU/ha requirements estimated by Roberts et al. (1996). These studies however, only considered dairy areas that contribute a small amount to the total New Zealand dairy sector, and thus are not representative of areas that are larger in size, or higher producing. This highlights a lack of national application of these maintenance P requirement estimations to the national dairy sector. These studies also do not include P added in effluent or imported supplementary feeds, which would reduce maintenance P requirements, further highlighting the need for updated maintenance requirements that encompass the modern farm system.

The most recent estimations of the P maintenance requirements of New Zealand's agricultural industries were conducted by Hedley et al. (2011), where the maintenance P requirements of the dairy, sheep and beef, arable and vegetable sectors were estimated and combined to determine the total maintenance P requirement in the 2007/2008 season. Although the initial estimations made by Hedley et al. (2011) were calculated using a simple output calculation (i.e. kg P/kg milk solids (MS) for dairy, and kg P/stock unit (SU) for sheep and beef), when converted to kg P/ha, the estimated maintenance P for the national dairy and sheep and beef sectors were 42 kg P/ha and 12 kg P/ha respectively. The average maintenance P requirement for the dairy sector calculated by Hedley et al. (2011) of 42 kg P at a stocking rate of 2.7 cows/ha, were significantly higher than the estimates made previously by Ledgard et al. (1991) and Roberts et al. (1996). One influencing factor was the level of production per cow used in the estimates. In their estimates, Roberts et al. (1996) assumed that the average cow with a live weight of 350 kg produced an average of 290 kg MS annually, while Hedley et al. (2011) assumed that the average dairy cow produced 350 kg MS annually (2.7 cows per ha producing 1,000 kg MS/ha/yr).

On the other hand, the estimated average maintenance P requirement for the sheep and beef sector calculated by Hedley et al. (2011) of 12 kg P/ha at a stocking rate of 13.8 SU/ha, was lower than the ranges estimated by Ledgard et al. (1991) and Roberts et al. (1996), likely due to the use of low average Olsen P values (12 mg P/L). Another major difference is that the estimations developed by Ledgard et al. (1991) and Roberts et al. (1996) were based on data from soil fertility

trials, and calculated for the maintenance of a target soil Olsen range of between 20-30 mg P/L, whereas the estimates made by Hedley et al. (2011) were made using the Overseer Nutrient Budgets II modelling software, creating nationally representative farm case studies in the model. The use of Overseer Nutrient Budgets II allowed for the input of average soil Olsen P values, and the nationally averaged farm data.

However, due to the dynamic nature of the New Zealand agricultural industry, with changes in land use, farm characteristics, supplement inputs and farm management practices having a large influence on the maintenance P requirements, the estimated average maintenance P requirements reported in Hedley et al. (2011) need to be reassessed in light of current agricultural practice. Regional variation in maintenance P requirement data are also lacking, despite this information being critical to identifying opportunities to increase productivity or to improve environmental sustainability.

Current nutrient models that take into account P inputs (fertilisers, imported feed, imported effluent) and P exports (meat, milk, wool, crop harvest, and effluent) of a farm system, along with the movement of P within a farm system (forage blocks, hay and silage etc.), plant uptake and pasture production, animal pasture and feed consumption, and dung and urine outputs, as well the changes in soil nutrient pools (organic, inorganic mineral, and soil inorganic P pools), provide the best opportunity to determine the current maintenance P requirements of New Zealand's agricultural industry at both a regional and national scale.

2.3 The phosphorus cycle

An understanding of the P cycle is necessary to understand the transformations of P within the farm and within soils and is critical to developing an farm P budget. (Radcliffe & Cabrera, 2007). The main additions of P and other nutrient to the soil are from fertiliser, organic P sources (animal dung and plant organic matter transfers) and from imported feeds. Whereas the main losses of P in the soil P cycle come from surface runoff, leaching, loss to animal or plant products or transfers within a paddock (Pierzynski et al., 2005) (Figure 2.3). Along with P inputs and outputs, the internal transfers of P within the soil profile affect the soil solution P, with processes such as sorption/desorption, immobilisation/mineralisation, and precipitation/dissolution, influencing the addition or removal of P from solution (Pierzynski et al., 2005). The sorption of P is an

important soil process in the regulation of P in the soil solution, and is the dominant process controlling P movement in the soil, and P concentrations in the soil solution (Meyer et al., 2023).

Sorption is the processes by which P is removed from the soil solution (Asomaning, 2019), and is influenced by soil pH, clay and organic matter content (anion storage), iron and aluminium oxides, soil temperature and time of equilibration (Goldberg, 1989; Muindi, 2019; Wall, 2015).

When P is removed from the soil solution by plant uptake, weakly adsorbed P can desorb from the soil colloids, replenishing the soil solution (Pierzynski et al., 2005; Ruat, 2016). Absorbed P (not readily desorbed) is not plant available and remains in the soil long term, often being called 'legacy P'. This legacy P can mobilise over time, becoming plant available and a continuous source of P not only to plants but also the wider environment (Stackpoole et al., 2019).

Other soil processes such as precipitation and immobilisation/mineralisation also influence the movement of P in the soil solution, with precipitation being the result of the reaction of P with dissolved iron, aluminium, manganese, or calcium, forming non-plant available phosphate minerals (Hyland et al., 2005). The immobilisation and mineralisation of P are opposing reactions, where mineralisation is the transformation of organic P into plant-available orthophosphates via soil microbial activity (Richardson et al., 2009), whereas immobilisation is the process whereby orthophosphates are converted back into unavailable organic P forms, again by soil microbial action (Patel & Goswami, 2020). Over time, as these soil microbes die, microbial P becomes available in the soil (Hyland et al., 2005).

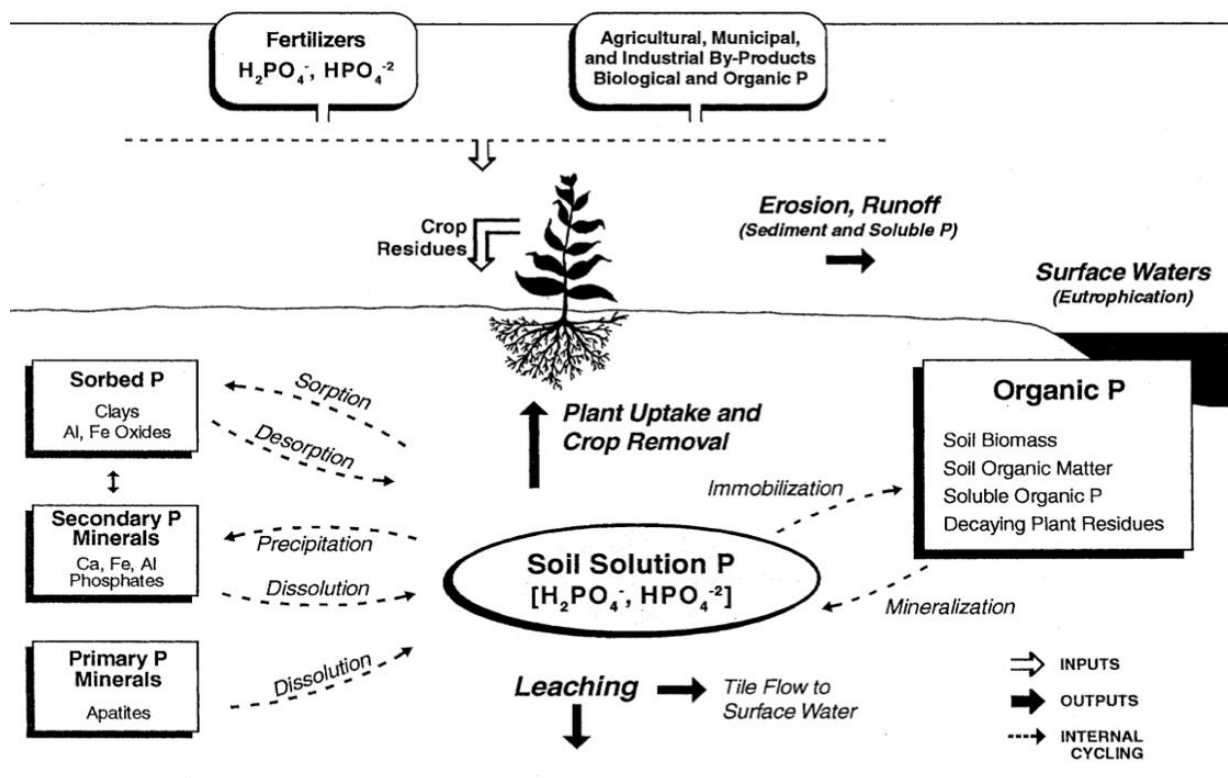


Figure 2.3. The soil phosphorus cycle. Source: Pierzynski et al. (2005).

2.4 Soil nutrient budgeting

The process of developing nutrient budgets, allows farmers, the wider industry, and regional councils to account for nutrients entering and exiting a farm system, catchment or country. Nutrient budgeting for target nutrients has been used across the world to inform and develop environmental policy (Gourley et al., 2012; OECD, 2008). Nutrient budgets have been defined as “nutrient accounting tools” used to weigh-up the nutrient inputs, sources, and outputs to and from different nutrient pools within a system, and thus predict environmental loss and fertiliser demand (Bhattacharyya et al., 2021; Gourley et al., 2007; Lyttle, 2018). Nutrient budgets are conducted based on a mass-balance method, with the aim of soil nutrient budgets being to capture all nutrient inputs and outputs of an agroecosystem (Majumdar et al., 2021).

Phosphorus budgets are used across a wide range of agricultural industries (Anderson et al., 2024; Kohmann et al., 2021; Ranger & Turpault, 1999; You et al., 2024), but tend to be most commonly used in the pastoral farming and arable industries. Nutrient budgets have become essential tools for managing farm nutrient losses in accordance with the environmental policies

developed and implemented in Europe (Goodlass et al., 2003; Hanegraaf & den Boer, 2003), the US (Koelsch, 2005) and New Zealand (Gourley et al., 2007; Lyttle, 2018).

In a survey of 'input-output accounting systems' in Europe, Goodlass et al. (2003) identified over 50 farm level accounting systems, with 26% covering N, P and K budgeting. Of the 50 accounting systems, 13 covered N and P, with only 4 systems covering P specifically. Due to the varying approaches that can be taken in developing a nutrient budget, Öborn et al. (2003) separated the soil nutrient budgets into three major types; 1. farm-gate, 2. field/soil surface balance, and 3. farm/soil system budgets.

2.4.1 Farm-gate P balance

Farm-gate budgets [also referred to as whole farm nutrient mass balances (Rugoho et al., 2018)] are the simplest and easiest to use as they utilise readily available data and can account for multiple elements. In its basic form, the budget calculates the difference between total nutrients imported and total nutrients exported from a selected area. These budgets are also easy to understand, proving them useful to farmers and policy makers alike (Öborn et al., 2003). As such, this type of budget can be conducted not only at a farm scale, but also at a catchment and/or country scale (Majumdar et al., 2021). However, a limitation of this type of budget is that they do not take into account site information (climate, soil characteristics), or internal fluxes (Öborn et al., 2003). As a result, the budgets don't often quantify environmental losses, such as leaching, runoff, volatilisation or denitrification (Gourley et al., 2007). This can result in an over estimation of the P surplus, especially for farms on high ASC soils such as the allophanic soils found in New Zealand, as a large portion of the estimated P may actually be sorbed and thus not plant available.

Using a slightly modified farm-gate budget, Gourley et al. (2011) found that of the 41 farms from across Australia studied, only 5 farms were in a net P deficit (-7 to -1 kg P/ha), with the rest of the farms measuring P surpluses ranging from 10-133 kg P/ha. The majority of the nutrient budgets used in Australia are simple farm-gate approaches, developed by a range of industry professionals (government research and extension staff, consultants and fertiliser companies) (Gourley et al., 2007). Wivstad et al. (2023) used a farm-gate approach to assess the N and P balances of arable and dairy (organic and conventional) farms in 3 Swedish counties. They found that overall, organic farms had markedly lower N and P surpluses (41 and 33%, respectively), contributed to by the use of organic P sources (compared to the synthetic fertiliser P used by the

conventional dairy system), which are not immediately plant available and require mineralisation to become plant available. Although farm-gate P nutrient budgets do not tend to quantify environmental losses of P (such as leaching and runoff), adjustments can be made in order to accommodate for these sources of P loss, as well as for changes in soil nutrient stores (Öborn et al. 2003).

2.4.2 Field/soil surface balance

A field budget focuses on the nutrients entering the soil surface and exiting via crop or pasture uptake (Einarsson, 2020). As depicted by Gourley et al. (2007), the field budget differs from the farm-gate budgets by including nutrients brought in with seeds, excluding animals, feed, and bedding, and connecting nutrient distribution within a system to the outputs and losses. These budgets are often used for cropping systems but have been used in grazed systems as well (Messiga et al., 2015). These budgets allow for any addition or depletion of nutrient from the soil pools to be accounted for, however there is the risk of double accounting if extrapolated to a larger scale. Öborn et al. (2003) outlined that it can be difficult to obtain relevant, site and year specific data needed for the nutrient loss calculations, with significant assumptions having to be drawn about leaching losses and transport mechanisms. Using a soil surface budgeting software called P-FLUX, Williams et al. (2022) calculated P budgets for 61 crop production systems across 22 American states and 2 Canadian provinces. It was found that overall, P inputs exceeded outputs/losses, resulting in a median P surplus of 3.2 kg P/ha/yr (with a range from -32.7 to 340.6 kg P/ha/yr).

This type of budget can be scale up to a national scale, provided that all the necessary data are available. Using a modified field budget, Panagos et al. (2022) assessed the P budget of topsoil in the European union (EU) and United Kingdom (UK). Phosphorus inputs consisted of inorganic fertilisers, manure, atmospheric deposition and chemical weathering, while outputs consisted of crop harvest, crop residue removal and losses via erosion. They estimated that across the EU and UK, the topsoil had an average P surplus of 0.8 kg P/ha/yr, with an average P input of 16 ± 2 kg P/ha/yr. This surplus varied significantly between countries (as well as some regional variation), with 11 countries having a mean P surplus greater than 4 kg P/ha/yr, whereas 9 countries had P deficits of greater than -3 kg P/ha/yr. The importance of considering internal and external nutrient flows was highlighted by Bučienė et al. (2003), as the farm-gate budget showed a P surplus of 3 kg P/ha, whereas the field budget showed a P deficit of 10 kg P/ha due to incorporation of the harvest crop removal, resulting in greater P outputs.

2.4.3 Farm system balance

A farm system budget builds on the field/soil surface and farm-gate budgets, attempting to capture all the nutrient movements in and out of a system. (Öborn et al., 2003; Oenema et al., 2003). This includes capturing all inputs (fertiliser, purchased feed, bedding materials, applied manure, seed, irrigation, and precipitation) and outputs (meat, milk, wool, exported manure, crops, hay and silage harvest and residual removal), as well as the transformations of nutrients within a system (pasture and crops eaten and excreted manure), changes to soil nutrient pools via mineralisation, immobilisation, sorption processes and denitrification (Pierzynski et al., 2005), and nutrient losses (Gourley et al., 2007). This type of budget requires a high level of input data, and is often used by researchers as it allows for the partitioning of nutrients (particularly P) into the different soil pools, such as P sorption, plant available P and organic P (Oenema et al., 2003). This approach is difficult as it relies on a comprehensive understanding of the soil/agricultural system and requires extensive research data on P cycling and P loss processes to model these systems accurately. Internationally, there are no standardized approaches to modelling the P budget, with many different approaches used around the world (Öborn et al., 2003).

2.5 Constructing a P budget

In its simplest form, a P budget = Inputs – Outputs (Einarsson, 2020), however, the scale and purpose of the budget heavily influences the way the budget is constructed. Farm-gate/mass-balance budgets do not tend to capture environmental P losses (runoff, accumulation in soil and erosion losses), nor do they provide detail on P transfer via manure, and P sorption and desorption from the plant available nutrient pool (Table 2.1).

Table 2.1. P inputs, outputs, losses, and internal flow pathways considered in farm-gate, field/soil surface, and farm system budgets, as described by Oenema et al., (2003) and Gourley et al., (2007)

Farm - gate Input	Field/soil surface* Input	Farm System* Input
Feed	Seed	Feed
Animals	Fertiliser	Animals
Bedding	Irrigation	Bedding
Fertiliser	Precipitation	Seed
Irrigation	Manure	Fertiliser
Precipitation		Irrigation
Manure		Precipitation
		Manure
Outputs	Outputs	Outputs
Milk, meat, wool	Milk, meat, wool	Milk, meat., wool
Manure	Crops, silage, hay	Manure
Crops, silage, hay		Crops, silage, hay
Irrigation		Irrigation
Losses	Losses	Losses
	Leaching	Leaching
	Accumulation in soil	Accumulation in soil
	Gaseous	Gaseous
	Runoff	Runoff

*Internal flow paths considered in these budgets are the transfer of nutrients from pasture and crops to the grazing animal, nutrients excreted by grazing animals within a paddock or farm (not exported), and the release of nutrients into the soil via the breakdown of manure or retained crop residual.

Phosphorus inputs include fertiliser applications, manure, imported feeds and natural additions from rainwater and irrigation. Outputs include P removed from crop harvest and crop exported off farm, P removed in livestock production (meat, milk, and wool), and exported manure (Gourley et al., 2007). Internal transfers and storage of P via sorption and desorption processes are important to consider, as they influence the environmental losses of P via runoff and erosion. Loss of P via leaching is not a common occurrence in New Zealand, however, P leaching has been reported, with P leaching being greater in coarser soils with greater macroporosity (thus preferential flow) (Gray et al., 2024). For housed animal systems (for both year-round, and seasonal systems) it is also important to consider the bedding materials used in the herd home. In New Zealand, livestock housing is used predominantly in winter, as such, bedding materials contribution is dependent on the size of the barn and the number of cows housed (Chrystal et al., 2016).

2.6 Phosphorus budgeting in New Zealand

Nutrient budgeting is commonly used in New Zealand for individual commercial farms, particularly for intensive dairy, but less so for the extensive sheep and beef sector. Simpler farm-gate nutrient budgets have been presented in the past for extensive high country (class 1) sheep and beef farms by Jarvis et al. (2002), where data collected from 30 South Island high country farms (from 1968/69 to 1995)/96) were used to generate historical P budgets, and for dairy farms by O'Connor et al. (1996), where P input and P output data were collected for two Waikato dairy farms from 1992 to 1995, to generate a P budget calculated as:

$$P \text{ balance} = P \text{ input} - P \text{ output}$$

P budgets using an early version of Overseer were developed for 5-21 dairy and 5-9 sheep and beef farms in three mixed farm catchments in New Zealand by Power et al. (2002), which presented slightly more detailed P budgets, accounting for P loss via leaching/runoff and immobilisation/absorption. However, there has been no attempt to calculate P balances for these industries in a way which can be aggregated to a national scale, or to allow estimates for the overall national agricultural P balance.

2.6.1 Overseer

Overseer is a modelling software used extensively in New Zealand, often to meet national and regional regulatory requirements (Gray et al., 2016b; Wheeler et al., 2003). Despite being a farm-system budgeting model, the Overseer model uses farm-level data inputs that are readily available to the farmer (farm soil tests, herd size, production levels, etc.), to develop detailed nutrient budgets and maintenance requirements for a range of farm systems. The nutrient budget model takes into account three main processes, nutrient inputs (addition of fertiliser, effluent, and/ or supplements), nutrient outputs (nutrient removal as products, leaching, runoff and volatilisation), and internal transfers (immobilisation, mineralisation, adsorption, weathering or changes in pool sizes) (Wheeler, 2022).

The Overseer model uses physical farm data (farm area, livestock numbers/stocking rate, area used for crop/forage/silage production, types of crops grown etc.) along with nutrient input and output data (fertiliser, imported feeds, imported effluent, meat, milk, wool, exported effluent, and exported crops), to develop nutrient budgets and maintenance requirements for eight key

nutrients (N, P, potassium (K), sulphur (S), calcium (Ca), magnesium (Mg), sodium (Na) and soil acidity (pH) (Wheeler, 2022). According to Wheeler (2013), the Overseer P budget model is based on a range of sub-models, with the aim of capturing the key drivers of the biophysical and management processes on farm. The nutrient budgets are conducted assuming a 'quasi-equilibrium' status, where Overseer assumes that the inputs and site characteristics are in equilibrium with farm production (Wheeler, 2013; Wheeler, 2022). The Overseer model is split into two parts, with the first part defining the sources of nutrients and the method and destination of nutrient movement within a farm, based on input data from the user. The second part is the function of the nutrient sub-models, which define the processes of nutrient loss (runoff/leaching, atmospheric), or changes in forms (splitting nutrients excreted into dung and urine sources) (Wheeler, 2013). The nutrient budget sub-model focused on in the current research is the P loss sub-model, as it determines the loss of P via runoff and leaching, as well as the partitioning of P to the soil pools (Wheeler, 2022), which in turn provides an estimate of the P balance of a farm system.

The P loss sub-model

The P-loss sub-model was originally created nearly two decades ago, with the core model accounting for most of the loss pathways from pastoral agriculture. However, some agricultural systems were not included due to lack of data (Gray et al., 2016b). With improved data availability, several changes and additions have been made to the Overseer model to more widely model agricultural P loss. The original P loss sub-model was derived from the Metherell (1994) Immobilisation model, with the McDowell et al. (2005) model more recently included to more accurately account for P loss via leaching/runoff. This model further incorporates the methods described by Rajendram et al. (2003) for the adjustment of Olsen P to a weight basis, as the Olsen P measured by analytical laboratories is done on a volume basis, and utilises the findings of (Roberts & Edmeades, 1993) to inform the change in soil test values (the amount of P required to raise the Olsen P by 1 unit).

The P loss sub-model separates P loss into two types 1. background (soil) P loss (which is estimated as the sum of the TP losses from the soil as influenced by different transport and management factors) and, 2. incidental (fertiliser) P loss (which rely on the same transport factors as background losses, with the addition of management factors). Along with incidental P loss from fertiliser application, incidental P loss from effluent application is also included as the

risk of P loss from land application can be high on soils that are susceptible to preferential flow, either due to their coarse texture, or the addition of artificial drainage.

Runoff, which is the dominant source of P loss across most of New Zealand's soils is calculated in the P sub-model using the following equation:

$$NBrunoff_p = SoilPloss + FertPloss + EffPloss$$

Where:

SoilPloss is the background P loss (kg P/ha/year)

FertPloss is the incidental fertiliser P loss (kg P/ha/year)

EffPloss is the incidental effluent P loss (kg P/ha/year)

Further equations account for important factors such as livestock behaviour, dissolved P and particulate P concentrations, topography and runoff propensity, P loss due to soluble and rock fertilisers, and P loss from liquid and solid dairy farm effluent, and pig effluent. More details of the P model can be found in the Overseer technical manual (Wheeler, 2022).

Within the P loss equations, there are specific factors such as high-risk months, slope, Olsen P, and soil type, which significantly influence the P loss from the soil. High-risk months are classified as those where the potential for saturation is greater than 60% of the available water balance (Wheeler, 2022). In New Zealand, these high-risk months tend to fall between April to October, varying slightly in each region. If fertiliser is applied during these months, P loss is elevated. Slope is compulsory user input and is modelled in overseer with a determined slopePlossfactor for each of the topography classes. The loss risk factors are 0.15 for Flat, 0.5 for rolling, 0.75 for easy hill, and 1.0 for steep hill topographies (McDowell et al., 2005).

Soil type and the corresponding ASC also influences P loss in conjunction with topography. When entering the soil type, Overseer allows for the 3 most dominant soil types to be entered and the percentage of the area they cover. Along with the soil type, the soil ASC can be specified if farm soil test data is available, allowing for the most accurate P loss calculations. If soil P data is not available, then the default values are used.

2.6.2 Maintenance P requirements

The calculation of maintenance P requirements was included in the Overseer model so that farmers could know how much fertiliser they would need in order to maintain production under the current soil test levels and farm management practices. The estimation of maintenance requirements takes into consideration whole farm management, livestock behaviour (campsites), and current soil test levels (Pers. comms Overseer Science Team, 2025; Wheeler, 2022).

Although there are no regulated P loss limitations (like there are for N loss) in New Zealand, the Overseer model has several functions alerting users to changes in soil test levels and elevated nutrient loss. One indicator provided by the Overseer model is P maintenance requirements. Phosphorus maintenance requirements is the estimated amount of P needed to maintain a constant soil test P value, taking in to account P losses (Roberts & Morton, 2023). The maintenance P requirement of a block or area on the farm is influenced by effluent application, the import or supplementary feed, feed harvesting and STP values. An increase in the amount of effluent applied, the amount of supplementary feed imported and the soil Olsen P values would result in a decrease in maintenance P estimations as effluent and supplementary feed are sources of P to the block, and decreased Olsen P values means a lower concentration of P is required to be maintained in the soil solution. However, an increase in silage/hay harvested, can result in increased maintenance estimations, as a greater amount of P is being removed from the soil via the harvested pasture.

Using the estimated maintenance P requirements, in conjunction with the nutrient budgets, the Overseer P model is able to advise users on the possible outcomes of the current management practices. Using the findings of Roberts and Edmeades (1993) (Table 2.2), the model is able to estimate if and by how much the current management may affect soil Olsen P values, and warn of the risk of P loss from certain soils or blocks on the farm.

Table 2.2. Amount of capital P fertiliser required to raise the soil Olsen P by one unit, separated into the range of application and average application.

Soil	Range of application rates required to raise Olsen P by 1 unit (kg P/ha)	Average application rate required to raise Olsen P by 1 unit (kg P/ha)
Ash	7-18	11
Pumice	4-15	7
Sedimentary	4-7	5
Peat	6-9	-

Source: (Roberts & Morton, 2023)

There are however some limitations with the Overseer nutrient budgeting model. One limitation is the possible underestimation of P losses to the environment, due a number of best management practices assumed to be applied to all Overseer simulations (Wheeler, 2013). This means that if best management practices aren't followed on farm, the P loss will be higher than what is estimated by Overseer. Overseer is also limited by the fact that it does not account for P loss from very large storms, nor can it account for P loss associated with physical damage caused by livestock (McDowell, 2013). This means that when it comes to modelling P loss mitigations, there are a range of mitigation strategies (that may well reduce P loss from farm), which cannot be modelled in Overseer and so their effectiveness cannot be estimated. A further limitation of Overseer and the P loss model is its application to arable and horticultural industries. Due to the complex nature of these systems, they can be difficult and time consuming to model, with confidence in the P budget outputs decreasing with increasing farm complexity (Mathers, 2016).

2.6.3 Summary and research gaps

This review outlines the importance of demand, input, and output data for the estimation of maintenance P requirements, and the difficulty in obtaining such data at a large scale. As such, the usefulness of different types of nutrient budgeting models (which supply differing levels of information to the end user) is highlighted, with specific attention drawn to the usefulness of the Overseer Nutrient budgeting model for New Zealand agricultural systems.

The Overseer nutrient budgeting model is the only model in New Zealand that is able to estimate P maintenance requirements for pastoral farming, and farm-system level P budgets for pastoral production and arable and horticultural farming. However, due to complexity and dynamic nature of arable and horticultural systems, the use of Overseer is limited. This review has highlighted the lack of current estimates of maintenance P requirements for the key agricultural sectors, as past estimates of maintenance are no longer comparable to current production levels. The review has also shown a dearth of industry and national scale P balances. This lack of P balance data means that we cannot benchmark our P management between industries and regions within New Zealand or internationally and therefore are unable to measure New Zealand's performance in terms of P management. International research has shown that agricultural P balances associated with intensive pastoral systems are generally highly positive (Gourley et al., 2012; Parfitt et al., 2008; Power et al., 2002; Sattari et al., 2016) and so it is critical that these balances are determined for New Zealand agricultural systems, to inform the sustainability of future P management. Given the range in soil types, topographies and climates across New Zealand, the calculation of P maintenance values and P balances at a regional scale is also needed to assess economic productivity and environmental risk.

2.6.4 Objectives

The objectives of this Masters thesis are to:

1. To use industry and government data to estimate the P maintenance requirements of agricultural systems both at a regional and national scale,
2. To use industry and government data to determine the overall P balance of agricultural systems both at a regional and national scale,
3. To use P maintenance, P balance and soil test data to estimate the likely future requirements for P fertiliser in New Zealand.

Chapter 3 Methods

3.0 Introduction

To analyse the soil phosphorus (P) maintenance requirements of New Zealand's major agricultural systems, farm typologies were developed, utilising similar frameworks to those described and used by Monaghan et al. (2021) and McDowell et al., (2020) for the sheep and beef and dairy industries, respectively. The nutrient budgets for sectors examined in the current study were prepared using the Overseer Nutrient Budgeting Software (v6.5.9) (Gray et al., 2016a; Wheeler, 2022), and were modelled at a regional level using representative regional farm case studies. The regional representative case studies were then aggregated up to a national level. The arable and horticultural industries were also included in this investigation, however their nutrient budgets were determined using a simpler farm gate nutrient budgeting approach similar to that used by Hedley et al. (2011), due to lack of information available to allowing modelling with Overseer.

3.1 Overseer – Phosphorus budget model

Overseer calculates nutrient budgets for eight key nutrients [N, P, K, S, Ca, Mg, Na, and pH], with the inputs, outputs and internal transfers being considered for these nutrients (Wheeler, 2022). The P model in Overseer is based on previous New Zealand research (Wheeler, 2022), with the slow release, immobilisation, plant P and relative yield aspects of the model based on the work of Metherell (1994) and the P leaching and runoff model based on research by McDowell et al. (2005). The current model also incorporates the methods described by (Rajendram et al., 2003) for the adjustment of the measure of Olsen P from a volumetric basis to a weight basis.

Using the budget model, changes in the soil nutrient pools can be assessed, and are calculated using the following equations:

- Change in Organic Pool = Immobilisation – Mineralisation
- Change in Inorganic Mineral Pool = Adsorption + Lime Dissolution – Slow Release
- Change in Inorganic Soil Pool (Plant Available Pool) = Sum (Inputs) – Sum (Outputs)

Where:

- Inputs = Fertiliser + Rain Nutrient + Irrigation + Nitrogen Fixation + Slow Release + Effluent + Supplement Added.

- Outputs = Product Out + Supplement Removed + Ammonia Volatilisation + Denitrification + Leaching + Surface Runoff + Artificial Drainage + Immobilisation + Adsorption + Lime Dissolution + Transfer from and to Structures.

3.1.1 P loss Sub-model

The P loss sub-model is used to calculate P Runoff, Immobilisation, and Adsorption values used in the Change in Inorganic Soil Pool using the following equations:

- $\text{Runoff} = \text{SoilPloss} + \text{FertPloss} + \text{EffPloss}$
- $\text{Adsorption} = \text{Plabile} * \text{SoilPloss} * 0.75 * \text{ASC}/100$
- $\text{Immobilisation} = \text{Plabile} * \text{Ploss}_{\text{soil}} - \text{Adsorption} - \text{Leaching}$

Where:

- SoilPloss is the background P loss (kg P/ha/year)
- FertPloss is the incidental fertiliser P loss (kg P/ha/year)
- EffPloss is the incidental effluent P loss (kg P/ha/year)
- PLabile: calculated based on entered Olsen P and soil Order
- $\text{Ploss}_{\text{soil}}$: P loss factor (kg P/(kg P/year)) value, dependent on soil order.
- Leaching: A function of soil hydrological drainage class (determined by soil texture and order) and reported with runoff losses as runoff losses.

3.1.2 Modelling of maintenance phosphorus requirements

The maintenance P requirements of a block is tied to the change in Inorganic Soil Pool, as the maintenance calculations aim to balance the P inputs with outputs, in order to maintain the soil labile P pool at a constant level (Pers. comms Overseer Science Team, 2025). As such, changes to Olsen P have the largest impact on soil maintenance P requirements in Overseer. The soil order also affects the soil maintenance P requirements, as it is a key factor in the Adsorption and Immobilisation calculations, influencing the ASC and P loss factor.

3.2 Sector case studies

3.2.1 Dairy

According to the Livestock Improvement Corporation Ltd (LIC) (2022) and Stats NZ (2021), the dairy sector covers 2.3 million ha (17 % of New Zealand's agricultural land) and in the 2021/2022

season, produced 1.9 billion kg milk solids. The FANZ (2022g) reports that the dairy sector uses 49% of the countries elemental P (in fertiliser), with superphosphate being the industries predominant form of P fertiliser in 2021/22 (48% of the industries total P) (Stats NZ, 2024). The North Island is home to 71% of the countries milking herds and 58% of all cows milked, with the greatest concentration of herds found in the Waikato (28%), and the Taranaki (14%) regions. The South Island is home to 29% of the national milking herds, but contained 48% of the total number of cows milked in the 2021/2022 season. The North Canterbury and Southland regions are home to the highest number of cows with 15% and 12% respectively, of the national herd found in these regions (LIC, 2022).

3.2.2 Sheep and Beef

With 25.3 million sheep and 3.9 million cattle (B+LNZ, 2023a) utilising 8.3 million ha (63% of New Zealand's agricultural land), predominantly in the hill, hard hill, and steep-land areas of New Zealand (Stats NZ, 2024), the sheep and beef sector uses 43% of the countries elemental P (in fertiliser) to support production (FANZ, 2022g). Similarly to the dairy sector, superphosphate is the predominant form of P fertiliser used on sheep and beef farms (58%) (Stats NZ, 2024). Sheep and beef farming is split fairly evenly across New Zealand, with 54% of farms located in the North Island, and 46% in the South Island (B+LNZ, 2023a).

3.2.3 Arable and horticulture

The arable and horticultural sectors cover 227,594 ha and 126,803 ha of New Zealand's agricultural land, respectively. These two industries, along with the forestry and deer sectors, utilise the remaining 8% of elemental P (in fertiliser) applied in New Zealand. Horticulture in New Zealand is found predominantly in the Bay of Plenty, Hawkes Bay, Marlborough and Otago regions (New Zealand Apple & Pears, 2023; NZ Winegrowers, 2023; Stats NZ, 2024; Zespri International, 2023), with 62% of the total pip fruit and 81% of kiwifruit production located in the Hawke's Bay, 71% of wine production found in the Marlborough region and 63% of stone fruit produced in the Otago region

Arable farming in New Zealand occurs predominantly in the Canterbury region, where 78% of the total wheat, 60% of barley, 71% of peas, and 96% of herbage seeds are produced in this region (Stats NZ, 2024). Oats and maize are also dominant crops in New Zealand's arable sector, with 38% of the total oats and 20% of maize production found in the Southland and Manawatū/Whanganui regions, respectively.

3.2.4 Summary

Given that dairy and beef and sheep sectors are the largest users of P fertiliser in NZ, this research focussed on developing detailed and representative P budget case studies using data from DairyNZ's Dairybase/Baseline dataset, Beef and Lamb NZ, Stats NZ, Fertiliser Association of New Zealand and Overseer. A more rudimentary national level case study analysis was undertaken for the arable and horticultural industries because the availability of P use and cycling data for these industries was very limited.

3.3 2021/22 production season

The 2021/22 season was selected for the case study analysis as this season contained the most comprehensive data for the dairy and sheep and beef industries. The Dairybase/Baseline information utilised for the dairy sector contained data from 2012/13 to 2021/22 on P fertiliser application, summer and winter cropping block area, total supplementary feed use and types of imported feed used. The Dairybase 2021/2022 season data provided detailed information on the types of supplementary feeds imported, the amount of imported feeds fed, as well as valuable fertiliser application data that were not available in more recent data sets. This information allowed for more accurate analysis of P inputs and exports in the P budget, and a more accurate reflection of the maintenance requirements and P balance when modelled in Overseer. As such, 2021/2022 season data for all other dairy inputs, as well as for sheep and beef, arable and horticultural sector data was selected, to achieve consistent data and to allow a more accurate national P budget comparison.

3.4 Data sources

3.4.1 Dairybase/Baseline

Permission to use and analyse Dairybase/Baseline (further referred to as Dairybase) data has been provided by DairyNZ (contract No. 2023-6044A). Dairybase is a data collection initiative, owned and funded by DairyNZ, in which dairy farmers can voluntarily participate. Dairybase collects physical, financial, and environmental farm data annually. Baseline is an extension of Dairybase, collecting data beyond fertiliser and feed use and therefore less farmers tend to contribute to this survey. These data are then used for benchmarking, research, and development to benefit the dairy sector (Macintosh et al., 2025). A potential limitation of the

Dairybase dataset is its voluntary nature and representativeness of the whole dairy sector. The number of farmers participating in the surveys has increased overtime, increasing from 1,783 in 2013 to 1,860 in 2022 and from 137 in 2013 to 378 in 2022 for Dairybase and Baseline respectively (Macintosh et al., 2025). In a recent study, Macintosh et al. (2025) found that the Baseline data from 2013-2022 represents on average, 2.2, 2.8 and 3.1% of the national dairy herd, milk solids production, and productive dairy land area respectively. For the 2021/22 season specifically, the baseline data represents 3.5, 4.6, and 5.3% of the national statistics for the same categories.

3.4.2 New Zealand Dairy Statistics

The New Zealand Dairy Statistics [an annual census conducted by DairyNZ and the Livestock Improvement Corporation Ltd (LIC)] is a census of the national dairy herd and provides the most comprehensive range of data and statistical analysis on dairying herds in New Zealand (LIC, 2025), including physical farm data (total effective area and total herd and cow numbers, as well as regional averages) and farm production data (total milk solids produced and regional averages per herd, per cow and per effective hectare). The annual report is compiled using data collected from 100% of dairy farms across New Zealand, including data collected directly from dairy companies, the LIC Herd Improvement database and other dairy related data sources (LIC, 2025). Despite its thorough coverage of New Zealand dairy farms, the data collected in this data base is limited and mainly focussed on farm production (i.e. milk solids production annually, per cow and per effective hectare), and farm breeding and the genetic value of the current national dairy herd. This means that some data, necessary for the development of maintenance P estimates and P budgets (i.e. fertiliser application, imported feeds, types of imported feeds, forage crop area etc.) could not be obtained from the this dataset, and were obtained from the other databases/datasets previously mentioned.

3.4.3 Comparison between Dairybase and LIC data

The Dairybase data is representative of a small proportion of production data, with approximately 20% of New Zealand's dairy farmers contributing to the Dairybase/baseline survey in the 2021/22 season (DairyNZ, 2024). The farms in the 2021/22 survey also only cover 22% of the total effective dairying hectares and 25% of the total milk solids (kg MS) produced that season (Table A.1).

Due to the voluntary nature of the Dairybase data, it was necessary to compare the Dairybase farm production data to the LIC production data to assess its representativeness and suitability for the current research. When comparing the Dairybase and LIC per hectare production, the

Dairybase farms on average produce 7% more kg milk solids per hectare, along with having more effective hectares and a greater stocking rate in each production region (Table A.2). The higher milk solids production suggests elevated imported supplementary feed inputs, which could introduce a significant amount of P into the farm system, influencing the soil P maintenance requirements.

In order to assess this effect on soil P maintenance, two representative farms were modelled for the 'Waikato + Bay of Plenty' region, one farm modelled using averaged Dairybase data and the other using LIC Dairy statistics data and adjusted Dairybase data. The Waikato + Bay of Plenty region was chosen for the comparison as this region has the highest number of herds, and the most effective hectares in both Dairybase and LIC. The Dairybase farm was modelled using farm data, including peak cows milked, effective area (for milking platform, forage crops and hay/silage), net tonnes supplementary feed imported, fertiliser application rates, annual total milk solids produced, and replacement numbers all found in Dairybase. The LIC farm was modelled using the LIC annual dairy statistics for herd size, total effective area, and total average milk solids. Since supplementary feed is not reported in the LIC data, supplementary feed data from Dairybase was calculated on a kg DM per cow basis and applied to the LIC herd size. The fertiliser application rates per hectare reported in Dairybase were used as is, due to a lack of alternative data at the regional level.

With the increased supplementary feeds imported by the Dairybase farms, the weighted average farm P maintenance requirement of the 'Dairybase' farm was slightly lower (40.4 kg P/ha) than the 'LIC' farm's weighted average P maintenance requirements (42.5 kg P/ha) (Table 3.1). When each of the maintenance requirements were applied to the total effective dairy hectares in the Waikato + Bay of Plenty region, the difference in P requirements was exacerbated, resulting in a difference in maintenance P requirement of 1.19 million kg P. To ensure the accuracy of the fertiliser data accessed from Dairybase, the per hectare P fertiliser application rates reported by Dairybase were multiplied out to the total effective hectares per region and totalled to calculate a total P applied nationally of approximately 48,000 tonnes. This is approximately 3,000 tonnes more than the 45,000 tonnes estimated by StatsNZ, however it is acknowledged that the StatsNZ estimation assumes a P content of 13% for the unspecified fertiliser category, and as such, may underestimate the total amount of P fertiliser applied to the dairy sector. Although P fertiliser applied does not affect the Overseer derived maintenance requirements, it does affect the P loss and the overall farm P budget.

Because of the large difference in maintenance P requirements at the regional level between the two data sources, the LIC (2022) data was used to develop the dairy case studies, in combination with Dairybase feed data (adjusted), and fertiliser data (unadjusted), to avoid underestimating the national maintenance P requirements of the dairy sector.

Table 3.1. Comparison of block level and weighted average whole farm P maintenance requirements between a case study using only Dairybase data, and a case study using LIC herd numbers, total effective area and total average milk solids data and adjusted supplementary feed data and fertiliser data from Dairybase, for the Waikato + Bay of Plenty region, for the 2021/2022 season.

Waikato + Bay of Plenty	Dairybase case study	LIC case study
Area (ha)		
Farm effective area	180	170
Effluent area	29	24
Non-effluent	79	75
Silage block	72	72
Support block	67	60
Block maintenance requirements (kg P/ha)		
Effluent area	0	0
Non-effluent	29	30
Silage block	45	48
Support block	26	26
Total block P requirements (kg P)		
Effluent	0	0
Non-effluent	2,303	2,235
Silage block	3,218	34,32
Support block	1,739	1,555
Total farm P requirement	7,260	7,222
Total regional P requirement (kg P)	22,300,861	23,490,051
Regional effective dairy area (ha)	552,952	552,952
Weighted whole farm maintenance requirements (kg P/ha)		
	40	43

Source: with permission Dairybase (2024) and LIC (2022).

3.4.4 Beef and Lamb NZ

Beef and Lamb NZ (further referred to as B+LNZ) is an industry organisation representing New Zealand's sheep and beef farmers (Beef & Lamb NZ, 2024). B+LNZ provides essential benchmarking data, economic reports, sector production reports and export statistics.

In order to estimate the number of sheep and beef farms across New Zealand, B+LNZ uses the StatsNZ Agricultural Production Census data (with non-commercial farm information removed, such as prisons, universities, and government owned farms etc.). From the latest census data, it is estimated that there are 9,165 sheep and beef farms across New Zealand, with 54% located in the North Island (23% located in Northland, Waikato and the Bay of Plenty). The benchmarking data, which has been used as the basis for the sheep and beef case studies in this research, were collected from 510 randomly selected farms from across New Zealand (6% of New Zealand's sheep and beef farms). The censuses were used to generate these benchmarking data, with the farms randomly selected after being stratified by geographical region and stock units (B+LNZ, 2022). These data are considered the most robust and representative data on sheep and beef production available in New Zealand.

3.4.5 Stats NZ

Stats NZ is a government department that collects data from people and organisations across New Zealand via surveys and censuses. It is required by law to take part in the surveys and censuses sent out by Stats NZ. The data collected by Stats NZ is reported anonymously, at district, regional, and national levels, as well as on a sector basis. The P fertiliser used and area under production information has been taken from the Agricultural production statistics: Year to June 2022 (final) Agricultural and horticultural land use and Fertilisers - N and P datasets (Stats NZ, 2021, 2022a, 2024).

3.4.6 Fertiliser Association of New Zealand

Soil Olsen P data were obtained from 103,006 soil samples across all agricultural sectors for the 2021/2022 season, provided by the Fertiliser Association of New Zealand (FANZ). The Olsen P values obtained from this data set for the dairy and sheep and beef industries were regional values, aggregated to match the production regions identified in Table 3.2, whereas the arable and horticultural Olsen P values were presented as national values.

3.4.7 Overseer

Selected data were sourced from the national Overseer database (Overseer data were extracted on 10/03/2025 from Overseer version 6.5.9) by accessing anonymised farm data entered by farmers using the Overseer software, to obtain key rainfall (mm) and air temperature (°C) data. These data were collected from the Overseer national data base for the period 2021-2022. Duplicate farms (farms with files for multiple years) were excluded so that only the most recent year-end file was used. The data were filtered to select for dairy or sheep and beef farms, and the respective production regions for each sector, so that the average annual rainfall and average annual air temperature could be determined for the dairy and sheep and beef sectors and their respective production regions. Climate and rainfall data cannot be overridden in the establishment of Overseer case studies, so the data collected from the Overseer Science team was used to ensure the case study farms for each region (within the dairy and sheep and beef sectors) were mapped in an area with rainfall and air temperatures as close to the 'real-farm' data as possible. This was an important step as rainfall has significant influence on P loss.

3.5 Data used in P budget model

The data used for this study were based on the data input requirements of the Overseer nutrient budgeting model and are similar to those used by Hedley et al. (2011). The model requires in-depth data on farm soil order, texture and anion storage capacity, climate, all forms of P inputs (i.e. fertiliser, irrigation and imported feed), major nutrient transfers on farm (i.e. effluent application and grazing management) and all nutrient outputs (meat, milk and wool production, crop harvest, and export of hay or silage) (Wheeler et al., 2006). Further information also necessary for the P budget, and to inform the soil maintenance requirements, included the number of animals (average herd size for dairy and number of stock units used for sheep and beef cattle), crop rotation (summer and winter fodder crops) and farm structures (feed pads, type of effluent storage, wintering barns, etc).

3.5.1 Farm scenario regions

Due to the different landscapes that the dairy and sheep and beef industries occupy across New Zealand (dairy on predominantly flat- gently rolling land (Carr et al., 2024), sheep and beef on predominantly rolling to steep hill country (Morris & Hickson, 2016)) and the distribution of these industries across the country, these two industries have been modelled differently (Table 3.2).

The dairy regions were selected to best represent the regions used by Dairybase (2024) and LIC (2022), grouping regions with similar soils and production levels.

The sheep and beef case studies were based on pre-existing farm classes and survey regions used in the B+LNZ Bench marking report and economic service (B+LNZ, 2022, 2025c), which use eight farm production classes and five production regions, to represent the varying topography, soil fertility, and climate that occurs across the New Zealand sheep and beef farming areas. Table 3.3 provides a description of each farm class and an estimate of the number of farms in each class, and Table 3.4 presents the sheep and beef production regions, the production classes present and the number of farms in each production class and production region. This classification resulted in a total of 15 sheep and beef farming case studies across New Zealand, which have been modelled in Overseer.

Table 3.2. Farming regions selected to represent the key soils, climates and characteristics of New Zealand dairy and sheep and beef farm systems.

Dairy regions	Sheep and beef regions
Northland + Auckland	Northland+ Waikato + Bay of Plenty
Waikato + Bay of Plenty (including the Central Plateau and Western Uplands)	Taranaki + Manawatū
Taranaki	Gisborne + Hawkes Bay + Wairarapa
East Coast + Lower North Island	Marlborough + Canterbury
Westcoast + Marlborough	Otago + Southland
Canterbury	
Otago + Southland	

Table 3.3. Sheep and beef farm class descriptions and estimated number of farms in each class.

B+LNZ Farm class	Description	Estimated No. of farms in NZ
1 South Island High country	Extensive. Run at high altitudes, mix of operations (breeding sheep, fine wool, breeding cows and deer). Stocking rate up to 3 SU/ha.	200
2 South Island Hill country	Traditionally produce store stock, prime stock produced in good seasons. Stocking rate 2-7 SU/ha with significant proportion of beef cattle.	620
3 North Island Hard hill country	Steep hill or low fertility soils, producing store stock. Stocking rate 6-10 SU/ha.	920
4 North Island Hill country	Easier hill and higher fertility than class 3. High proportion of stock sold in forward store or prime condition. Stocking rate 7-13 SU/ha.	3055
5 North Island finishing	Easy contour land with high production potential. Large proportion of stock sent to slaughter with replacements typically brought in. Stocking rate 8-15 SU/ha.	1045
6 South Island Finishing breeding	Breeding/trading finishing stock, with proportion of stock sold as store. Cash cropping may also be done. Stocking rate 6-11 SU/ha on dryland farms, over 12 SU/ha on wetter or irrigated farms.	1820
7 South Island finishing	High producing grassland farms. Some cash cropping done. Stocking rate 9-14 SU/ha.	1040
8 South Island Mixed finishing	Highly productive land. High proportion of revenue from grain and small seed production. Some grazing and stock finishing.	465

Source: B+LNZ (2025c)

Table 3.4. Sheep and beef farming regions and the major farm classes present for the 2021/2022 case study analysis.

Region	Production class (2-8)* and number of farms in each class		
	3	4	5
Northland, Waikato & Bay of Plenty	225	1664	240
Taranaki & Manawatū	275	565	255
Gisborne, Hawkes Bay & Wairarapa	420	825	550
	2	6	8
Canterbury & Marlborough	375	1070	465
	2	6	7
Otago & Southland	225	610	1040

Source: B+LNZ (2022)

*Class 1 farms have been excluded from this analysis as they are very low input systems, with minimal fertiliser and feed inputs.

Dairy case studies

Parameters used for the dairy case studies (Table 3.5) are based on those used by Macintosh et al. (2025), with a greater focus on the parameters that directly impact on soil P maintenance (i.e. specific supplementary feed breakdowns, and forage cropping areas). Data was averaged for each of the regions specified in Table 3.2 and compiled (Table A.3) to generate Overseer data inputs which represent a single representative case study farm for each region. The dairy case studies have been developed in such a way to capture all land used to support milk production [milking platform, areas used for supplementary feed (silage, hay and seasonal forage crops), and support blocks].

Table 3.5. Data parameters and their descriptors for use for the development of representative regional dairy farm scenarios in Overseer.

Parameter	Descriptor	Source
Rainfall (annual average)	mm/yr	Pers. comms Overseer Science Team (2025)
Temperature	°C	
Effective area	ha	LIC (2022)
Herd size	number of cows	
Replacement rate	%	
Average stocking rate	cows/ha	
Annual average milk solids produced	kg MS	
Milk solids produced per cow	kg MS/cow	
Milk solids produced per effective hectare	kg MS/ha	
Area harvested for hay/silage	ha	Dairybase (2024)
Summer and Winter crop grazed (area ^A & type ^B)	ha	Dairybase (2024) ^A , DairyNZ Economics Group (2019) ^B
Imported feed	t DM	Dairybase (2024)
Feed from storage	t DM	
Harvested feed (current season)	t DM	
Days in season irrigated	Number of days	
Irrigation interval	Days	
Irrigation area	ha	
Irrigation type	Centre Pivot, Mixed, K-line, Rotorainer, Flood	
Annual irrigation water applied	mm/yr	
Soil Olsen P	Weighted average	FANZ (2022b)
N, P, K, S applied	kg /ha/yr	Dairybase (2024)
Lime	kg /ha/yr	
Effluent storage type	Holding pond, holding pond-separated, spray from sump, pond discharge	
Effluent area	Best practice assumed - no more than 150kg N/ha applied	
Soil orders	Dominant soil type and % of land under dairy in each region.	NZSSS (2024)
Soil ASC	Default ASC	Wheeler (2018a)

ha: hectares, MS: milk solids, DM: dry matter, ASC: anion storage capacity.

Soil order information (dominant soil order and % cover of the dominant soil orders) were approximated using the NZ soil order ap (NZSSS, 2024). The ASC values were kept as the default values that are already part of the Overseer model and P-loss sub model (Table 3.10). Soil Olsen P data were sourced from the FANZ (2022b), as the median soil Olsen P for the 2021/22 season and calculated as the weighted average for each region, using the total effective area under dairy as reported by the LIC New Zealand dairy sector census data.

Sheep and beef

Parameters that influence soil P maintenance were used for these sheep and beef case study farms (Table 3.6). Sheep and beef farm area data (total, effective, cropping and supplement harvest/forage feed areas in ha), stocking rate (Open SU's), and pasture and crop fertiliser data (N, P, K, S, and lime in kg/ha applied) were all collected from the 2021/22 benchmarking reports (B+LNZ, 2022) and economic service report (Pers. comms B+LNZ, 2025a) and compiled (Table A.4 & A.5). The soil order type and area were approximated using the same method as for the dairy sector, and the default ASC values (provided via Overseer (v 6.5.9) model) were also used.

Table 3.6. Data parameters, and their descriptors, used in the development of representative regional sheep and beef farm scenarios for the 2021/2022 season in Overseer (v6.5.9).

Parameter	Descriptor	Source
Rainfall (annual average)	mm/yr	Pers. comms Overseer Science Team (2025)
Temperature	°C	
Farm class	B+LNZ farm class 1-8	B+LNZ (2022)
Total area	ha	
Effective area	ha	
Topography distribution	area under flat, rolling, easy hill, and steep hill	Saggar et al. (2015)
New grass area	ha	
Cash crop	ha	
Tree plantation	ha (difference between total area and effective area)	
Hay/silage area	(ha)	
Summer crop (area ^A & type ^B)	ha	Saggar et al. (2015) ^A , Sise et al. (2017, 2018) ^B
Winter crop (area ^A & type ^B)	ha	Saggar et al. (2015) ^A , Sise et al. (2017, 2018) ^B
Open sheep	Stock units (SU)	B+LNZ (2022)
Open cattle	Stock units (SU)	
Stocking rate	SU/ha	
Wool shorn (greasy)	kg	
Pasture N, P, K, S	kg/ha	
Pasture lime	kg/ha	
Crop N, P, K, S	kg/ha	
Crop lime	kg/ha	
Olsen P	Topography adjusted values (25-16 mg P/L from flat to steep hill)	FANZ (2022c)
Soil orders	Dominant soil type and % of land under sheep and beef in each region	NZSSS (2024)
Soil ASC	Default ASC	Wheeler (2018a)

ha: hectare, SU: stock units, pasture N: nitrogen fertiliser applied to pasture, pasture P: phosphorus fertiliser applied to pasture, pasture S: Sulphur fertiliser applied to pasture, pasture K: potassium fertiliser applied to pasture, pasture lime: lime fertiliser applied to pastures crop N: nitrogen fertiliser applied to crops, crop P: phosphorus fertiliser applied to crops, crop K: potassium fertiliser applied to crops, crop S: sulphur fertiliser applied to crops, crop lime: lime fertiliser applied to crops ASC: anion storage capacity.

Overseer data entry

The following method was used to enter the data into Overseer to produce representative farm nutrient budgets.

3.5.2 Farm area and blocking

As these case studies were entered at a regional level, the farm and block boundaries were not physically drawn in Overseer and the average farm area and subsequent block areas were entered manually for each region (Tables 3.7 & 3.8). The dairy farm area was split into 3 blocks (milking platform, silage/hay block, and effluent block), with a support block modelled separately for each dairy region. It was assumed that all pasture supplement was made on farm, while maize silage (and replacement cows) came from the support block. The total effective area for the dairy farms were determined using the LIC (2022) data, with size of the hay/silage block determined using Dairybase (2024). The size of the effluent block was adjusted for each region, so that no more than 150 kg N/ha was applied in effluent. This ensured the case studies were based on best practice. The size of the support block was determined by calculating the area required to grow the amount of maize silage imported onto the farm and then adjusting the pasture block size so that it produced between 10-13t/ha.

The total and effective area for the sheep and beef farms were determined using B+LNZ benchmarking data and economic survey data (B+LNZ, 2022; Pers. comms B+LNZ, 2025a) The modelling of the sheep and beef farm area was done similarly to that of Monaghan et al. (2021), where each farm model was split into multiple nutrient management blocks based on topography, use for forage, and use for cash cropping. The topography distribution was modelled based on Saggart et al. (2015) (see section 1.6.1.2). A trees and scrub block was allocated to all sheep and beef farms as the difference between the total and effective area and the cash cropping block was modelled for the farm classes 5, 6, 7, and 8 only (Pers. comms Morris, 2025).

Pasture type

It was assumed that all land grazed by dairy cows, and areas of flat-rolling hill on sheep and beef farms were a ryegrass/clover mix. New grass blocks on sheep and beef farms were also assumed to be a ryegrass/clover mix. Easy hill and steep hill blocks on the sheep and beef farms were assumed to have brown top pasture.

Topography and pasture production

Farm topography influences soil fertility, therefore runoff risk and P loss to water (McDowell et al., 2004), which ultimately affects soil maintenance P requirements. As such, topography is a required input in Overseer when setting up a farm budget (Wheeler, 2022) and includes a SlopePloss factor to account for the effect of slope on P loss. The SlopePloss factor values are 0.15 for flat, 0.5 for rolling, 0.75 for easy hill and 1.0 for steep hill (McDowell et al., 2005; Wheeler, 2022). To accommodate for the various topographies present across the sheep and beef farms, the sheep and beef case studies were broken up into 4 topography classes using the average proportion of land area outlined by Saggar et al. (2015). The topography classes outlined by Saggar et al. (2015) were low (<12), medium (12-24) and high (>24) slopes, which closely related to the flat (0-7)/rolling (8-15), easy hill (16-25) , and steep (>26) topography classes (respectively) in Overseer. However, flat and rolling topographies cannot be entered simultaneously for a block of land, and so for areas classified as low slope (<12) by Saggar et al. (2015), half of the block was classified as flat and the other half as rolling topography in Overseer.

Due to the effect of slope on soil nutrient levels and thus plant growth (Chapman & Macfarlane, 1985), the pasture productivity rating in Overseer was adjusted accordingly. The pasture productivity rating for flat and rolling topography was assigned as 1.0, with easy hill assigned 0.75, and steep hill 0.5. Farm topography was assumed to be flat for all dairy farms and their corresponding support blocks.

Table 3.7. Average effective area of dairy farms in regions across New Zealand

Region	Milking platform effective area (ha)*	Estimated support block effective area (ha)
Northland + Auckland	132	42
Waikato + Bay of Plenty	170	59
Taranaki	109	37
East Coast + Lower North Island	189	63
Westcoast + Marlborough	162	58
Canterbury	235	131
Otago + Southland	217	96

*Source: LIC (2022)

Table 3.8. Average effective area of the different sheep and beef farm classes in regional across New Zealand.

Region	Farm class effective area (ha)						
	land class						
	2	3	4	5	6	7	8
Northland + Waikato + Bay of Plenty	-	723	361	251	-	-	-
Taranaki + Manawatū	-	927	488	207	-	-	-
Gisborne + Hawke’s Bay + Wairarapa	-	948	592	392	-	-	-
Marlborough + Canterbury	1414	-	-	-	490	-	386
Otago + Southland	1454	-	-	-	600	272	-

Source: B+LNZ (2022).

3.5.3 Climate

The climate plays an important role in farm productivity and P loss, and as such it is important to ensure the average rainfall for each farm region is accurate. The Overseer model utilises long term (>30 years) climate and rainfall data from the National Institute of Water and Atmospheric Research (NIWA), calculating mean monthly air temperature and soil temperatures based on the region or nearest town selected. The Overseer model also accesses rainfall data using the NIWA data base for its hydrology sub-model, which uses a daily time step to represent the average annual rainfall for each rainfall region (Wheeler, 2018b). When entering a farm into Overseer, the long-term averages for air and soil temperature and rainfall are automatically selected based on the location of the farm.

Regional average rainfall and temperature data provided by Overseer for the dairy and sheep and beef regions examined in this study are presented in Table 3.9. Separate climate data was derived using Overseer for the dairy and sheep and beef regions to account for the effect of stark changes in topography common on sheep and beef farm, on rainfall across the farm. These rainfall and temperature data were used when entering the location of the regional case studies for both the dairy and sheep and beef industries, so that the average temperature and rainfall of the case study farms matched the long-term averages (Table 3.9).

Table 3.9. Regional average rainfall and temperature for the dairy and sheep and beef regions of New Zealand.

	Average rainfall (mm)	Average temperature (°C)
Dairy regions		
Northland + Auckland	1353	15.2
Waikato + Bay of Plenty	1352	13.7
Taranaki	1688	12.7
East Coast + Lower North Island	1207	13.0
Westcoast + Marlborough	2999	11.9
Canterbury	692	11.4
Otago + Southland	930	10.2
Sheep and beef regions		
Northland + Waikato + Bay of Plenty	1488	13.4
Taranaki + Manawatū	1223	12.2
Gisborne + Hawkes Bay + Wairarapa	1051	12.8
Marlborough + Canterbury	730	11.3
Otago + Southland	922	9.7

Source: (Pers. comms Overseer Science Team, 2025) (Overseer version 6.5.9).

3.5.4 Soil order and anion storage capacity

Soil order and the associated ASC value significantly influence the overall P budget as ASC influences how much P is sorbed by the soil and therefore how much P is plant available after the application of fertiliser or effluent. In Overseer, each soil order has an associated default average ASC (Table 3.10), which is used in the Adsorption, Immobilisation, and total P loss calculations. As the default ASC is used in the P budget calculations, overriding the ASC has little effect on the P budgets and maintenance P requirements (Pers. comms Overseer Science Team, 2025). As such, the dominant soil orders in each of the dairy and sheep and beef regions were determined using the New Zealand soil order map (NZSSS, 2024) and a sector distribution map (Monaghan et al., 2021) overlaid onto the soil map. These soil orders were then entered into the individual Overseer case studies.

Table 3.10. Soil anion storage capacity (ASC) values used in the Overseer nutrient budgeting model for the 14 soil orders of New Zealand.

Soil order	Anion storage capacity
Allophanic	83
Brown	43
Gley	43
Granular	49
Melanic	32
Organic	57
Oxidic	59
Pallic	21
Podzol	32
Pumice	49
Raw	23
Recent	23
Semiarid	9
Ultic	26

Source: Wheeler (2018a)

3.5.5 Soil test P data

Soil Olsen P values were collected from FANZ (see section 1.4.6). A total of 63,127 dairy farm soil samples (across all soil types) across New Zealand were included in the analysis (696 samples for Northland + Auckland, 11,647 samples for Waikato + Bay of Plenty, 3,169 samples for Taranaki, 2,428 samples for East Coast + Lower North Island, 4,360 samples for Westcoast + Marlborough, 22,590 samples for Canterbury, and 18,237 samples for Otago + Southland).

For the sheep and beef sector a total of 24,021 samples from all soil types and farm production classes across New Zealand were included (2,802 samples for Northland + Waikato + Bay of Plenty, 3,396 samples for Taranaki + Manawātū, 2,212 samples for Gisborne + Hawkes Bay + Wairarapa, 5,159 samples for Marlborough + Canterbury, and 10,452 samples for Otago + Southland). For each of the dairy and sheep and beef production regions, a weighted average Olsen P value was calculated and used in the Overseer farm case study analysis. Weighted average Olsen P values were also calculated for the total national dairy and sheep and beef sectors using the regional averages and are presented in Tables 4.7 & 4.8.

Although the arable and horticultural sectors were not modelled in Overseer, the soil Olsen P values for these sectors were also provided by (FANZ, 2022a, 2022e), at a national level, as the median Olsen P value for the 2021/2022 season. A total of 13,732 soil test results were available for the arable sector, and a total of 2,126 results were available for the horticultural sector in the 2021/2022 season.

3.5.6 Target Olsen P ranges

Soil test P values or Olsen P values can have a significant effect on the maintenance P fertiliser requirements and P loss. The optimum Olsen P target for all pastoral grazing on ash and sedimentary soils is considered 20-30 mg/L and 35-45 mg/L for pumice and peat soils, where pasture growth is at 97% of the maximum. For very high producing dairy farms, the optimal Olsen P value could extend to 30-40 mg/L (Roberts & Morton, 2016), however, it should be noted that the 2023 revised fertiliser recommendations for New Zealand dairy farms (Roberts & Morton, 2023) have removed the optimum range of 30-40 mg/L for high producing dairy farms. The optimum ranges for grazed pasture not only allow for maximum pasture growth but also provide a range where the risk of P loss from soils is reduced. As such, farmers should aim to have their soil test values within this range.

Dairy soil test values

The weighted average Olsen P values for each dairy production region were calculated using the FANZ (2022c) soil test data and compared against the optimum Olsen P for grazed pasture. All regions except Canterbury had a weighted average Olsen P value greater than the optimum range, and so two scenarios were run for each dairy region, 1) where the weighted average Olsen P was used, and 2) where all regional Olsen P values were set to 30 mg/L, the upper limit of the optimum range. The purpose of the two scenarios was to investigate the effect of the higher Olsen P values on the maintenance P requirements. Optimum soil test values were assumed for the other critical soil nutrients i.e. quick test potassium, sulphur and magnesium and calcium, according to Roberts and Morton (2023).

Sheep and beef soil test values

As mentioned previously, the optimal Olsen P value for pastoral land is between 20-30 mg/L. However, due to the varied topography on typical sheep and beef farms and the difficulty in getting fertilisers to some of these areas, the optimal Olsen P values are more inclined to reflect

the economic optimum, rather than biological optimum (Roberts & Morton, 2024). The weighted average Olsen P values calculated using the (FANZ, 2022c) soil test data determined an average Olsen P value of 22-25 mg/L. However, since it is not possible to determine the topography these soil Olsen P values related to, it was assumed that an Olsen P value of 25 mg/L be used for the flat land. The Olsen P values were adjusted for each topographic class, decreasing by 3 Olsen P units as topography increased (i.e. 22 mg/L for rolling, 19 mg/L for easy hill and 16 mg/L for steep hill) (Carey, 2007; Pers. comms Hanly, 2024).

3.5.7 Fertiliser

Fertiliser application rates for N, P, K and S were collected on a per hectare basis for the dairy and sheep and beef industries from the Dairybase/baseline and B+LNZ benchmarking databases for the 2021/22 season. For the dairy sector, the fertiliser application rates were assumed to be applied to the milking platform and hay/silage blocks only. The fertiliser application rates for the forage and cropping blocks were based on the recommendations by Morton et al. (2020) and Nicholls et al. (2009), assuming a medium level of background nutrients. For the sheep and beef sector, the pasture and forage crop fertiliser rates were provided separately, with the pasture fertiliser rates applied across the whole farm. Fertiliser application to the sheep and beef cash cropping blocks were based on recommendations by Nicholls et al. (2009).

When entering the dairy and sheep and beef fertiliser information into Overseer, best management practices (BMP's) were assumed, and adjustments were made to the application rates as necessary, to remain within the BMP's and regulations. The best management practices include, avoiding single P applications of over 100 kg P/ha, avoiding applications of P fertiliser between April and October as these months are at highest risk of surface runoff, splitting potassium (K) applications (applying equal amounts in Spring and Autumn) if more than 50kg K/ha is required and avoiding K application close to calving or supplement harvest (Roberts & Morton, 2023, 2024).

Nutrient regulations include the N-Cap regulations, outlined by the Ministry for the Environment (MFE, 2023), which requires that no more than 190 kg N/ha of synthetic N fertiliser be applied to grazed pasture without a resource consent. As such, any region with an average synthetic N application rate over 190 kg N/ha (for both dairy and sheep and beef), were adjusted accordingly, otherwise the average annual application rate was used. The annual N fertiliser rate was split into 3 applications and applied in October, December and March, to avoid high rainfall months and utilise the increased pasture growth rates over spring and autumn. This N cap does not include

land under fodder crops, and so a standard rate of nutrients [30kg N/ha for turnips, 50 kg N/ha for fodder beef, and 100 kg N/ha (applied in two split applications of 50 kg N/ha each)] was applied either at sowing (fodder beet and kale), at 4-6 weeks (second application of N to kale), or prior to second grazing (turnips) to meet the crop's nutrient requirements. Applications were selected as being outside the months of April to October to avoid increased risk of runoff and leaching. Crop nutrient requirements were determined using Nicholls et al. (2009), assuming a medium level of background soil nutrients (≥ 150 ppm soil N).

The average N, P, K and lime fertiliser application rates (Table A.3) collected from Dairybase were assumed to be applied to the milking platform and silage blocks only, with no fertiliser applied to the effluent block. The fertiliser requirements of the summer and winter forage crops were determined using Morton et al. (2020), assuming a medium background soil fertility.

Specific pasture and crop N, P, K, S and lime fertiliser application rates were able to be determined for the sheep and beef farms (Table A.4 & A.5), with the pasture application rates being applied to all pasture blocks and the crop fertiliser being applied to the forage crop blocks. Fertiliser requirements for the cash cropping blocks on class 5, 6, 7 & 8 farms were determined using cropping farm fertiliser recommendations (Nicholls et al., 2009), also assuming a medium level of background soil nutrients.

3.5.8 Supplementary feed -Dairy

The modelling of supplementary feeds is particularly important in the dairy case studies, as imported supplementary feeds such as palm kernel expeller, barley grain and brewer's grain introduce a significant amount of P into the farm system.

Imported feed

Using Dairybase, imported feed data were collected as both total tonnes imported, and total kg DM/cow fed. The net tonnes imported value was used to determine the dominant feed types imported for each region, where the tonnes of imported of each feed type were calculated as a percentage of total tonnes imported. The percentage of each of the dominant feed types were then applied to the total kg DM/cow of imported feed fed, to approximate the contribution of each feed type on a per cow basis. The kg DM/cow of each feed was then applied to the LIC average number of cows per herd, to determine the total amount of each of the supplementary feed types imported on an average farm, and to reduce the overestimation of feed imports associated with

the higher producing Dairybase farms. The imported supplementary feeds for each region can be found in Appendix A (Table A.3). Maize silage has been included as an imported feed and is assumed to be grown on the support blocks, with a default standing yield of 17.5 t/ha and then imported onto the farm.

Dairybase also reports on the amount of feed fed from storage. Similarly to the imported feeds, the percentage contribution of each of the stored feeds was calculated and applied to the total stored feed kg DM/ fed per cow value (found in Dairybase) to estimate how much of each stored feed is fed per cow. The kg DM/cow value (of the individual stored feeds) was then applied to the LIC average number of cows per herd to approximate the total tonnes of each feed type fed from storage, according to the LIC herd size. All imported and stored feed was modelled in Overseer as fed out, with no specification on the month fed.

Harvested feed

The area harvested for hay and silage was averaged using the Dairybase data, with the harvest yields calculated according to typical values expected. Production of hay and silage varies due to environmental factors (temperature, rainfall, sunshine hours, etc.), however typical harvest values range from 3-5 t DM/ha depending on pasture productivity (Howse et al., 1996). The amount of silage and hay harvested was entered into Overseer so that no more than 4 t DM/ha was harvested and was further adjusted so that no more than 30% of the total block's pasture production was converted into supplementary feed. It was also assumed that all feed harvested in the current season was put into storage.

It is important to note that while many farms may import pasture silage (thus making it an imported source of P), due to the lack of differentiation in the datasets between harvested and imported pasture silage, this source of feed was treated as a harvested feed and thus an internal recycling of nutrients.

Fodder crops

Using the Dairybase dataset, the average area under summer and winter fodder crop was identified for each dairy production region. The dominant type of feed was identified using the DairyNZ Economics Group (2019) report, which assessed the non-pasture feed consumption of similar regions to those used in this study. The timing of crop planting was based on de Ruiter et

al. (2009) in conjunction with the grazing dates reported in the DairyNZ Economics Group (2019) report. For all crops, the default yield provided by Overseer was used, along with the assumption that direct drilling was used for cultivation.

3.5.9 Supplementary feed - Sheep and beef

The area under summer and winter forage crops, area used for hay and silage, and area used for "cash" cropping were determined using the B+LNZ economic service report (Pers. comms B+LNZ, 2025a). These areas were assumed to occur on the flat to rolling topography of the farm. The types of feed grown were determined using the report by Sise et al. (2017, 2018), with the planting period also determined using de Ruiter et al. (2009). Cash cropping information has only been entered for farm classes 5-8, as it is unlikely that the North Island hill and hard hill country farms (classes 2, 3, & 4) will be using important grazing land for the production of cash crops (Pers. comms Morris, 2025). Cash cropping on sheep and beef farms refers to the production of grain, cereal, legume, or silage crops to be sold upon harvest.

Forage crops

The dominant forage crops grown on sheep and beef farms are kale, swedes and leafy turnips, with baleage used to cover the rest of the feed requirements over summer and winter. The distribution of livestock to these forage crops was based on Sise et al. (2017, 2018), where it was determined that the leafy turnip crop is used solely for lamb grazing, the kale crop solely for beef/other enterprise grazing and the swedes grazed 50/50 by sheep and beef/other enterprises. No other enterprises have been modelled in the current sheep and beef case studies, and so it is assumed that beef grazing is the primary enterprise to graze the kale and the full 50% of the swedes. Like with the dairy forage crops, direct drilling was assumed as the method of cultivation, and the Overseer default crop yield was used.

Baleage

It was assumed that the baleage fed was grown on farm from the silage block. The amount harvested could not be specified for each regional case study, and it has been assumed that no more than 4t DM /ha were harvested (assuming a typical harvest of 3-5t DM/ha). The baleage was

distributed 50% to the sheep, 20% to the beef cattle and the remaining 30% stored, according to Sise et al. (2017, 2018).

3.6 Overseer analysis

Once the regional case studies were completed, the Overseer nutrient budgets and other nutrient reports for each region were analysed. The soil P maintenance, farm P nutrient budget and effluent reports were compiled for each block of the dairy and sheep and beef farms.

The P inputs and outputs were determined from the nutrient budget reports, along with the changes in the soil nutrient pools (organic, inorganic mineral, and inorganic soil pools). The maintenance P requirements (kg P/ha) were determined for all blocks within the dairy and sheep and beef farms (grazed blocks, effluent block, and hay/silage blocks) excluding the forage crop and cash cropping blocks (these blocks do not have maintenance P requirement reports). For the dairy sector, the maintenance P requirements were also determined by setting the soil Olsen P value of 30 mg/L, in order to compare the effect of Olsen P on the maintenance requirements.

The block P maintenance requirements were then applied to the area under each block and added together to determine the total farm P requirements (kg P). The total farm P maintenance requirements were then multiplied by the total effective dairying or sheep and beef area within each of the respective sector production regions (according to LIC (2012) and B+LNZ (2022)) to determine the total regional P maintenance requirements (kg P). The total regional P maintenance requirements of each region were then added together (for each sector) and divided by the total effective hectares in the dairy or sheep and beef sector, in order to estimate the average maintenance P requirements per hectare in the respective agricultural sector (kg P/ha). It is important to note that the sheep and beef analysis excludes the production class 1 farms (South Island high country), due to the minimal P applied and greater reliance on recycled P in these farm systems.

To assess the farm P nutrient budgets, the average whole farm nutrient budget was taken from Overseer for each of the dairy and sheep and beef farms modelled. A national nutrient budget for the dairy and sheep and beef sectors were created by multiplying the P inputs and outputs from the representative case study farm by the regional effective hectares, in order to get the total values, which were then added together (within each respective sector) and divided by the total effective hectares in the dairy or sheep and beef sectors. It should be noted that for the dairy sector, the average whole farm nutrient budget does not include P additions in effluent, due to

the recycled nature of the P contained within the effluent, meaning there is no transfer of nutrients across the farm boundary, and nutrients are only captured in the individual block budgets (Overseer, 2022).

3.7 Arable and horticulture

Due a lack of available data regarding average farm management practices, farm effective area, cropping rotations, and potential integration of livestock grazing (particularly for the arable farms) the arable and horticultural sectors were unable to be modelled in Overseer, and no nutrient budget was created for either of the sectors, nor could soil maintenance P requirements be estimated. As such, the 2021/2022 season P fertiliser use of these two industries has been used as a proxy of maintenance P requirements.

The current total area under arable and horticultural production was gathered from the Stats NZ (2024) Agricultural production census, with historical data on land area being collected via Pers. comms Stats NZ info-centre (2025). The land use type within each of the arable and horticultural sectors were kept the same as those presented in the Stats NZ (2024), which are defined by the Australian and New Zealand Standard Industrial Classification 2006 (ANZSIC06) (Australian Bureau of Statistics, 2006-revision-2.0).

3.8 Statistical analysis

To develop the regionally representative case studies, individual farm data, and farm production class data had to be averaged in order to provide a single set of information, which could then be entered into Overseer to obtain the maintenance requirements and nutrient budgets at both regional and national scales. Both average and weighted average calculations were used, with weighted average calculations used where possible. When calculating the effective hectares, herd size, milk solids (per cow, per ha, and annual total), and tonnes DM of imported, harvested and stored supplementary feeds, a standard average calculation was used. When calculating the average regional Olsen P, and the regional and national average maintenance requirements the weighted average was calculated.

Correlation tables were constructed for the dairy and sheep and beef sectors using the data analysis tool in Microsoft Excel, to analyse the relationships between the variables entered into

the dairy and sheep and beef Overseer (v6.5.9) case study files, and the estimated maintenance P requirement and estimated P budget values generated by Overseer (v6.5.9).

Chapter 4 Case study data

4.0 Introduction

This study required detailed and disparate sources of farm production and fertiliser use data to be collated at a sector and regional level in order to undertake the current Overseer model analysis. The data presented in this chapter represents farm characteristics, productivity and P inputs and outputs which have not been collated elsewhere and represent an important data set for future studies on P budgeting in the New Zealand agricultural industry.

4.1 Rainfall and temperature

The breakdown of rainfall and temperature data below provides a clearer view on how the individual agricultural regions (used in this research) are affected, and how their climatic environment may influence P use and P loss.

Dairy

Long term annual average climate data were sourced from Overseer (v 6.5.9), with the most current long term dataset being recorded from 1991-2020 (Overseer, 2025). The long term annual average rainfall of North Island dairy farms ranged from 1,200 mm in the East coast + Lower North Island region to 1,690mm in Taranaki region (Figure 4.1). Rainfall in the Northland + Auckland and Waikato + Bay of Plenty regions were very similar, with approximately 1,350 mm of rainfall annually. In the South Island, the rainfall varied more significantly, with the West coast + Marlborough region experiencing approximately 3,000 mm of rain annually (nearly four times as much rain as the rest of the South Island), whereas the Canterbury and Otago + Southland regions experienced approximately 690 mm and 930 mm of rain, respectively. The average annual air temperature ranged from 15.2°C in Northland + Auckland, to 10.2°C in Otago + Southland.

Sheep and beef

The average annual rainfall experienced on North Island sheep and beef farms (Figure 4.2) ranged from approximately 1,050 mm in the Gisborne + Hawke's Bay + Wairarapa region, to approximately 1,480 mm in the Northland + Waikato + Bay of Plenty region. In the South Island, the average annual rainfall ranged from 730 mm to 930 mm in Marlborough + Canterbury and Otago + Southland regions, respectively. The average annual air temperature decreased moving south, down the country, with the highest average temperature of 13.4°C experienced in the

Northland + Waikato + Bay of Plenty region, and the lowest average temperature of 9.7°C experienced in the Otago + Southland region.

Arable and horticulture

Arable and horticultural farming occurs predominantly in the drier regions of New Zealand, with the average annual arable rainfall ranging from 600 mm in Canterbury to 1,000 mm in the Manawatū + Whanganui region, with Southland receiving an annual average of 940 mm of rainfall (Figure 4.3). The horticultural regions experienced a greater variation in rainfall, with the annual average ranging from 530 mm in Otago to 1,380 mm in Tauranga, and the Marlborough and Hawkes Bay regions receiving 690 mm and 770 mm of rainfall, respectively (Figure 4.4). The average annual air temperatures of the arable regions ranged from 10°C in Southland, to 12.5°C in Manawatū + Whanganui, with Canterbury measuring 12°C. The horticultural regions again showed greater variability in regional temperatures, with the average annual air temperatures ranging from 10.5°C in Otago to 14°C in Tauranga. The Hawkes Bay region had a similarly high annual average air temperature of 13.5°C, with the Marlborough region sitting in the middle of the four main horticultural regions at 12.5°C.

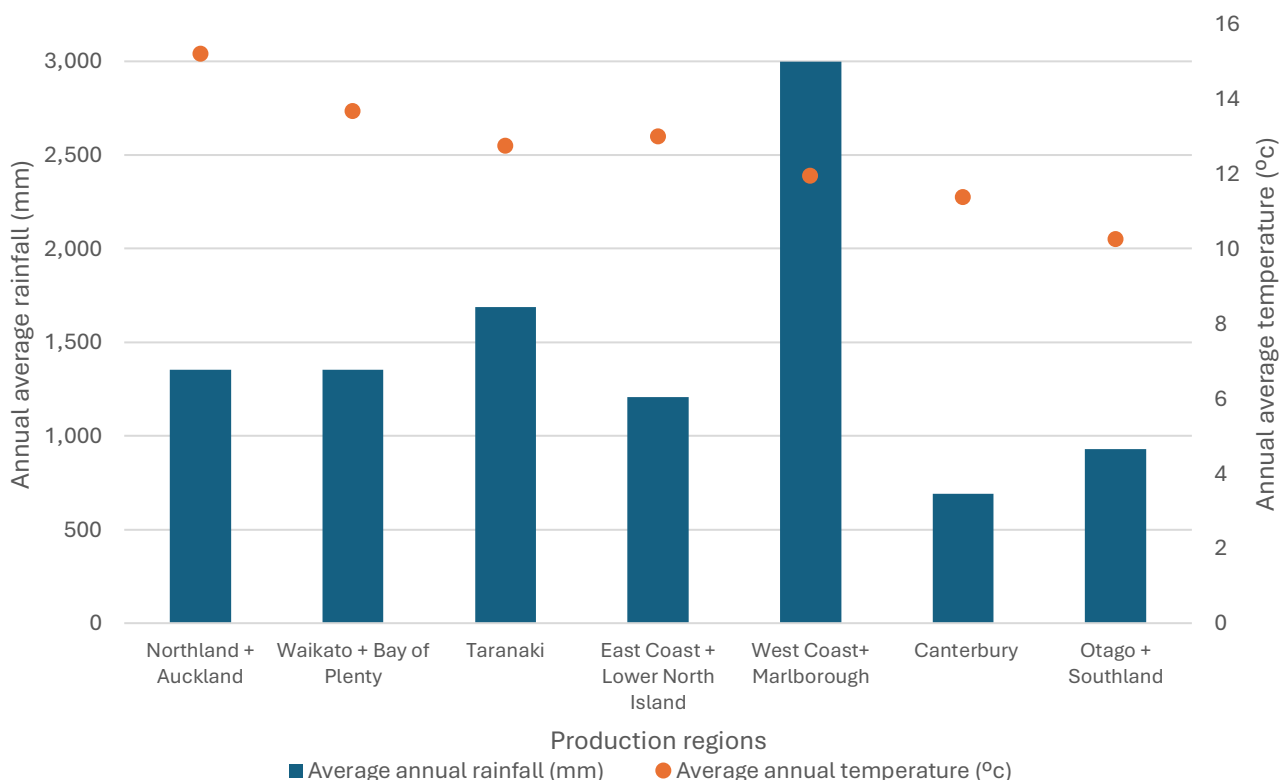


Figure 4.1. The long-term average annual rainfall (mm) and air temperature (°C) of each of the dairy production regions used in the farm case studies modelled in Overseer for the 2021/2022 season. Source: Overseer (v 6.5.9).

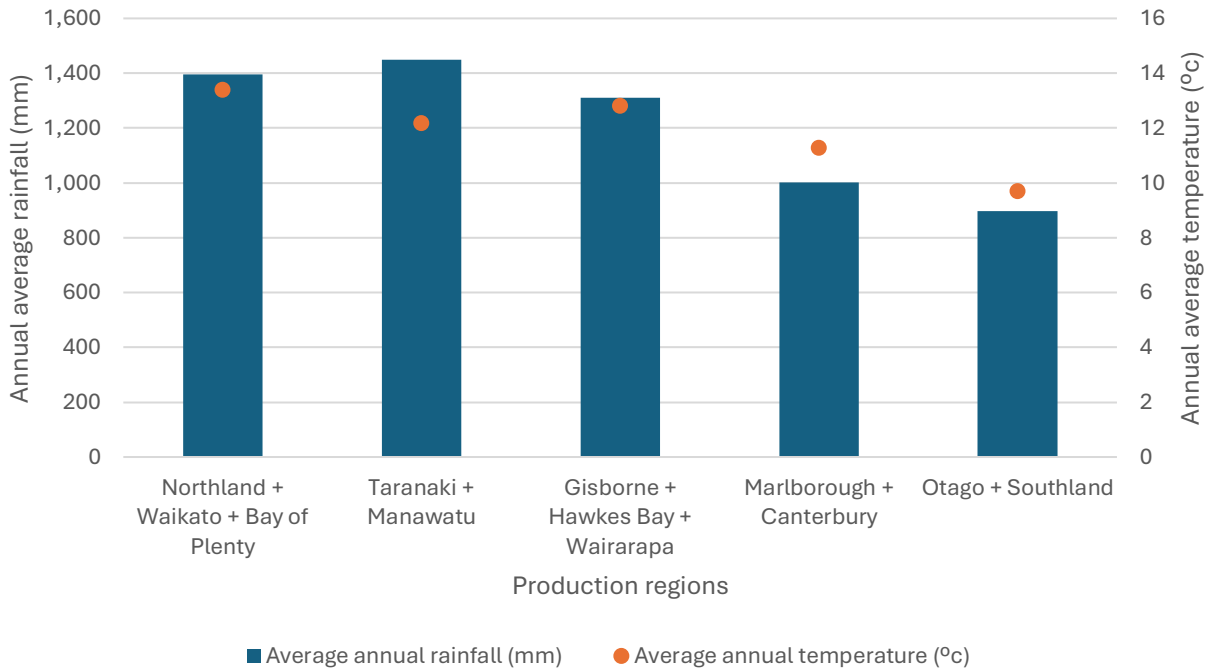


Figure 4.2. The average annual rainfall and temperature for each of the sheep and beef production regions used in the farm case studies modelled in Overseer for the 2021/2022 season. Source: Overseer (v 6.5.9).

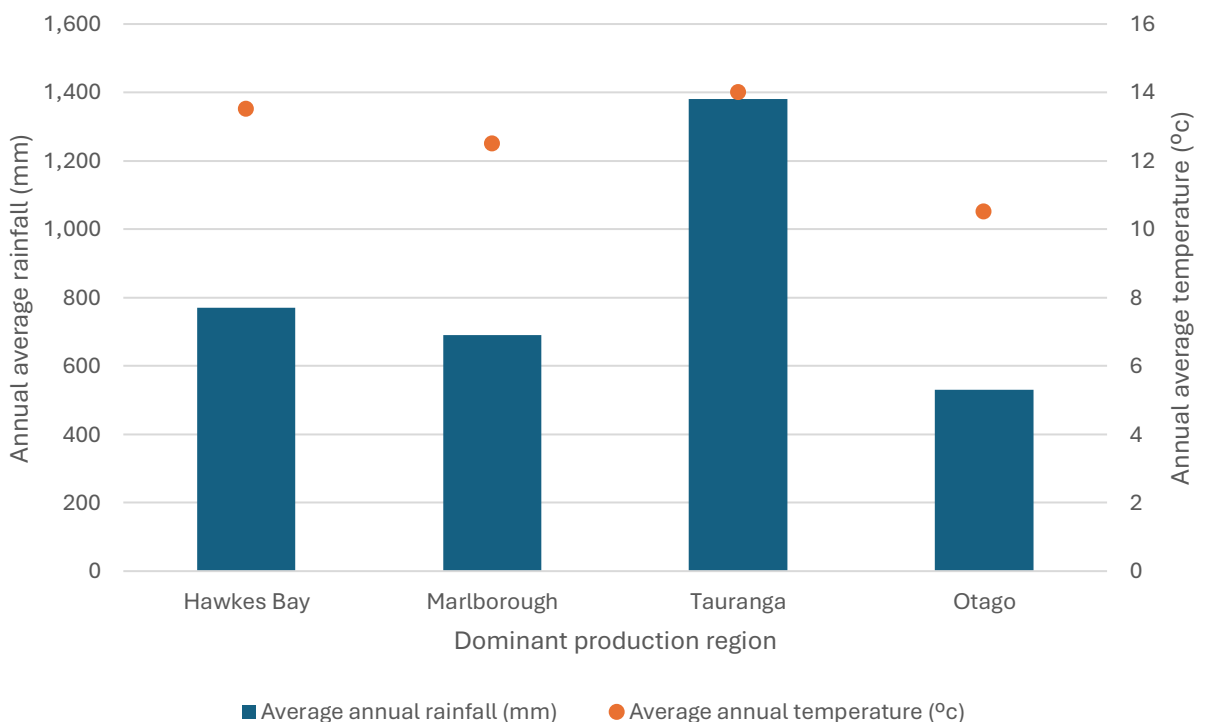


Figure 4.3. Annual average rainfall and temperature for each of the dominant horticultural production regions. Source: (Chappell, 2013a, 2013b, 2016; Macara, 2015).

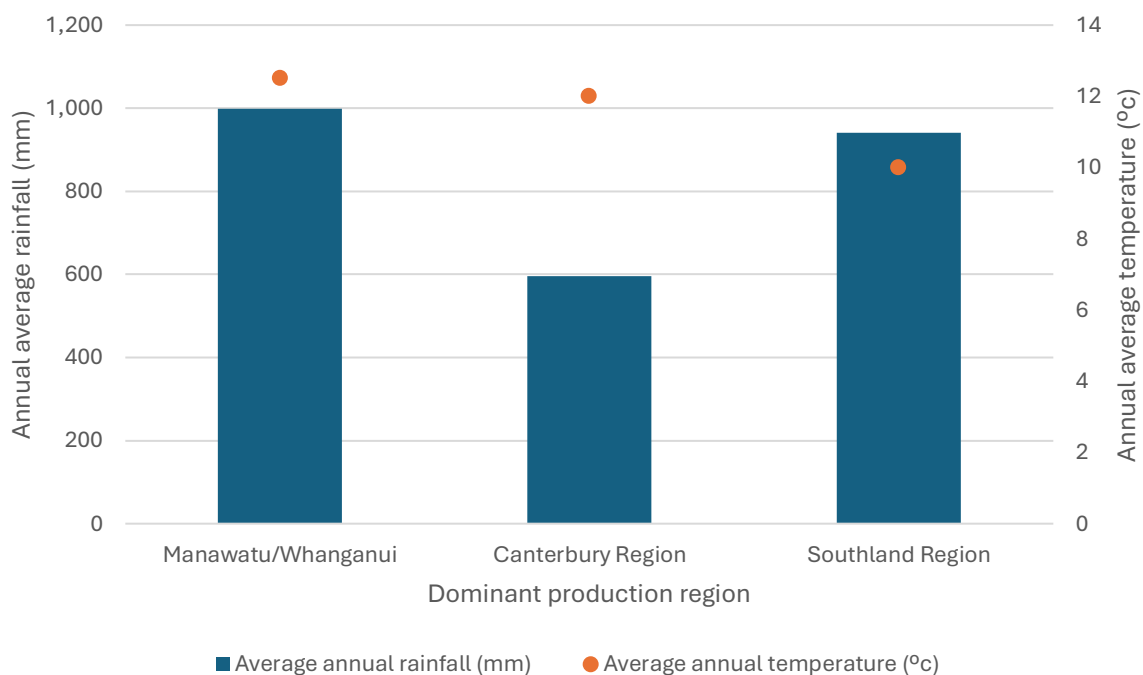


Figure 4.4. Annual average rainfall and temperature for each of the dominant arable production regions. Source: (Chappell, 2015; Macara, 2013, 2016).

4.2 Soil characteristics

Soil characteristics such as drainage class, texture, anion storage capacity (ASC), and soil organic matter are all strongly influenced by soil parent material and the soil order they belong to. In New Zealand, there are 14 soil orders (Table 3.10) (Hewitt, 2010; Wheeler, 2018a) with brown, pallic, allophanic and pumice soil orders covering the majority of the land used for farming (Roberts & Morton, 2023). Using the New Zealand Soil order map (NZSSS, 2024), the dominant soil orders for each of the dairy and sheep and beef regions were identified. The dominant soils identified for the representative dairy and sheep and beef sectors are listed in Tables 4.1 & 4. 2, with the sedimentary brown soil order being the most common across both sectors, followed by allophanic and pallic soils.

In the dairy sector, the sedimentary brown soil is found across all regions except for the Waikato + Bay of Plenty and Taranaki regions, where allophanic soils are more prominent. Pallic soils are another common soil found under dairy farming land, being found predominantly in the East Coast + Lower North Island, West Coast + Marlborough, Canterbury, and Otago + Southland dairy regions (Table 4.1).

In the sheep and beef sector, brown soils are found in all regions, and across most farm production classes (Table 4.2). Allophanic soils are found in the North Island, under the Northland + Waikato + Bay of Plenty and Taranaki + Manawatū hard hill and hill country farms. The pallic soil order is found under the Gisborne + Hawkes Bay + Wairarapa and Marlborough + Canterbury hard hill, hill country and finishing farms, along with the Taranaki + Manawatū and Otago + Southland finishing farms. Other soil orders sound under the dairy and sheep and beef sectors include the granular, podzol, ultic, recent, and gley soil orders.

Table 4.1. Dominant soil orders present across New Zealand dairy regions according to the New Zealand Society of Soil Science soil order map

Dairy regions	Soil orders
Northland + Auckland	Brown, Ultic
Waikato + Bay of Plenty	Allophanic, Granular, Pumice
Taranaki	Allophanic
Lower North Island + East Coast	Pallic, Brown
Westcoast + Marlborough	Brown, Podzol
Canterbury	Pallic, Brown, Recent
Otago + Southland	Pallic, Brown

Source: Monaghan et al. (2021); NZSSS (2024).

Brown soils cover 43% of New Zealand and tend to be well drained under moderate rainfall and are found on terraces and hill country, whereas the pallic soils (found on terraces and rolling hills, covering 12%) tend to be poorly drained under moderate rainfall, and well-drained under low rainfall (Landcare Research, 2025; Roberts & Morton, 2023). The allophanic and pumice soils cover 5% and 7% of New Zealand respectively and are largely found in the central North Island (Landcare Research, 2025). Well-drained allophanic soils are found around the Waikato and Taranaki regions, whereas the pumice soils are found more in the East Coast (Hawkes Bay and Poverty Bay areas) (Roberts & Morton, 2023). The podzol, ultic, recent, and gley soil orders cover 13%, 3%, 6%, and 3% of New Zealand respectively, and vary in fertility, and drainage characteristics (Landcare Research, 2025).

The anion storage capacity (ASC) (which is one of the soil characteristics that influence the amount of P sorbed and the amount of plant available P) varies greatly across the soil orders, with the allophanic soils having the highest ASC (83%), followed by the granular, pumice, brown, gley, podzol, recent, and pallic soil orders (Table 3.10).

Table 4.2. Dominant soil orders present across New Zealand sheep and beef regions according to the NZSSS soil order map.

Sheep and beef regions	Soil orders	
	Hard hill and hill country production classes 2, 3, 4	Finishing production classes 5, 6, 7, 8
Northland + Waikato & Bay of Plenty	Brown, Allophanic, Granular	Ultic, Granular
Taranaki + Manawatū	Brown, Allophanic	Brown, Pallic, Gley
Gisborne + Hawkes Bay & Wairarapa	Pumice, Brown, Pallic	Brown, Pallic
Marlborough + Canterbury	Brown, Pallic	Pallic, Brown, Recent
Otago + Southland	Brown	Brown, Pallic

Source: Monaghan et al. (2021); NZSSS (2024).

4.3 Phosphate-based fertiliser use

Fertiliser use varied significantly across the agricultural industry and regionally in New Zealand. An average of 142,829 tonnes of fertiliser P was sold in the 2021/2022 season, which is a 34% decrease from the historical high (219,000 tonnes) seen in 2005 (Figure 2.2). It is important to note that there is an approximately 2,343 ton difference between the total P applied (in fertilisers) reported in Table 4.4 by Stats NZ (2024) (approximately 141,657 tonnes) and the total elemental P purchased as reported by (FANZ, 2022g) (144,000 tonnes), which could be due to differences in data analysis, as a specific fertiliser breakdown for the Stats NZ compound fertiliser data was not available at the time of this data collection, so an assumed average P concentration of 13% was used to estimate the P content of this fertiliser category. As such, an average value for the fertiliser P applied, of 142,829, was used for the 2021/2022 season.

Using the Stats NZ (2024) figures to better understand the main sources of fertiliser P in New Zealand's agricultural industry, it can be seen that single superphosphate (SSP) and diammonium phosphate (DAP) are the two most common P fertiliser products used in New Zealand, across all industries (Table 4.3), with most of the fertiliser applied in the North Island (52% of DAP and 58% of SSP) in 2021-2022. In the North Island, 19% of the total DAP and 15% of SSP was applied across the Waikato region and 11% of the DAP and 14% of SSP is applied across the Manawatū + Whanganui regions. In the South Island, 19% of DAP and 14% of the countries SSP was applied across Canterbury and 15% of the DAP and 13% of the countries SSP was applied across Southland. Compound fertilisers, which contain a number of nutrients also make up a large portion of the fertiliser applied in New Zealand. Compound fertilisers, which contain the remainder of the P applied in New Zealand, were applied largely in the North Island (65%),

with 22% applied in the Waikato. In the South Island, the Canterbury and Southland regions applied 14% and 10% (respectively) of compound fertilisers in the 2021/22 season (Table 4.3).

At a sector level, the dairy, sheep and beef, and arable sectors apply 45%, 54%, and 39% of their P in the form of SSP, and 24%, 19%, and 26% of their P in the form of DAP, respectively (Table 4.4). The horticultural sector however only applies 13% and 11% of its P in the form of SSP and DAP respectively, with 75% of the P applied coming from the compound fertilisers. This compound fertiliser category includes trade-name fertilisers like "YarraMilla, PastureMag, Cropmaster, etc.", and custom blends which all vary in P concentrations, containing as much as 22% P (Ballance, 2025; Ravensdown, 2025).

Table 4.3. Amount of diammonium phosphate (DAP), single superphosphate (SSP) and compound fertilisers containing P applied (tonnes) in New Zealand in the 2021/2022 season, by region across all industries. "S" values in the Nelson region represent values that have been suppressed by StatsNZ due to lack of data to meet the required representation threshold.

Region	DAP (tonnes)	DAP applied as % of total	SSP (tonnes)	SSP applied as % of total	Compound fertilisers containing P (tonnes)	Compounds applied as % of total
Northland	6,703	5	35,633	5	13,532	4
Auckland	1,300	1	7,083	1	8,619	3
Waikato	28,455	19	113,896	15	73,410	22
Bay of Plenty	5,202	4	32,541	4	31,031	9
Gisborne	2,594	2	33,442	4	8,194	2
Hawke's Bay	6,569	4	51,417	7	22,982	7
Taranaki	6,039	4	35,965	5	15,567	5
Manawatū + Whanganui	15,609	11	105,531	14	35,431	11
Wellington	4,188	3	31,757	4	7,124	2
North Island	76,657	52	447,266	58	215,890	65
Tasman	1,232	1	16,598	2	3,147	1
Nelson	S	S	S	S	50	0
Marlborough	887	1	5,325	1	3,603	1
West Coast	3,678	2	12,041	2	11,861	4
Canterbury	27,462	19	110,825	14	47,153	14
Otago	15,403	10	69,480	9	19,226	6
Southland	21,877	15	103,221	13	32,467	10
South Island	70,603	48	317,834	42	117,508	35
New Zealand	147,261		765,100		333,397	4

Source: Stats NZ (2024).

The total amount of P applied per sector as reported by Stats NZ (2024) is broken down as 35% used for dairy, 55% to land under sheep and beef (a total of 90% to dairy and sheep and beef), 4% to arable land and 3% to horticultural land, with a total of approximately 141,657 tonnes of P in fertiliser applied across all industries (StatsNZ 2024) (Table 4.4). The distribution of P fertiliser between the dairy and sheep and beef sectors (35% and 55% of all P in fertilisers, respectively) is slightly different from that reported by FANZ (2022d) (49% to the dairy sector and 43% to the sheep and beef sectors in Table 4.5) with stats NZ reporting a greater proportion of elemental P applied to the sheep and beef sector.

An average fertiliser distribution between the two data sources, results in approximately 42% of fertiliser P having been applied to land under dairy, and 49% of fertiliser P having been applied land under sheep and beef in the 2021/2022 season (Table 4.5).

An average of 91% of the total P fertiliser sold in New Zealand was applied to the pastoral farming sectors emphasising the importance of P fertiliser to these sectors and the fact that P use in agriculture is strongly influenced by the pastoral sectors.

Apart from P fertilisers, the dairy sector also applies the majority of nitrogen (N) fertilisers used in NZ, applying 61% of the total amount of urea, and 58% of the ammonium sulphate fertilisers (Figure 4.4), followed by the sheep and beef sector, applying 25% and 30% of the total amount of urea and ammonium sulphate fertilisers, respectively (Stats NZ, 2024).

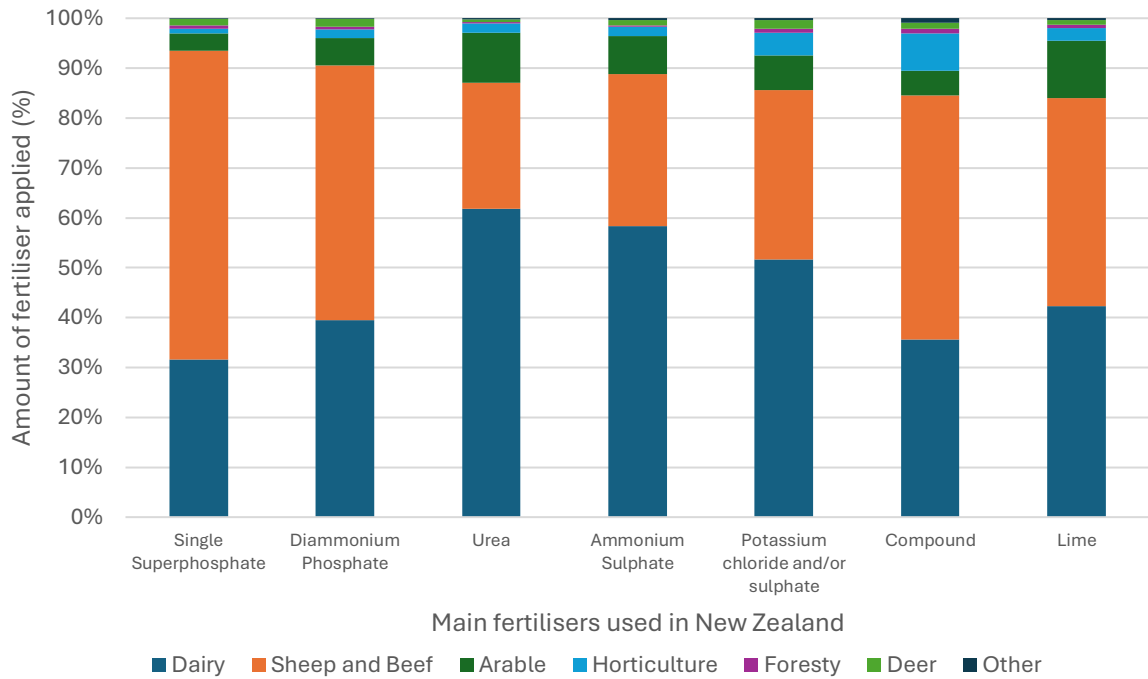


Figure 4.5. Proportion of the main fertiliser and lime products used by each of the dairy, sheep and beef, arable, horticulture, forestry, deer, and other industries (Other includes the poultry, pig, and horse industries). Single superphosphate: 9% phosphorus (P), 11% sulphur (S), Diammonium phosphate: 18% nitrogen (N), 20%P, 1%S, Urea: 46% N, Ammonium sulphate:20% N, 23% S, Potassium Chloride or Potassium Sulphate: 50% potassium (K), or 41.5% K, 18% S, Compound: assumed 13% P. Source: (Stats NZ, 2024).

Table 4.4. Amount of P applied as diammonium phosphate, single superphosphate and compound fertilisers by sector, across all regions. Single superphosphate: 9% phosphorus (P), 11% sulphur (S), Diammonium phosphate: 18% nitrogen (N), 20%P, 1%S, Urea: 46% N, Ammonium sulphate:20% N, 23% S, Potassium Chloride or Potassium Sulphate: 50% potassium (K), or 41.5% K, 18% S, Compound: assumed 10%.

Sector	DAP (tonnes P)	DAP as % of sector total	SSP (tonnes P)	SSP as % of sector total	Compound fertilisers (assuming 13% P) (tonnes)	Compound fertilisers as % of sector total	Total P per sector (tonnes)	Total P as % per sector
Dairy	11,739	24	21,975	45	15,606	32	49,320	35
Sheep and beef	14,935	19	42,380	54	21,057	27	78,372	55
Arable	1,618	26	2,450	39	2,142	34	6,210	4
Horticulture	525	11	608	13	3,460	75	4,593	3
Forestry	155	15	495	47	403	38	1,054	0.7
Deer	454	25	859	47	532	29	1,845	1
Other	26	10	95	36	142	54	263	0.2
Total	29,452		68,863		43,342		141,657	

Source: Stats NZ (2024).

Table 4.5. The total fertiliser P applied according to FANZ (2022) in the 2021/2022, the distribution of fertiliser P across the pastoral farming sectors (by tonnes and percentage), and the averaged fertiliser P use according to the Stats NZ (2024) and FANZ (2022) data for the pastoral farming sectors, showing the average percentage distribution and averaged tonnes P for the 2021/2022 season.

Sector	percentage of total phosphorus used (%)	Fertiliser P applied (tonnes)	Average percentage of P applied	Average P applied (between Stats NZ and FANZ) (tonnes)
Dairy	49	70,560	42	59,988
Sheep and beef	43	61,920	49	69,986
	92	132,840	91	129,974
P applied to the pastoral sector				
Total P applied to the agricultural industry		144,000		142,829

Source: FANZ (2022d)

4.3.1 Annual fluctuations in P fertiliser use

Dairy sector

Data on P use in the dairy sector was sourced from both Stats NZ (2024) and from Dairybase (2024), with the StatsNZ data providing a sector overview, and the Dairybase data providing more detailed farm average information. The average application of fertiliser P to dairy farms in the 2021/2022 season was 28 kg P/ha (Table 4.6), with national P fertiliser application generally decreasing over time, with a large 34.4% decrease from 43 kg P/ha measured in 2011/2012 to an average farm application rate of 28 kg P/ha applied in 2021/2022 (Figure 4.6). Fluctuations in P application were seen in 2013/2014 (increasing to 39.1 kg P/ha) and again in 2016/2017 to 34.2 kg P/ha, however, from 2016/2017 onwards, the P fertiliser application rates have been decreasing slowly.

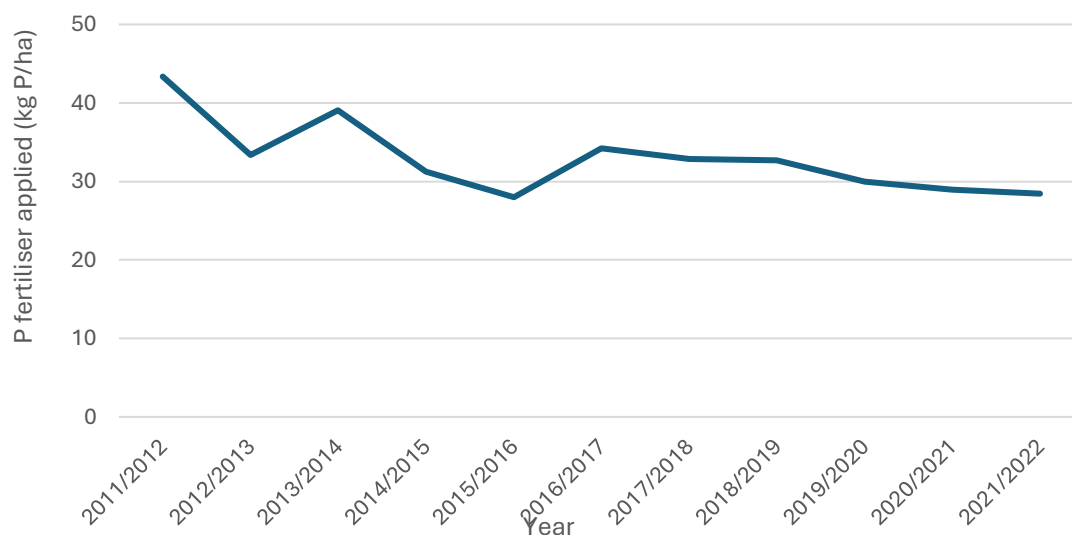


Figure 4.6. Average application rate of phosphorus (P) fertiliser applied across all dairying regions of New Zealand from 2011/2012 to 2021/2022, as recorded by farms in the Dairybase dataset. Source: with permission Dairybase (2024).

Sheep and beef sector

The average application rate of fertiliser P to the sheep and beef sector was 20 kg P/ha for the 2021/2022 season (Table 4.6). Over time (from 2011/2012 to 2021/2022), P fertiliser application rates have remained relatively stable, ranging from 11kg P/ha to 29 kg P/ha across all farm classes (Figure 4.7), with the exception of a large spike in the average fertiliser P application rate to the production class 8 farms in 2014/2015 (40.6 kg P/ha applied that season). The application of P to the production class 8 farms subsequently decreased in the following year, to 23.7 kg P/ha. Application rates to the class 1 and 2 farms have been consistently low over the last 10 years, with the steep topography and sometimes remote location of these farms making P application difficult. From 2019/2020 to 2021/2022, the average whole farm P fertiliser application rates decreased annually on the farm production classes 1, 2, 3, 4, 5 & 7 (Figure 4.7), decreasing to an average application rate of 9kg P/ha, 15.1kg P/ha, 19.1 kg P/ha, 21.2 kg P/ha, 24 kg P/ha and 25.8 kg P/ha (respectively) in 2021/2022. On the other hand, class 6 and 8 farms saw an increase in P fertiliser application over this same period, increasing to 21.2 kg P/ha and 27.2 kg P/ha in 2021/2022.

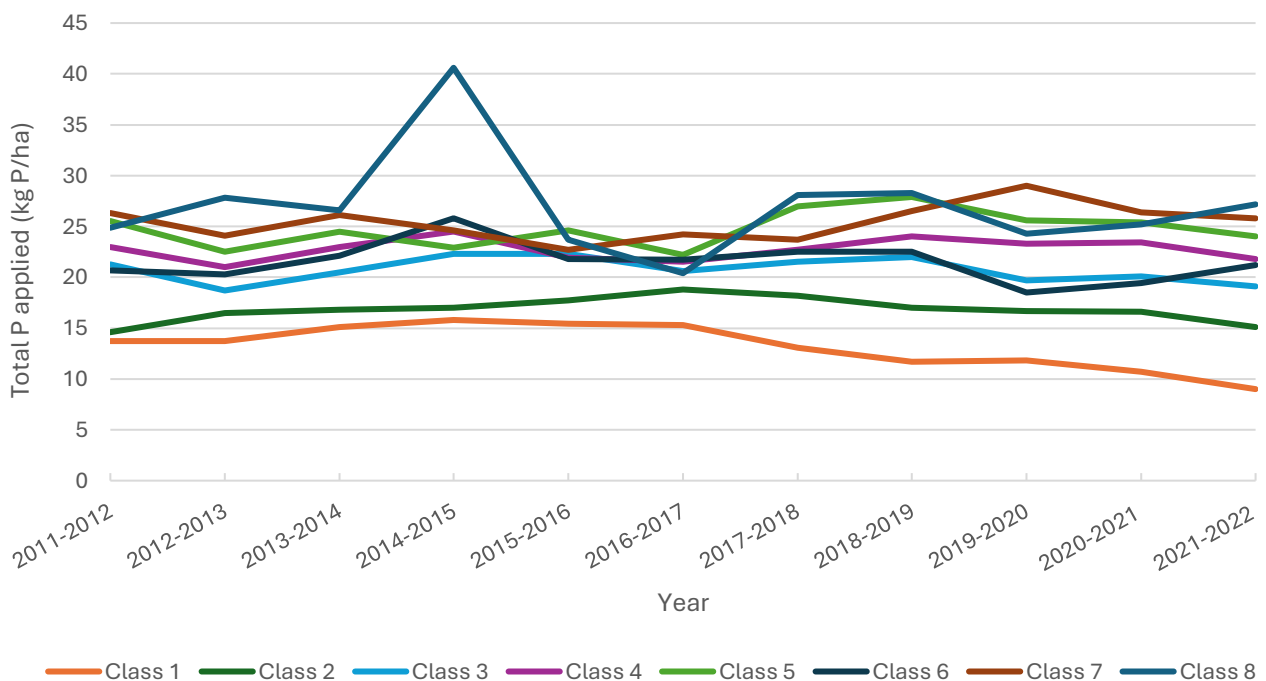


Figure 4.7. Amount of phosphorus (P) applied per hectare (cropped and grazed area combined) to sheep and beef farms across all regions of New Zealand, by farm production class from 2011/2012 to 2021/2022. Source: B+LNZ (2025a).

Arable and horticultural sectors

Due to a lack of data availability, fluctuations in P fertiliser application over time could not be attained for the arable and horticultural industries. Due to the way the arable and horticultural crops are harvested, with P being removed via grain, whole plant, or fruit harvest, little P is recycled back into the farm system and P fertiliser is often applied to replace the amount of P removed via the crop, rather than to maintain soil levels (Clark et al., 1986; Nicholls et al., 2009; Steele, 1985).

The arable sector applied approximately 6,210 tonnes of P in the 2021/2022 season [according to Stats NZ (2024)], with approximately 46% (2,874 tonnes of P) of that applied to "Other grain growing" (which consists of land growing maize, wheat, barley, and oats), and 54% (3,336 tonnes of P) of the total arable P being applied to "Other crop growing" (which consists of field peas, herbage seeds and other non-specified crops) (Table 4.7). The weighted average P fertiliser application to the arable sector was estimated to be 27 kg P/ha (Table 4.6), with average application rates of 17 kg P/ha and 55 kg P/ha seen on the grain and cropping land (respectively) in the 2021/2022 season (Table 4.7).

As a whole, the horticultural sector applied approximately 4,600 tonnes of P in the 2021/2022 season. The majority of the horticultural P was applied to land under vegetable, kiwifruit and 'other fruit and tree nut production' (2,033, 1,074, 699 tonnes, respectively) (Table 4.8). The P fertiliser application rates within the horticultural sector varied significantly between the different land uses, ranging from as little as 6 kg P/ha applied to areas growing olives, to as much as 102 kg P/ha applied to areas growing 'Other fruit and tree nuts'. However, the weighted average P application rate for the national horticultural sector was estimated to be 36 kg P/ha for the 2021/2022 season (Table 4.6).

Table 4.6. Weighted average application rates of phosphorus (P) applied in fertilisers (kg P/ha) to the dairy, sheep and beef, arable, and horticultural sectors of New Zealand for the 2021/2022 season.

Sector	P applied in fertilisers (kg P/ha)
Dairy ^a	28
Sheep and beef ^b	20
Arable ^c	27
Horticulture ^c	36

Source: ^aDairybase (2024) ^bPers. Comms B+LNZ (2025a), ^cStats NZ (2024).

Table 4.7. Amount of phosphorus (P) applied (kg P) in single superphosphate (SSP), diammonium phosphate (DAP), and compound fertilisers to the arable sector, and the total P applied (kg P). Grain growing includes land under maize (grain and silage), wheat (bread and feed), barley, peas, and oats, while other crop growing includes herbage seeds and other undisclosed arable crops.

	Area	SSP applied (tonnes P)	DAP applied (tonnes P)	Compound fertilisers applied assuming 13% P (tonnes P)	Total P applied (tonnes P)	P applied (kg P/ha)
Grain growing	166,629	947	905	1,022	2,874	17
Other crop growing	60,965	1,503	713	1,120	3,336	55
Total	227,594	2,450	1,618	2,142	6,210	27

Source: Stats NZ (2024)

Table 4.8. Amount of phosphorus (P) applied (kg P) in single superphosphate (SSP), diammonium phosphate (DAP), and compound fertilisers to the area under horticultural land (ha), the total P applied (kg P) and the total P applied per hectare of each of the enterprises within the horticultural sector, for the 2021/2022 season. "Other fruit and tree nut" includes avocados, persimmons, tamarillos, feijoas, passion fruit, chestnuts, macadamias, walnuts, and hazelnuts. "Other" includes all other unspecified horticultural crops.

	Area (ha)	SSP (tonnes P)	DAP (tonnes P)	Compound assuming 13 % P (tonnes P)	Total P (tonnes P)	P applied (kg P/ha)
Apples and Pears	10,164	20	8	121	149	15
Grapes	41,304	55	15	208	277	7
Kiwifruit	14,686	173	95	806	1,074	73
Stone fruit	2,277	6	2	34	42	18
Citrus fruit	1,673	28	10	24	62	37
Berry fruit	1,869	2	5	13	20	11
Olive	693	0.1	0	4	4	6
Vegetable	39,453	288	376	1,368	2,033	52
Other fruit and tree nut	6,885	33	10	657	699	102
Other	7,799	4	4	225	233	30
Total	126,803	608	525	3,460	4,593	36

Source: Stats NZ (2024)

4.4 Soil Olsen P

The soil Olsen P value of New Zealand's agricultural industry has stayed relatively similar over the last 10 years, with only a 5 unit increase from 2012 to 2022, with the median value for the 2021/2022 season being approximately 30 mg P/L (FANZ, 2022f). At a sector level however, there is large variation in soil Olsen P values between the sectors, and the production regions within the sectors.

4.4.1 Dairy

Soil Olsen P is an important measure of soil nutrient status and helps inform fertiliser application requirements (Roberts & Morton, 2023). As reported by Roberts and Morton (2023), the agronomic optimum soil Olsen P concentration (where 97% of relative pasture production is achieved) for grazed pasture on ash (volcanic) and sedimentary soils is between 20-30 mg/L, and 35-45 mg P/L for pastures on pumice and peat soils. Soil test data reported by FANZ (2022f) show that the regional average Olsen P values for the dairy regions in New Zealand (across all soil types) range from 30mg P/L in the Canterbury region to 43 mg P/L in the Waikato + Bay of Plenty region, while the national weighted average dairy Olsen P value is 37 mg P/L (Table 4.9). All dairy production regions in New Zealand had average soil Olsen P values at or above the target range for the 2021/2022 season.

Table 4.9. Weighted average Olsen phosphorus (P) values (mg/L) for New Zealand dairy farming regions for the 2021/22 season.

	Weighted average Olsen P (mg/L)
Northland + Auckland	37
Waikato + Bay of Plenty	43
Taranaki	39
East Coast + Lower North Island	34
West Coast + Nelson/Tasman	33
Marlborough + Canterbury	30
Otago + Southland	32
New Zealand	37

Source: FANZ (2022b).

4.4.2 Sheep and beef

Although the agronomic optimum Olsen P value for grazed pasture on ash and sedimentary soil is 20-30 mg/L (Roberts & Morton, 2023), for sheep and beef farms where topography limits fertiliser application, the economic optimum Olsen P is often targeted, resulting in Olsen P concentrations lower than the agronomic optimum target range. The weighted average Olsen P values for sheep and beef farms show that of the farms and areas tested, the soil under sheep and beef farms is generally within the lower end of the target range, ranging from 22-26 mg/L, with the national average Olsen P value for sheep and beef farms in New Zealand estimated to be 24 mg P/L (Table 4.10). The values presented in Table 4.10 are likely to be representative of the flatter, more productive farms/areas of farms, as the steeper terrain is less likely to be soil tested.

Table 4.10. Weighted average Olsen phosphorus (P) concentrations (mg/L) for New Zealand sheep and beef farming regions for the 2021/22 season.

	Weighted average Olsen P (mg/L)
Northland, Waikato, Bay of Plenty	26
Gisborne +Hawkes Bay + Wairarapa	22
Taranaki + Manawatū/Whanganui	23
Marlborough + Canterbury	24
Otago + Southland	26
New Zealand	24

Source: FANZ (2022c)

4.4.3 Arable and horticulture

The target Olsen P values for the arable and horticulture sectors are slightly different than for grazed pasture, with most arable crops requiring a minimum Olsen P of 10-15 mg/L for optimum production/yield (Nicholls et al., 2009), whereas horticultural crops have no identified target range as P application targets set according to the crop type and current soil test values (FANZ, 2022f). From the soil test data provided by (FANZ, 2022a, 2022e), the national weighted average Olsen P value of arable soils is estimated to be 26 mg/L (which is in excess of target values for most crops, but is within the target range any pasture grown in rotation with crops) and the national weighted average Olsen P value of horticultural soils is 40 mg/L (Table 4.11), which is higher than the grazed pasture target values for biologically optimum soil P.

Table 4.11. National weighted average Olsen phosphorus (P) values (mg/L) for the arable and horticultural industries of New Zealand, for the 2021/22 season.

	National weighted average Olsen P (mg/L)
Arable ^a	26
Horticulture ^b	40

Source: FANZ (2022a)^a, FANZ (2022e)^b.

4.5 Production

4.5.1 Dairy

In the 2021/2022 season, the national dairy sector occupied 1.7 million effective hectares (4% increase from 2011/2012), with approximately 10,800 herds (9% decrease from 2011/2012) producing a total of 1.87 million kg of milk solids (MS) (10% increase from 2011/2012) (Table 4.12). The national average for effective dairy hectares was 158 ha, with the South Island having a greater average area (217 ha) than the North Island (133 ha) (Table 4.12). Regionally, the average effective hectares ranged from 109 effective ha in the Taranaki region to 235 ha in the Canterbury region for the 2021/2022 season. The National average herd size, and MS produced per hectare were 449 cows and 1,098 kg MS/ha, respectively, with the South Island having nearly double the number of cows on average (647 cows) and producing 206 kg MS/ha more on average (1,221 kg MS/ha) than the North Island (366 cows and 1,015 kg MS/ha) in the 2021/2022 season. Regionally, the Canterbury region produced the highest average total kg MS, and kg MS/ha in the 2021/2022 season, producing 338,915 kg MS, at an average of 1,451 kg MS/ha. In contrast, the Northland + Auckland region recorded the lowest average total kg MS and kg MS/ha in the 2021/2022 season, producing 105,613 kg MS at an average of 767 kg MS/ha (Table 4.13).

Over the last 10 years, the New Zealand dairy sector has observed large increases in land area and in the average herd size (Table 4.12). Between 2009 and 2012, the land area under dairy increased by 120,000 ha (7% increase), with a further 4% increase in the area under dairy in 2022 from 1.64 million ha to 1.7 million ha (Table 4.12). This 4% increase in land area supported a 12% increase in the average number of cows per herd (from 393 cows in 2012 to 449 cows in 2022), and a 10% increase in milk solids production (a 184 million kg MS increase from the 1,684 million kg MS processed in 2012). Despite the increase in herd size, there was a 9% decrease in the total number of herds across New Zealand, suggesting a combining of herds or the retirement of farms out of dairying.

Table 4.12. Changes in area occupied by milking herds, herd size, stocking rate, and production rates (per cow and per ha) in the New Zealand dairy sector from 2011/2012 to 2021/2022, including a comparison to the 2008/2009 production values used by Hedley et al. (2011).

	2008/2009	2011/2012	% change from 2008/2009 to 2011/2012	2021/2022	% change from 2011/2012 to 2021/2022
Total effective area (10 ⁶ ha)	1.52	1.64	7	1.7	4
Number of herds	11,618	11,798	2	10,796	-9
Average herd size (No. cows)	366	393	7	449	12
Stocking rate (cows/ha)	2.83	2.83	0	2.85	1
Milk solids (kg MS)					
per cow	323	364	11	386	6
per ha	921	1,028	10	1,098	6
National total (10⁶) (kg MS)	1,393	1,684	17	1,868	10

Source: Hedley et al. (2011), LIC (2012, 2022).

Table 4.13. Dairy production data by region showing the average effective hectares, cow numbers, stocking rate, and milk production (per hectare, per cow and annual total), for the 2021/22 season, along with North Island, South Island and National averages.

	Northland + Auckland	Waikato + Bay of Plenty	Taranaki	East Coast + Lower North Island	North - Island	Westcoast + Marlborough	Canterbury	Otago + Southland	South - Island	Nationally
Average farm effective area (ha)	132	170	109	189	133	162	235	217	217	158
Average herd size	310	464	304	507	507	395	805	607	647	449
Average stocking rate (cows/ha)	2.52	2.77	2.79	2.69	2.75	2.49	3.42	2.8	2.98	2.85
Average milk production (kg MS)	105,613	158,100	119,561	182,747	134,931	132,198	338,915	250,531	264,848	173,010
Average milk production (kg MS/ha)	767	1,051	1,096	1,029	1,015	780	1,451	1,146	1,221	1,098
Average milk production (kg MS/cow)	332	366	394	382	369	330	420	416	409	386

Source: LIC (2022)

4.5.2 Sheep and beef

In New Zealand, there are approximately 9,165 sheep and beef farms, which are located over a range of topographies, from flat/rolling to easy and steep hill topographies, each filling a unique role in the sheep and beef production system. The dominant farm production class in New Zealand is the class 4 (North Island Hill Country) (33%), followed by class 6 (South Island Finishing/Breeding) (20%) farms (Figure 4.8). The class 4 North Island Hill country farms consist predominantly of easy (27.7 to 57.9% of area) and steep hill (27.6 to 61.1% of area) topographies (Table A.4), with the majority of class 4 farms found in the Northland + Waikato + Bay of Plenty region (1665 farms). The class 6 South Island finishing/breeding farms are found predominantly in the Marlborough + Canterbury region, and consist predominantly of flat/rolling (20.5 to 51.5% of area) and easy hill (37.7 to 54.5% of effective area) topographies (Table B.1). The South Island finishing and mixed finishing farms (class 7 and 8 respectively) made up 16% of the New Zealand sheep and beef farms (Figure 4.8), also consisting of predominantly flat, rolling and easy hill (Table B.1). The flatter topographies of the class 6-8 farms facilitate lamb and calf finishing, and cash cropping (the production of crops, not used as feed for the own farm's stock, but sold off farm).

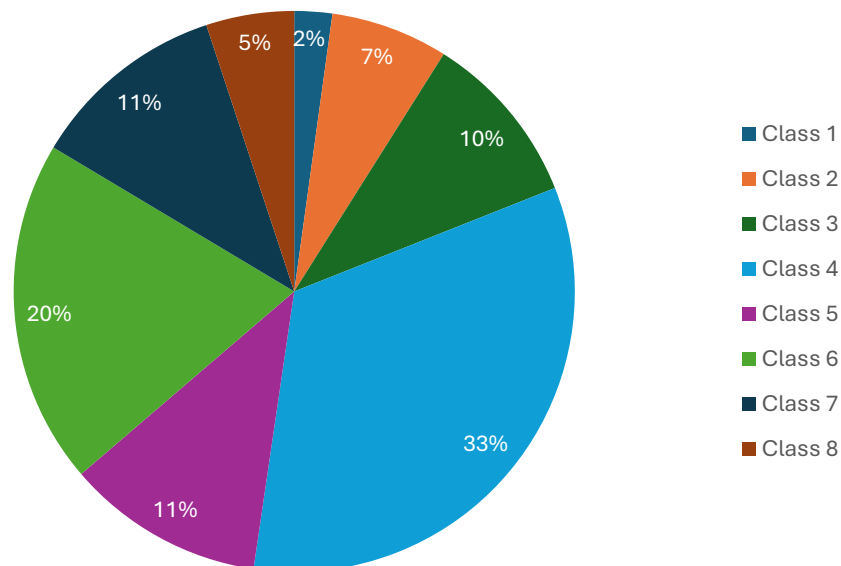


Figure 4.8. The eight sheep and beef farm production classes and their proportion of the total number of sheep and beef farms in New Zealand. Source: (Pers. comms B+LNZ, 2025a).

While dairy has seen a steady increase in milk production, the sheep and beef sector has seen a decreases in lamb/mutton production alongside increases in beef production (Table 4.14). The effective area under sheep and beef grazing decreased by 10% from 7.7 million ha in 2011/2012, to approximately 6.9 million ha in 2021/2022, with a 24% decrease in the total number of sheep. The number of beef animals however, increased by 5% over the same period, facilitating a 14% increase in beef and veal production (Table 4.14).

Table 4.14. Changes in area occupied by sheep and cattle livestock, number of animals and production rates (wool and meat) in the New Zealand sheep and beef sector from 2011/2012 to 2021/2022.

	2011/2012	2021/2022	Change (%)
Total area (million ha)	9.7 ^a	8.3 ^b	-14
Effective area (million ha) ^b	7.7	6.9	-10
Number of sheep (million) ^c	31.3	25.3	-24
Number of beef (million) ^c	3.7	3.9	5
Greasy wool (kg/head) ^c	5.4	5.1	-6
Greasy wool (000 tonnes) ^c	168.3	128.8	-31
Lamb + mutton (000 tonnes) ^c	448	435	-3
Beef + veal (000 tonnes) ^c	624	724	14

Source: Morris (2013)^a, Stats NZ (2024)^b, B+LNZ (2023a)^c.

4.5.3 Arable and horticulture

Over the last 10 years, the area under horticulture and arable and has reported marginal decrease of 0.5 and 3.5% respectively from 2011/2012 to 2021/2022 (Table 4.15 & 4.16). The most significant changes in area in the horticultural sector were associated with grapes, kiwifruit, and ‘Other’ land uses, increasing by 16.9, 15.1 and 109.5% respectively. These increases in area were however, offset by a decrease in area under berry (28.1%), olives (58.2%) and indoor and outdoor vegetable growing (23.0%).

Similarly to the horticultural area, the area under arable crops saw a large decrease in the area under wheat and barley (21.7 and 26.7%, respectively), which were nearly balanced out by the increasing area under pea, oat and herbage seed crops (23.1, 37.8 and 26%, respectively). The area under

maize production has remained relatively stable over the last 10 years, with a small 4.9% increase from approximately 66,900 ha in 2011/2012 to approximately 70,232 ha in 2021/2022.

Table 4.15. Change in area under horticulture and the percentage change from 2011/2012 to 2021/2022. “Other fruit and tree nut” includes area under avocados, tree nuts and specialty fruit like feijoa, persimmons and passionfruit. “Other” includes flower, and bulb growing and nurseries.

	2011/12	2021/2022	Change (%)
Apples and Pears	9,538	10,164	6.6
Grapes	35,334	41,304	16.9
Kiwifruit	12,757	14,686	15.1
Stone fruit	2,276	2,277	0
Citrus fruit	1,857	1,673	- 9.9
Berry fruit	2,598	1,869	- 28.1
Olive	1,657	693	- 58.2
Vegetable (Under cover + Outdoor)	51,234	39,453	- 23.0
Other fruit and tree nut	6,418	6,885	7.3
Other	3,723	7,799	109.5
Total	127,392	126,803	- 0.5

Source: Stats NZ (2024), Pers. comms Stats NZ info-centre (2025).

Table 4.16. Change in area under the main arable crops and the percentage change, from 2011/2012 to 2021/2022, under these crops. “Other” includes area under crops not specified in the Stats NZ (2024) census.

	2011/12	2021/22	Change (%)
Maize	66,956	70,232	4.9
Wheat	54,751	42,872	- 21.7
Barley	65,703	48,171	- 26.7
Peas	6,399	7,880	23.1
Oats	3,885	5,354	37.8
Herbage seeds	38,148	48,075	26.0
Other	8,035	5,010	- 37.7
Total	188,328	173,687	- 3.5

Source: Stats NZ (2024), Pers. comms Stats NZ info-centre (2025)

4.6 Supplementary feeds

Supplementary feeds play an important role in calculating the maintenance P requirements of soil under livestock grazing, as imported feeds like palm kernel expeller (PKE), brewers grain and other grain feeds, introduce large amounts of P into the farm system (Gourley et al., 2010) and reduce the requirements for fertiliser P.

4.6.1 Imported feeds

Dairy

According to the adjusted supplementary feed data, the most significant imported feeds into New Zealand dairy farms are PKE, barley grain, maize silage, and brewers grain, with the average amounts imported to each farm being 176, 57, 55 and 19 t DM, respectively. Cereal straw and silage, maize grain, molasses, concentrates, and lucerne hay/silage each make smaller contributions to the total imported feeds (Table 4.17). The "Other" imported feed category includes tapioca, soyabean meal, fruits and vegetables (kiwifruit, carrots, etc.), and broll [a mixture of wheat bran, husk and flour, i.e. wheat milling byproducts (O'Connor & Sun, 2002)]. The amount of PKE imported in the 2021/2022 season varied significantly between the dairying regions of New Zealand, with the least amount of PKE imported in the Northland + Auckland region (112 t DM), and the most imported in the Otago + Southland region (268 t DM) (Table B.2).

The Otago + Southland region, on average, imported the most supplementary feed, bringing in an average of 608 kg DM/cow, followed by the Canterbury and Waikato + Bay of Plenty region farms (an average of 497 and 483 kg DM/cow, respectively) (Figure 4.9). Of the feeds imported to farm, PKE and maize silage featured in every region, making up 46% and 15% of the total imported feeds for the 2021/22 season (Figure 4.10). Barley and brewer's grains were predominantly utilised by the South Island farms and made up 10% and 4%, respectively, of total feed imports, while maize grain was predominantly used by North Island dairy farms but only accounted for 2% of the total feed imports for the 2021/2022 season (Figure 4.10). Other feeds imported such as cereal straw and concentrates were predominantly favoured by South Island farms, with the lucerne silage and Proliq being favoured by the North Island dairy farms (Table B.2).

Table 4.17. Average tonnes of supplementary feed (t DM/farm) imported into New Zealand dairy farms, and the range between dairying regions for the 2021/2022 season, for each of the most commonly imported supplementary feeds according to Dairybase (2024).

	Average tonnes imported to farm (t DM/farm)	Range (t DM)
PKE	176	112-268
Maize silage	55	6-130
Barley grain	57	2-179
Brewers grain	19	3-43
Lucerne silage	8	4-15
Maize grain	12	2-26
Molasses	10	3-22
Proliq	7	5-15
Cereal Straw	8	2-20
Concentrates	32	13-55
Other	45	9-73
Total	429	250-608

Source: with permission, Dairybase (2024)

*Pasture silage not included - treated as harvested feed

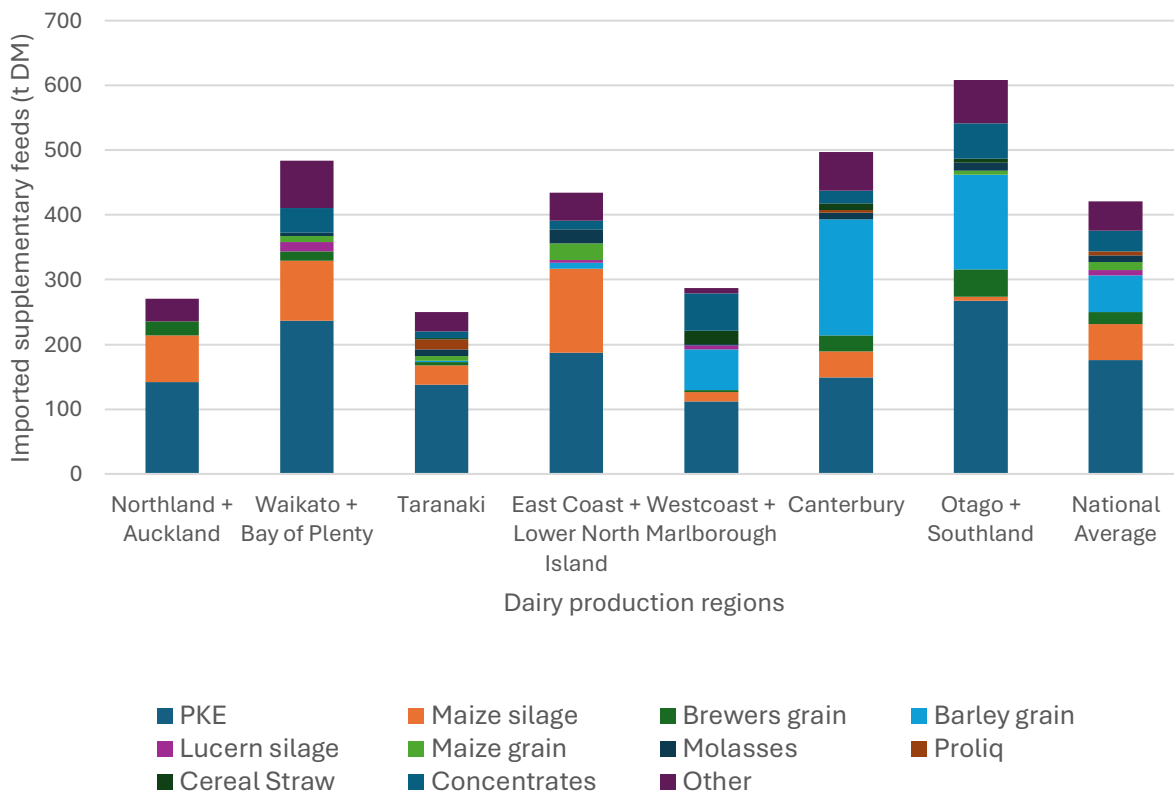


Figure 4.9. Averaged supplementary feed imported to the regionally representative case study farms, for each dairy production region, from Dairybase for the 2021/22 season. Sourced with permission from Dairybase (2024).

The amount of PKE, maize silage, and barley grain imported made up 67% (41%, 13%, and 13%, respectively) of the total average amount of supplementary feed imported to farm annually in New Zealand (Figure 4.10). Imported concentrates and "other" supplementary feeds contributes 7 and 13% (respectively) to the average feed imports.

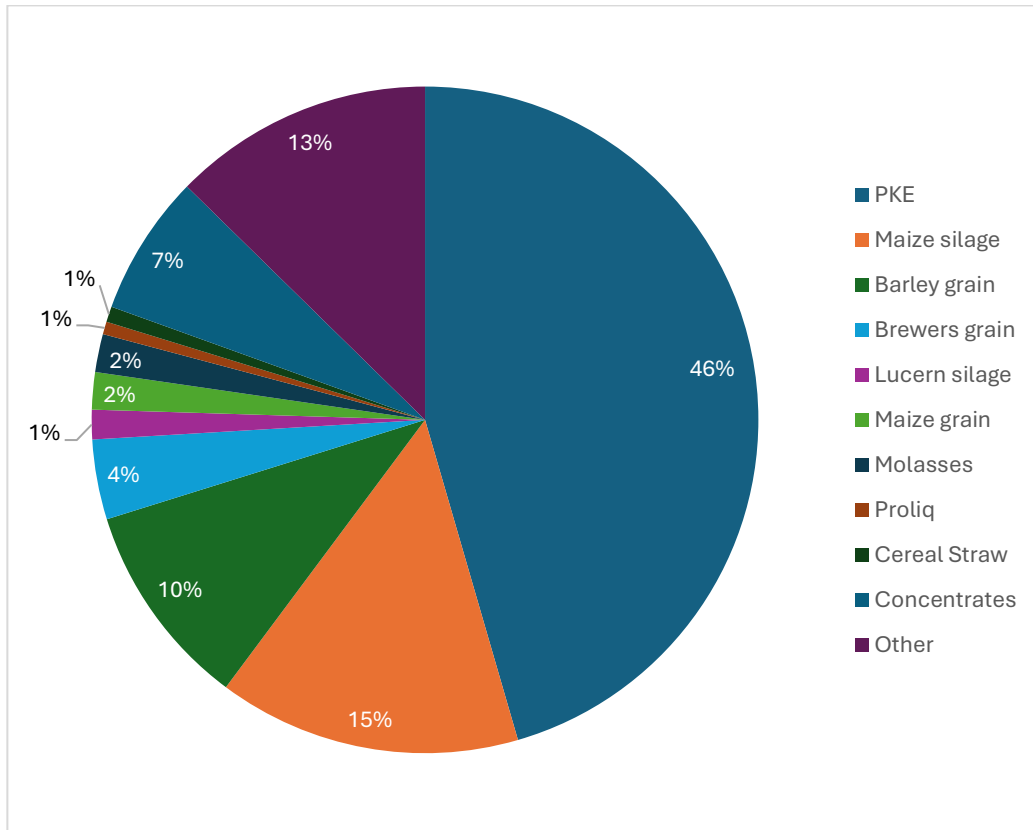


Figure 4.10. Proportion of supplementary feeds imported on to New Zealand dairy farms in 2021/22, calculated as the average kg DM/cow from the more detailed Dairybase (2024) data and multiplying this by the average number of cows, according to the more representative LIC (2022) data.

The importation of supplementary feed can introduce a large amount of P into the dairy systems. Using the nutrient content estimates of Gourley et al. (2010) it was estimated that in the 2021/2022 season an additional 2,208 kg P/farm were imported on average to New Zealand dairy farms via supplementary feeds (Table 4.18).

Table 4.18. Phosphorus (P) content of the most common imported feeds in New Zealand dairy farms, and the amount of P (kg P) imported (on average) per farm across the New Zealand dairy sector, for each feed type, and in total, in the 2021/2022 season. Based on the average tonnes imported (Table 4.17).

Imported feed type	Average P content as % of DM^{ab}	National average P imported in supplementary feeds (kg P/farm)
PKE	0.65	1,144
Maize silage	0.26	143
Barley grain	0.36	205
Brewers grain	0.67	124
Lucerne silage	0.42	34
Maize grain	0.39	55
Molasses	0.21	21
Proliq (mineral additive)	1.70	113
Cereal Straw	0.09	7
Concentrates	0.45	145
Other	0.50	225
Total		2,208

Source: DairyNZ (2012)^a, Gourley et al. (2010)^b.

4.6.2 Forage crops

Dairy

The forage crop data presented in Table 4.19 was sourced from Dairybase (2024) and the DairyNZ Economics Group (2019) to determine the average summer and winter crop block area, and dominant seasonal crop grown in each region. The most commonly used summer crop in New Zealand, across all the dairy regions was turnips, with fodder beet having been the most common winter crop. In the South Island regions, winter kale and swedes were used in conjunction with the fodder beets to help increase feed availability over that period (Table 4.19), with the winter cropping block, in general, being larger than the summer cropping block, except for the 'Taranaki' and 'East Coast + Lower North Island' regions where the summer crop block was larger in the 2021/2022 season.

Table 4.19. Area (ha) under summer and winter crops in the New Zealand dairying regions and the dominant crop types for each region.

	Summer crop (ha) ^a	Crop ^b	Winter crop (ha) ^a	Crop ^b
Northland + Auckland	15	Turnips	-	-
Waikato + Bay of Plenty	14	Turnips	15.2	Fodder beet
Taranaki	8	Turnips	4.8	Fodder beet +kale
East Coast + Lower				
North Island	12.26	Turnips	8.4	Fodder beet + Kale
West Coast +				Fodder beet +
Marlborough	11.2	Turnips	16	Swedes
				Fodder beet + Kale +
Canterbury	10.3	Turnips	15.13	swedes
				Fodder beet + Kale +
Otago + Southland	13.3	Turnips	13.9	Swedes

Source: Dairybase ^a, DairyNZ Economics Group (2019) ^b

4.6.3 Forage crops

Sheep and beef

As with the dairy sector, forage crops grown on farm are used to increase feed supply during seasonal deficits, most commonly during the winter and summer seasons. The data used in Table 4.20 were collected from the sheep and beef supplemental feed use reports produced by Sise et al. (2017, 2018), and Pers. comms B+LNZ (2025b). The predominant winter crops in the sheep and beef sector were kale and swedes, with leafy turnips used as summer feed. In their analysis of supplementary feed use in the sheep and beef industries of New Zealand, Sise et al. (2017, 2018) recorded that summer leafy turnips were used only for lamb grazing, winter kale was only grazed by cattle/beef livestock, and swedes were grazed by the cattle and mature sheep livestock.

Table 4.20. Area (ha) under summer and winter crops in New Zealand sheep and beef regions (by farm production class) and the dominant crop types for each region. The Summer crop used was leafy turnips and the winter crop was kale and swedes.

Production class	Summer crop area^b (ha)	Winter crop area^b (ha)
Northland + Auckland + Bay of Plenty		
3	2	2
4	3	4
5	3	13
Taranaki + Manawatū		
3	11	24
4	7	11
5	5	7
Gisborne + Hawkes Bay + Wairarapa		
3	6	7
4	12	7
5	6	13
Canterbury + Marlborough		
2	15	39
6	11	42
8	2	51
Otago + Southland		
2	15	39
6	3	38
7	2	18

Source: Pers. comms B+LNZ (2025b).

4.7 Discussion

4.7.1 Climate, fertiliser use and Olsen P

The long-term average rainfall data show that the areas dominated by dairy and sheep and beef farming tend to receive higher rainfall than the areas under arable and horticulture. While rainfall supports pasture growth, it can increase the risk of P loss, especially over the wetter winter and early spring months (Nash & Murdoch, 1997), where frequent and heavy rainfall events coincide with grazing events and winter grazing (McDowell et al., 2007), resulting in increased runoff and drainage events and thus P loss in dissolved and particulate forms (Gray et al., 2024).

The drier climate experienced in the Hawkes Bay, Marlborough, Canterbury and Otago regions (Figures 4.3 & 4.4), although challenging at times, is advantageous for crop production such as

wheat, maize and barley (hence the dominance of these crops in the South Island) as the lower rainfall experienced on average allows the grain crop to dry quickly to the desired moisture content. A drier climate is preferred in the production of most fruit crops, resulting in the faster ripening of fruit and increased sweetness (Mesejo et al., 2024; Villette et al., 2020). However, it can have negative implications on P utilisation, as reduced soil moisture significantly reduces the amount of soluble P in soil solution and thus the amount of P available for plant uptake (Mahmood et al., 2025; Suriyagoda et al., 2014). The use of irrigation, predominantly in the Canterbury region helps to overcome the limitations of the low rainfall climate, with approximately 546,205 ha of agricultural land irrigated across all sectors (Irrigation NZ, 2021).

Air temperature is another important factor that could influence P cycling, due to the strong relationship between air and soil temperature (Amato & Giménez, 2024; Islam et al., 2015). Overseer utilises the relationship between air and soil temperature to estimate the soil temperature in the top 5-10 cm of the soil profile, to aid in the modelling of processes such as mineralisation, immobilisation and denitrification (Wheeler, 2018b). Warmer soil temperatures can increase the amount of labile P in the soil P cycle by encouraging microbial P mineralisation and soil organic matter decomposition (Gianniny et al., 2024).

Phosphorus inputs to the agricultural industry in New Zealand, via chemical fertilisers have changed significantly over time, with an overall decrease seen in the total P fertiliser applied from 2011/12 to 2021/22 (Figure 2.2). Phosphorus fertiliser sales are largely impacted by dairy and sheep and beef farm revenue and the global price of Phosphate rock. Fluctuations in lamb and milk pricing have resulted in changes to the amount of P fertiliser applied (Hedley et al., 2011). The overall decline in average P fertiliser application rates, alongside interannual fluctuations in average application in the dairy sector (Figure 4.5) have likely been influenced by changes in the farmgate profit and P fertiliser prices. For example, between 2013/2014 and 2015/2016, P fertiliser application decreased by 11 kg P/ha, with farmers receiving an approximate \$5 decrease in farmgate price from \$8.40/kg MS in 2013/14 to \$3.90/kg MS in 2015/16 (Fonterra, 2014, 2016).

In the sheep and beef sector, increases in cash crop revenue and high forecast whole farm revenue could likely explain the peak in P fertiliser applications seen on the class 8 farms in the 2014/2015 season, and the increases in P application rate from 2019/2020 to 2021/2022 on the class 6 and class 8 farms across the South Island (B+LNZ, 2015, 2023b, 2025d). The lower average P application rate to the sheep and beef sector, in comparison to the dairy sector is due to the fact that on sheep

and beef farms, soil test values are targeted from an economic perspective, where sufficient fertiliser is applied to increase pasture production, for the lowest cost possible, often resulting in fertiliser applications that only cover the maintenance requirements ((Hedley et al., 2011; Roberts & Morton, 2024). As such, when farms are experiencing lower economic returns, less money is spent on P fertiliser.

The horticultural sector applied greater quantities of P per hectare (36 kg P/ha) than the dairy (28 kg P/ha), sheep and beef sector (20 kg P/ha) and the arable sector (27 kg P/ha) in the 2021/2022 season, despite utilising only 3% of the total annual fertiliser P, and occupying only 1% of the total agricultural land (Stats NZ, 2024). The application of P fertilisers within the horticultural sector varies significantly (Table 4.7), with the largest average application rate of P applied to the "Other fruit and tree nut" land use (102 kg P/ha) being greatly influenced by the inclusion of avocado farms. The avocado industry has been known to apply large amounts of P fertiliser in order to meet plant P requirements, determined using leaf sampling (van der Heijden & Kok, 2022). With no set industry standards (Monserrate et al., 2022), fertiliser recommendations have been made by farm consultants on a case by case basis. However in recent years, with greater understanding of how soil P concentrations affect avocado fruit production and post-harvest fruit quality (Hofman et al., 2002), industry recommendations have changed, with reduced P applications being advised in order to minimise the accumulation of cadmium in the soil, as well as the over enrichment of P.

Soil test P or Olsen P values relate to the amount of P applied to the soil and the soil's ability to retain P (ASC), with continual application of high levels of P (that are in excess of plant requirements) resulting in an accumulation of nutrients in the soil and increased Olsen P values (McDowell et al., 2001a). In the dairy sector, all production regions have weighted average Olsen P values at or above the target Olsen P value range of 20-30 mg P/L (Table 4.9), with the weighted sector average (an Olsen P of 37 mg P/L) also sitting above the target range. The elevated soil P nutrient status of the dairy soils increases the risk of P loss during surface runoff and leaching events (Koopmans et al., 2002; McDowell et al., 2001a), especially in the Waikato+ Bay of Plenty region where the Olsen P value (43 mg P/L) was significantly higher than the ash and sedimentary soil target range (20-30 mg P/L). However, soil P loss may not be as significant in the allophanic soils in the Waikato + Bay of Plenty and the Taranaki regions, (Table 4.1) due to the higher ASC of these soils and in turn a lower risk of P loss, compared to the recent or pallic soils found in other regions (Taylor et al., 2016). However, farm management practices, if managed poorly can result in large P losses for any soil.

Although the arable and horticultural industries do not have set sector Olsen P targets, the weighted average Olsen P values for the 2021/2022 season were found to be sufficient for most arable and horticultural production, as well as being within or above the target range set for pasture growth (Table 4.11). While P fertiliser application varies across the horticultural sector, the high application to the 'Other fruits and tree nuts', 'Vegetable', 'Kiwifruit', and 'Citrus' land uses (Table 4.8) contribute to elevated horticultural Olsen P values of 40 mg P/L in the current study. In an analysis of the soil quality of horticultural sites in Auckland, Curran-Cournane et al. (2014) found that 77% of sites exceeded the guideline Olsen P values [Olsen P target range of 20-40 mg P/L for brown, gley, organic, recent and ultic soils, and 20-50 mg P/L for allophanic and granular soils, based on the recommendations of (Mackay et al., 2013)], with soil Olsen P values ranging from 11 mg P/L to 361 mg P/L under a range of horticultural soils. The elevated horticultural Olsen P values measured in the current study, highlight an increased risk of P loss as dissolved and P in runoff.

4.7.2 Sector production

The area under dairy has increased by 4% from 2011/2012 to 2021/2022 (Table 4.12), while the area under sheep and beef, arable and horticulture decreased by 10%, 3.5%, and 0.5% (respectively) over the same period (Table 4.14, 4.15, & 4.16). This corresponded with an increase in milk solids produced from the dairy sector, a large decrease (-24%) in the number of sheep farmed and a slight increase (5%) in the number of cattle farmed. The increase in milk solids is a significant source of P exported from the dairy farm system, with approximately 30% of P consumed by dairy cows exported in milk and meat products (DairyNZ, 2013). This means that 30% of the P consumed is not recycled back into the farm system, resulting in a P deficit that requires replacement, often in the form of fertiliser P. However, with the application of P fertilisers to the dairy sector decreasing, but the soil Olsen P values remaining relatively stable, it suggests that P is being added to the farm system in another way. One significant source of P to the dairy system is imported supplementary feeds. Table 4.18 shows that the average New Zealand dairy farm imported 2.2 tonnes of P annually in the form of imported supplementary feed in the 2021/22 season. Although it may not be a large amount of P in comparison to the amount of fertiliser P applied in the dairy sector, this additional P is often overlooked as an input to soil P and contributes to the gradual accumulation of soil P and the potential loss of P to the surrounding environment from dairy farms.

Although the sheep and beef sector use very little to no imported supplementary feeds, the cash cropping areas of sheep and beef farms, and the wider arable and horticultural sectors contribute to nutrient transfers into the dairy system, and in turn the P enrichment of dairy soils. This is because

a lot of the cereal and grain crops grown in the sheep and beef and arable sectors are used for dairy feed (Millner & Roskrige, 2013), with fruits and vegetables such as kiwifruit, carrots, and potatoes also being used (Dairybase, 2024). This crop removal in the sheep and beef, arable and horticultural sectors result in a deficit of P that requires replacement via fertiliser P.

With the change in sheep and beef land area, and the shift towards more cattle livestock on sheep and beef farms (5% increase in cattle numbers), the risk of P loss from these larger class of livestock, especially on farms with steeper topography, is likely to increase. The most significant cause of P loss would likely result from the compaction and treading damage from the heavier cattle. When cattle are a component of hill grazing systems, P loss can be up to 1.6 kg P/ha/ year, whereas with sheep alone, losses are lower at around 0.11-0.75 kg P/ha/yr (Menneer et al., 2004).

The increasing number of cattle on sheep and beef farms and increasing dairy cow numbers also influences P loss from winter grazing blocks. The forage crops grown require additional fertiliser P applications, often between 15-30 kg P/ha/yr, and up to 60 kg P/ha/yr depending on soil fertility and crop type (Morton et al., 2020). As forage/fodder crops are largely used for winter grazing (Tables 4.19 & 4.20), the small grazing area and high stocking rate, in conjunction with a high likelihood of rainfall events at that time of year, increases the risk of treading and compaction damage, with P loss from these areas being a significant source of freshwater contamination if not managed properly (McDowell, 2006).

Chapter 5 Results

5.0 Dairy

Maintenance requirements

Each dairy case study region in Overseer was comprised of four block types; effluent, non-effluent and silage making up the milking platform, and a support block for grazing replacement heifers. Using the area weighted average Olsen P values for each region, the average national maintenance P requirement for the 2021/2022 season was estimated to be 35 kg P/ha/yr for the dairy sector (Table 5.1). Maintenance P was not required on effluent blocks for six out of the seven regions, with P applied from effluent meeting maintenance needs. Only in the West Coast + Marlborough region was maintenance P required for the effluent block, which was an average of 12 kg P/ha/yr.

Regionally, the average P maintenance requirements ranged from 26 to 51 kg P/ha (Table 5.1). The highest P maintenance requirements were determined for the West Coast + Marlborough and Waikato + Bay of Plenty regions which had P maintenance requirements of 51 and 42 kg P/ha, respectively. The higher maintenance requirement of the Waikato + Bay of Plenty region was potentially influenced by the elevated maintenance requirement of the larger silage block (48 kg P/ha/yr over 72 ha), and the higher ASC soils present in the region [i.e. allophanic soils with an average ASC of 83% (Table 3.10)]. The correlation between the weighted average maintenance P requirements and the soil ASC was moderately positive ($r=0.69$, Table C.5) across all regions. Soils with high ASC values (greater than 60%) require more P fertiliser to be applied to overcome the soil sorption processes and, therefore, ensure sufficient plant available P (Tyson et al., 2020). For the West Coast + Marlborough region, the higher maintenance P requirement is mostly influenced by the organic soils present, high rainfall, and significant change in soil P pools, with large amounts of P being partitioned into the organic soil pool. Across all regions, there was a strong positive correlation between rainfall and weighted average maintenance P requirement ($r=0.72$, Table C.5). The West Coast + Marlborough region is also the only dairy region that, on average, cannot meet the maintenance P requirements of the effluent block using farm generated effluent. This means that fertiliser P is required, on top of the effluent applied to maintain soil Olsen P levels. This in turn explains why the regional maintenance P requirements are elevated for West Coast + Marlborough.

Organic soils in the West Coast + Marlborough region have a high risk of P loss via runoff and leaching (Taylor et al. 2016) [due to their high porosity, hydraulic conductivity and low P retention (Simmonds et al., 2015)], and combined with an average annual rainfall of 2,999 mm has resulted in Overseer estimating that 3.3 kg P/ha/yr is removed as leaching/runoff and direct losses (Table 5.2). Furthermore, a strong, positive correlation was identified between rainfall and the partitioning of P to the organic soil pool across all regions ($r=0.89$), with less P going to the inorganic mineral and inorganic soil (plant available) pools.

The lowest maintenance P requirements were estimated in the Otago + Southland, Northland + Auckland, and East Coast + Lower North Island regions with values of 26, 27, and 27 kg P/ha respectively. The lower maintenance P requirements in these regions could be attributed to the low P exports in runoff, likely influenced by the low rainfall experienced in these regions, and the less extreme partitioning of P into the organic and inorganic mineral pools (when compared to the West Coast + Marlborough and Taranaki regions) due to the lower ASC values of the brown and pallic soil orders present in these regions (Table 4.1 & 4.3). The estimated maintenance P requirements for the support blocks of the dairy regions ranged from 20 kg P/ha in the East Coast + Lower North Island and Otago + Southland regions to 35 kg P/ha in the West Coast + Marlborough region.

Nationally, the total dairy maintenance P requirement for 2021/2022 was estimated to be 59,579 tonnes P per year (Table 5.1). Regionally, total P requirements were estimated to be the highest in the Waikato + Bay of Plenty region with 23,224 tonnes P/yr, followed by the Canterbury, and Otago + Southland regions, which had estimated total maintenance P requirements of 9,041 tonnes and 8,121 tonnes of P respectively (Table 5.1).

Phosphorus budget

In addition to determining the P maintenance requirements, the Overseer models provided averaged whole farm nutrient budgets, which were used to estimate a national dairy P budget. In Overseer, the pool determining a P surplus or deficit is the inorganic soil pool. Looking at the national dairy P budget (Table 5.2), an average of 25 and 10 kg P/ha/yr are applied to the total farm area of New Zealand dairy farms in the form of fertiliser and supplements, respectively (Table 5.2). The application of P fertiliser ranged from 19 kg P/ha in the Northland + Auckland region to 31 kg P/ha/yr in the West Coast + Marlborough region, with additions of supplementary feed P ranging from 7 kg P/ha/yr in the West Coast + Marlborough region to 13 kg P/ha/yr in the

Waikato + Bay of Plenty region. Phosphorus removal from the farm system is calculated as P removed via runoff/leaching and direct losses, and P removed as product. It was estimated that in the 2021/2022 season, the New Zealand dairy sector (as estimated in Overseer) lost an average of 1.2 kg P/ha/yr via runoff/leaching and direct losses, with the regional losses ranging from 0.7 kg P/ha/yr in the Otago + Canterbury region to 3.3 kg P/ha/yr in the West Coast + Marlborough region. Phosphorus exported off farm in product was on average 12 kg P/ha/yr in New Zealand, with regional values ranging from 9 kg P/ha/yr in the Northland + Auckland and West Coast + Marlborough regions, to 16 kg P/ha/yr in the Canterbury region. The correlation table (Table C.5) shows that rainfall and P loss via leaching/runoff was highly positively correlated across all regions ($r=0.89$).

The export of P as product is related to the milk and meat produced on farm, which is then exported out of the farm system. The Canterbury region produced the most milk solids per effective hectare (1451 kg MS/ha) and per cow (424 kg MS/cow) (Table A.2 & A.3) and had the highest stocking rate (3.42 cows/ha) of all the dairying regions. These high levels of production influence the export of P in the 2021/2022 season, with 16 kg P/ha exported in product. The low production rates of the Northland + Auckland region also reflects the relationship between production and P export in product, as this region produced an average of 797 kg MS/ha and 304 kg MS/cow in the 2021/2022 season (with a stocking rate of 2.52 cows/ha) and had the lowest P exports as product of 9 kg P/ha.

Nationally, in the 2021/2022 season, the average dairy P balance was 3 kg P/ha/yr in the inorganic soil pool (plant available pool). Moreover, the national dairy soils tend to be accumulating an average of 11 kg P/ha in the organic soil pool and 6 kg P/ha/yr in the inorganic mineral pool (P retained in soil or legacy P) in the same season. Further changes in P pools were a deficit/removal of P from standing plant material at -2 kg P/ha/yr, and an accumulation of P in the root and stover residuals and supplement storage at 2 kg P/ha/yr (Table 5.2).

Regional P balances ranged from an estimated deficit of 4 kg P/ha/yr in the West Coast + Marlborough region, to a surplus of 7 kg P/ha/yr in the Otago + Southland region (Table 5.2), with changes in soil inorganic mineral P pool ranging from an estimated accumulation of 2 kg P/ha/yr in the East Coast + Manawatū, Canterbury, and Otago + Southland regions, to 15 kg P/ha/yr in the Taranaki region. Phosphorus accumulation in the organic P pool ranged from 8kg P/ha/yr in the Canterbury region to 22 kg P/ha/yr in the West Coast + Marlborough.

Table 5.1. The weighted average dairy farm maintenance phosphorus (P) requirements (kg P/ha) for each dairy production region in New Zealand using weighted average Olsen P values to calculate the average block maintenance requirements (kg P/ha) and the total maintenance P requirements at the block, farm, regional and national level (kg P and tonnes P) for the 2021/2022 season. Modelled using Overseer v6.5.9.

Dairy maintenance requirements	Northland + Auckland	Waikato + Bay of Plenty	Taranaki	East Coast + Lower North Island	West Coast + Marlborough	Canterbury	Otago + Southland	New Zealand
Area (ha)								
Farm effective area	132	170	109	189	162	235	217	
Effluent block	18	24	20	30	23	68	40	
Non-effluent	87	75	52	128	99	123	107	
Silage block	27	72	37	31	40	44	70	
Support block	42	60	30	51	45	85	65	
Block maintenance requirements (kg P/ha)								
Effluent block	0	0	0	0	12	0	0	
Non-effluent	18	30	32	22	41	30	17	
Silage block	35	48	49	41	59	48	36	
Support block	26	26	24	20	35	21	20	
Total block P requirement (kg P)								
Effluent	0	0	0	0	276	0	0	
Milking platform	1,561	2,235	1,664	2,823	4,075	3,678	1,826	
Non-effluent	956	3,432	1,813	1,259	2,336	2,131	2,502	
Support block	1,097	1,555	720	1,010	1,575	1,785	1,300	
Total farm maintenance P requirement (kg P)								
	3,613	7,222	4,197	5,091	8,263	7,594	5,628	
Total regional maintenance P requirements (tonnes P)								
	3,988	23,224	6,361	4,068	4,776	9,041	8,121	59,579
Total regional effective area (ha)								
	145,698	552,952	165,198	151,006	93,644	279,765	313,117	1,701,380
Weighted average maintenance P requirements (kg P/ha)								
	27	42	39	27	51	32	26	35

Table 5.2. Phosphorus (P) budgets for regional case study dairy farms (using the weighted average Olsen P values for each region), showing the average inputs, outputs and change in soil pools (kg P/ha) and the nationally weighted averages (kg P/ha), for the 2021/2022 season. Modelled using Overseer, v6.5.9.

Inputs/Outputs (kg P/ha/yr)	Northland + Auckland	Waikato + Bay of Plenty	Taranaki	East Coast + Lower North Island	West Coast + Marlborough	Canterbury	Otago + Southland	National mean
P added								
Fertiliser	19	24	28	21	31	27	24	25
Supplements	8	13	11	8	7	8	11	10
P removed								
Leaching, runoff and direct losses	1.6	1.1	0.8	1.2	3.3	1	0.7	1.2
As product	9	11	12	11	9	16	13	12
Change in pools								
Organic pool	10	11	9	10	22	8	11	11
Standing plant material	-2	-3	-2	-2	-3	-2	-2	-2
Inorganic mineral	3	9	15	2	4	2	2	6
Change in supplement storage	0	4	4	1	4	2	2	3
Root and stover residuals	1	2	2	3	3	3	2	2
Inorganic soil pool (surplus/deficit)	4	1	-2	4	-4	6	7	3
Total farm P loss (kg P)	211	187	87	227	535	235	152	208

5.1 Sheep and beef

Maintenance requirements

The national average maintenance requirement of the sheep and beef sector (Table 5.3) was estimated to be 18 kg P/ha/yr for the 2021/2022 season. The regional averages ranged from 15 kg P/ha/yr in the Marlborough + Canterbury region to 22 kg P/ha/yr in the Northland + Waikato + Bay of Plenty region (Table 5.3). At a farm production class level, the weighted average maintenance P requirement ranged from 13 kg P/ha/yr on the Marlborough + Canterbury class 2 farms to 27 kg P/ha/yr on the Northland + Waikato + Bay of Plenty class 5 farms, with the North Island production classes tending to have the highest P maintenance requirements (Table C.1 & C.2).

The maintenance requirements of the sheep and beef regions were made up of the average of 6 different block types, differentiated by topography (flat, rolling, easy hill, and steep hill blocks) and block management [new pasture (re-established rye-clover pasture on flat topography) and silage blocks]. The average regional production class maintenance requirements ranged from 13 kg P/ha/yr for the Marlborough + Canterbury class 2 farms to 27 kg P/ha/yr for the Northland + Waikato + Bay of Plenty class 5 farms (Table C.1 & C.2). Across all regions and production classes, the maintenance P requirements of the silage blocks were estimated to be significantly higher than the other block level requirements, ranging from 29 kg P/ha/yr on the Taranaki + Manawatū region class 4 farms to 45 kg P/ha/yr on the Northland + Auckland + Bay of Plenty region class 5 farms.

Overall, the North Island sheep and beef farms tend to have higher maintenance P requirements than the South Island sheep and beef farms, with the weighted average maintenance requirements of the North Island sheep and beef farms estimated to be 20 kg P/ha/yr (ranging from 19 to 22 kg P/ha/yr in the Gisborne + Hawkes Bay + Wairarapa and Northland + Waikato + Bay of Plenty regions, respectively). The South Island sheep and beef farm maintenance P requirement was estimated to be 16 kg P/ha/yr (ranging between 15 and 17 kg P/ha/yr in the Marlborough + Canterbury and Otago + Southland regions, respectively).

Table 5.3. Average regional, North Island, South Island, and national maintenance phosphorus (P) requirements (kg P/ha) for the sheep and beef sector under current soil test levels adjusted for topography (Olsen P level of 25 mg/L for flat, 22 mg/L for rolling, 19 mg/L for easy hill and 16 mg/L for steep hill). The national sheep and beef maintenance value estimated by Hedley et al (2011) has also been included for comparison. Modelled using Overseer, v6.5.9.

	Estimated maintenance P requirements (kg P/ha/yr)	
	Based on scaled Olsen P	
	values	2007/2008 estimation*
Northland + Waikato + Bay of Plenty	22	
Taranaki + Manawatū	20	
Gisborne + Hawkes Bay + Wairarapa	19	
North Island	20	
Marlborough + Canterbury	15	
Otago + Southland	17	
South Island	16	
National	18	12

*2007/2008 estimation by Hedley et al. (2011) at a national level only.

Phosphorus budget

The P budget modelled for the sheep and beef sector showed an average of 11 kg P/ha/yr being added, across the total farm area (effective + non-productive), as fertiliser, ranging from 7 kg P/ha/yr in the Marlborough + Canterbury region, to 14 kg P/ha/yr in the Northland + Waikato + Bay of plenty region (Table 5.4). Phosphorus fertiliser additions vary further between the farm production classes, with the Marlborough + Canterbury and Otago + Southland class 2 farms applying the least amount of P at 3 kg P/ha/yr and 5 kg P/ha/yr, respectively and the Northland + Waikato + Bay of Plenty class 5 and Otago + Southland class 7 farms applying the most P fertiliser at 17 kg P/ha/yr and 18 kg P/ha/yr, respectively, in the 2021/2022 season.

The elevated fertiliser P application in the Northland + Waikato + Bay of Plenty region is likely influenced by farm topography, with a moderate negative correlation between P added in fertiliser and the area under steep hill ($r = -0.63$, Table C.6). The predominantly flat, rolling, and easy hill topography of the North Island class 5 farms (Table B.1), allows for higher rates of fertiliser P application (due to easier access to farm area thus lower spreading costs), whereas the lower pasture production potential of the steeper slopes present largely in the South Island class 2 farms, makes it less economic to apply high rates of P. Thus reducing the annual P application rate and overall farm Olsen P value.

However, despite the fact that the average Marlborough + Canterbury region class 8 farm is predominantly flat/rolling in topography [81.4% of farm area is under low slope <12° (Table B.1)], a relatively low average 'pasture P' application rate was determined for the 2021/2022 season, of 6 kg P/ha. When aggregated to a regional average in combination with fertiliser application to the other farm production classes in the Marlborough + Canterbury region, the average regional fertiliser P application rate remained low at 7 kg P/ha. This is likely because the class 6 and class 8 farms in the Marlborough + Canterbury region have a larger proportion of land under cash cropping compared to the rest of the sheep and beef regions and production classes, which in turn receive the majority of the fertiliser applied (Table A.4 & A.5).

The average total P removal from the national sheep and beef sector was modelled as 3 kg P/ha/yr, with 0.5 kg P/ha/yr removed as runoff/leaching, 2 kg P/ha/yr removed as product, and 0.2 kg P/ha/yr in supplements. The total P removal varied across the regions and farm classes, from 2.0 kg P/ha/yr removed in the Gisborne + Hawkes Bay + Wairarapa region (0.4 kg P/ha via leaching, runoff and direct losses and 1.6 kg P/ha exported as product) to 4.1 kg P/ha/yr in the Marlborough + Canterbury region (0.2 kg P/ha as leaching, runoff and direct losses and 3.9 exported as product) (Table 5.4).

The steeper hill topography of the Northland + Waikato + Bay of Plenty region's class 3 and 4 farms [hard hill and hill country farms (Table B.1)] likely had the largest influence on the elevated P loss via leaching and runoff of the total regional P balance, with the elevated rate of fertiliser P applied further increasing the amount of P lost. There was a moderate correlation between rainfall and the P lost in runoff ($r=0.55$).

The soil organic P pool increased at an average of 7.7 kg P/ha/yr, ranging from 6.2 kg P/ha/yr in the Taranaki + Manawatū region to 9.1 kg P/ha/yr in the Gisborne + Hawkes Bay + Wairarapa region. Further accumulation of P is seen in the inorganic mineral pool (legacy P), with 1.7 kg P/ha/yr accumulating on average, with a range of 1.0 kg P/ha/yr in the Gisborne + Hawkes Bay + Wairarapa and Marlborough + Canterbury regions, to 3.3 kg P/ha/yr in the Taranaki + Manawatū region (Table 5.4).

On average, New Zealand sheep and beef farms are operating in an overall P deficit of -2 kg P/ha/yr in the size of the soil inorganic pool (Table 5.4). The regional averages ranged from a P surplus of +1.1 kg P/ha/yr in the Taranaki + Manawatū region to P a deficit of -6.6 kg P/ha/yr,

Marlborough + Canterbury region. There is further variation on P budgets between the farm classes, with the largest P deficit seen on the Marlborough + Canterbury class 8 farms where an estimated -21 kg P/ha/yr reduction in the inorganic mineral pool was estimated (Table C.4). The types of enterprises undertaken on the sheep and beef farms likely have a large influence on the transformation of P in the soil, with the area under cash cropping being found to have a strong negative correlation with the partitioning of P into the organic soil and inorganic soil pools ($r=0.78$ and $r=0.82$, respectively). Cash cropping was also positively correlated to the amount of P exported as product and supplements ($r=0.98$), across all regions and farm classes. As such, the large cash cropping enterprises in the Marlborough + Canterbury region class 8 farms resulted in a large amount of P mining from the farm system.

Table 5.4. Phosphorus (P) budgets for the regionally representative sheep and beef case study farms, and the national average P budget of the sheep and beef sector, showing the averaged inputs, outputs and change in soil pools (kg P/ha) for the 2021/2022 season. Modelled using Overseer, v6.5.9.

Inputs and Outputs (kg P/ha/yr)	Northland + Waikato + Bay of Plenty	Taranaki + Manawatū	Gisborne + Hawkes Bay + Wairarapa	Marlborough + Canterbury	Otago + Southland	National
P added						
P fertiliser	14	12	11	7	11	11
P removed						
Leaching, runoff and direct losses	1.5	0.4	0.4	0.2	0.1	0.5
As product	1.9	1.7	1.6	3.9	2.0	2.3
Change in pools						
Standing plant material	-0.1	-1.0	-0.6	-1.1	-1.0	-0.8
Organic pool	7.1	6.2	9.1	7.1	8.3	7.7
Inorganic mineral	2.9	3.3	1.0	1.0	1.3	1.7
Change in supplement storage	0.1	0.0	0.2	0.0	0.0	0.1
Root and stover residuals	0.1	0.5	0.6	1.7	1.0	0.9
Inorganic soil pool (surplus/deficit)	0.4	1.1	-1.7	-6.6	-0.3	-2.0

5.2 Arable and horticulture

Due to the complexity of the arable and horticultural farm systems, and their dynamic relationship with soil P transfers and losses, it was not possible to model any average regional or national arable and horticultural farms in Overseer, and thus it was not possible to estimate the maintenance P requirements of these sectors for the 2021/2022 season in the same way as for the pastoral sector. Instead, the P use of these two sectors were assessed.

It should be noted that there is the possibility of having double accounted for some arable area in New Zealand, especially in the Marlborough + Canterbury region, where large portions of the farm area are used for cash cropping which can include the production of grain and cereals. This may result in a greater P use in the arable sector, or a slight over estimation of the sheep and beef maintenance P requirements.

The total P use in the arable sector was 6,210 tonnes in the 2021/2022 season (Table 5.5), with land growing grain applying a total of 2,874 tonnes P, and land under other crop growing applying 3,336 tonnes P (Table 4.8). This resulted in an average national arable fertiliser P application rate of 27 kg P/ha, ranging from an average of 17 kg P/ha/yr under grain growing to 55 kg P/ha under other cropping. The total fertiliser P applied to the horticultural sector was 4,593 tonnes for the 2021/2022 season (Table 5.5), with the amount of P applied to the respective horticultural land uses ranging from 4 tonnes P applied to olive growing to 2,033 tonnes applied to vegetable growing (Table 4.7). The average per hectare fertiliser P application rate for the horticultural sector was estimated to be 36 kg P/ha/yr, ranging from 6 kg P/ha under olives, to 102 kg P/ha/yr under 'Other fruit and tree nut' (Table 4.7).

5.3 Phosphorus requirements of New Zealand agriculture

The P requirements of the pastoral farming sectors of New Zealand was estimated to be 146,400 tonnes P in the 2021/2022 season, which was calculated as 4.82 million ha under sheep and beef effective areas requiring 18 kg P/ha in maintenance P, and 1.7 million ha under dairy requiring 35 kg P/ha in maintenance P (Table 5.5). When combined with the P use of the arable and horticultural sectors (227,594 ha under arable applying 27 kg P/ha and 127,000 ha under horticulture applying 36 kg P/ha), the total national P requirements for the 2021/2022 season were estimated to be 157,259 tonnes P (Table 5.5)

Table 5.5. Estimated total national agricultural fertiliser P maintenance requirements for the sheep and beef, dairy (using the current Olsen P values for the dairy regions), arable, and horticultural sectors for the 2021/2022 season. Modelled using Overseer, v6.5.9 and using the method of Hedley et al. (2011).

	Sheep and beef	Dairy	Pastoral total	Arable	Horticulture	National
Area (ha)	4,816,520	1,701,380		227,594	127,000	
P maintenance (kg P/ha)	18	35		27	36	
P maintenance (tonnes)	86,877	59, 579	146,456	6,210	4,593	157,259

Chapter 6 Discussion

6.0 Estimated phosphorus maintenance requirements

The national average maintenance P requirements for the dairy and the sheep and beef sectors were estimated to be 35 kg P/ha and 18 kg P/ha, respectively (Table 5.1 & 5.3), for the 2021/2022 season. These estimated P maintenance requirements have changed from the estimations made by Hedley et al. (2011) (Figure 6.1), with the estimated dairy maintenance requirements having decreased, and the sheep and beef maintenance requirements having increased over time. Hedley et al. (2011) estimated the dairy maintenance requirements to be 0.051 kg P/kg MS for cows on volcanic soils, and 0.046 kg P/kg MS for cows on sedimentary soils. The maintenance requirements of the sheep and beef sector was estimated to be 1.4 kg P/SU (stock unit) for the 2007/2008 season. When converted to a per hectare basis, the estimates by Hedley et al. (2011) were 42 kg P/ha for the dairy sector (across all soils) which is 7 kg P higher than the estimated maintenance P requirements for the dairy sector in the current study which examined the 2021/2022 season. Hedley et al. (2011) estimated the sheep and beef maintenance requirement to be 12 kg P/ha/yr (when converted from kg P/SU to kg P/ha) which is 6 kg P/ha lower than the estimated maintenance P requirements of the sheep and beef sector for the 2021/2-22 season.

The current research estimates for the 2021/2022 season, show a decrease in total maintenance P requirements for the dairy sector and an increase in maintenance P requirements for the sheep and beef sector, however it is important to acknowledge differences in the methodologies used in the current vs Hedley et al. (2011) study. The decrease in total estimated dairy maintenance P requirements (from 64,000 tonnes P to 59,579 tonnes P) are likely due to the inclusion of effluent and imported supplementary feed in the current study (Table A.3). The effluent and imported supplementary feed are additional sources of P into the farm system which reduce the amount of fertiliser P required to maintain soil Olsen P values in the dairy sector.

The increase in sheep and beef per hectare maintenance requirements is likely related to the increased soil Olsen P values measured in 2021/2022 and used in the current research. Hedley et al. (2011) stated that the Olsen P of the low to medium fertility sedimentary soils used for their case study farm was 12 mg P/L, which was lower than the Olsen P range of 16 mg P/L (for steep land) to 25mg P/L (for flat land) used in the current research. The elevated soil Olsen P values used in the current research result in the requirement of more fertiliser P to maintain the soil test

P levels (Coad et al., 2014; Tyson et al., 2020). However, the total maintenance requirement for the sheep and beef sector decreased from 91,000 tonnes P to 86,877 tonnes P, likely due to the decrease in sheep and beef area, and a shift in livestock types (sheep to cattle).

The total P requirements of the pastoral farming sectors in 2021/2022 was estimated to be 146,456 tonnes P/yr (Table 5.5), with the dairy sector estimated maintenance making up 41% of the pastoral maintenance requirement, and the sheep and beef sector making up the other 59% in the 2021/2022 season. When comparing fertiliser P use in the 2021/2022 season to maintenance requirements, P fertiliser use did not meet maintenance requirements as the maintenance requirements of the pastoral farming sectors alone was approximately 3,627 tonnes greater than the total amount of fertiliser P applied to the whole agricultural industry, of 142,829 tonnes [the average of both the FANZ (2022g) and Stats NZ (2024) P applied values] in the 2021/2022 season.

At a sector level, the average P applied based on the Stats NZ (2024) and FANZ (2022d) data estimated that 42% of the total (142,829 tonnes) fertiliser P was applied to land under dairy, and 49% was applied to land under sheep and beef (Table 4.4), which calculates to 59,988 tonnes and 69,986 tonnes respectively.

The averaged total fertiliser P applied to land under dairy (59,988 tonnes P) indicates that the estimated maintenance P requirements (59,579 tonnes P) of the dairy sector were met by fertiliser P applications, suggesting that soil Olsen P values are likely maintained, with minimal increase or decrease depending on the true application rate. The averaged total fertiliser P applied to land under sheep and beef (69,986 tonnes P) indicates the possibility that the estimated maintenance P requirements (86,877 tonnes P) of the sheep and beef sector were not met by fertiliser P applications, suggesting a mining of soil P reserves in order to support pasture production..

Although current P use/application is used as a proxy for P maintenance requirements for the arable and horticultural sectors in the current study, fertiliser P use can provide some guidance to the wider agricultural industry P maintenance requirements. Fertiliser P is often applied in arable and horticultural systems to replace the nutrients removed from crop/plant harvest, as many of the physical farming practices like cultivation and whole plant harvest affect the soil nutrient status. As such, soil maintenance requirements are hard to estimate/model.

The per hectare application of P to arable land increased by 200% from 9 kg P/ha estimated by Hedley et al. (2011) to 27kg P/ha in the 2021/2022 season. Hedley et al. (2011) reported on land under vegetable production, whereas the current study looks at the larger horticultural sector, which includes vegetable production. Table 4.7 provides a breakdown of the land uses included in the horticultural sector, and shows that the total tonnes of P applied to the area under vegetable production (under cover and outdoors) in the 2021/2022 season was approximately 2,033 tonnes (Table 4.7), which is a 55% decrease from the total tonnes reported by Hedley et al. (2011) (4,500 tonnes P), with the per hectare application rate also decreasing, from 68 kg P/ha to 52 kg P/ha (a 24% decrease) in the 2021/2022 season.

The large increase in the per hectare application rate to the arable sector could be attributed to the significant reduction in arable cropping area (38% decrease), from approximately 369,000 ha in 2007/2008 (Hedley et al., 2011) down to approximately 228,000 ha in 2021/2022, utilised to produce maize, wheat, barley, peas, oats, herbage seeds and other arable crops. Within the horticultural sector, a significant amount of P per hectare was applied to land under 'Other fruit and tree nut' production, which includes avocado growing, with approximately 102 kg P/ha applied in the 2021/2022 season.

Table 5.5, and fertiliser breakdowns by Stats NZ (2024) and FANZ (2022d) demonstrate that these industries are only small contributors to the total amount of fertiliser P used and the total maintenance requirements of the agricultural industries, not only in the 2021/2022 season, but likely in the future too. According to Stats NZ (2024) and FANZ (2022d), the arable and horticultural sector apply a total of 10,800 tonnes P (an average of 4 and 3.5%, respectively), which is a small amount in comparison to the total P applied by the pastoral sector. As such, the true P maintenance requirements of the arable and horticultural sectors are unlikely to have a significant influence on the total agricultural industry maintenance requirements.

Combining the P maintenance requirement of the pastoral sectors and the P use of the arable and horticultural sectors, the maintenance/use P requirements for the 2021/2022 season was estimated to be 157,259 tonnes of P, which is approximately 5,800 tonnes less than the estimated 163,000 tonnes of maintenance P required for the 2007/2008 season, and approximately 25,800 tonnes less than the forecast maintenance P requirements for the 2013/2014 season made by Hedley et al. (2011) (Figure 6.1).

While no analysis of the actual 2013/2014 season's maintenance requirement has been undertaken, Figure 6.1 indicates that the P maintenance requirements estimated in the current research is only slightly lower than the total maintenance P requirements estimated for the 2007/2008 season by Hedley et al. (2011), and shows that the estimated national maintenance requirements for both seasons are relatively close to actual P use in those same seasons. This suggests that there would be minimal impact on the soil Olsen P values at a national level, which is supported by the relatively stable trend in Olsen P values recorded by FANZ (2022f) over the same period. The decrease in estimated maintenance P requirements from that estimated by Hedley et al. (2011) is likely due to an increase in uptake of BMP's on farm which range from fencing off waterways, riparian planting, and strategic fertiliser applications to the improvement of effluent systems (management, storage and application), constructed wetlands and feed-pad facilities (Macintosh et al., 2025; McDowell et al., 2023) especially on intensive dairy farms. An overall decrease in agricultural area has also likely had an influence.

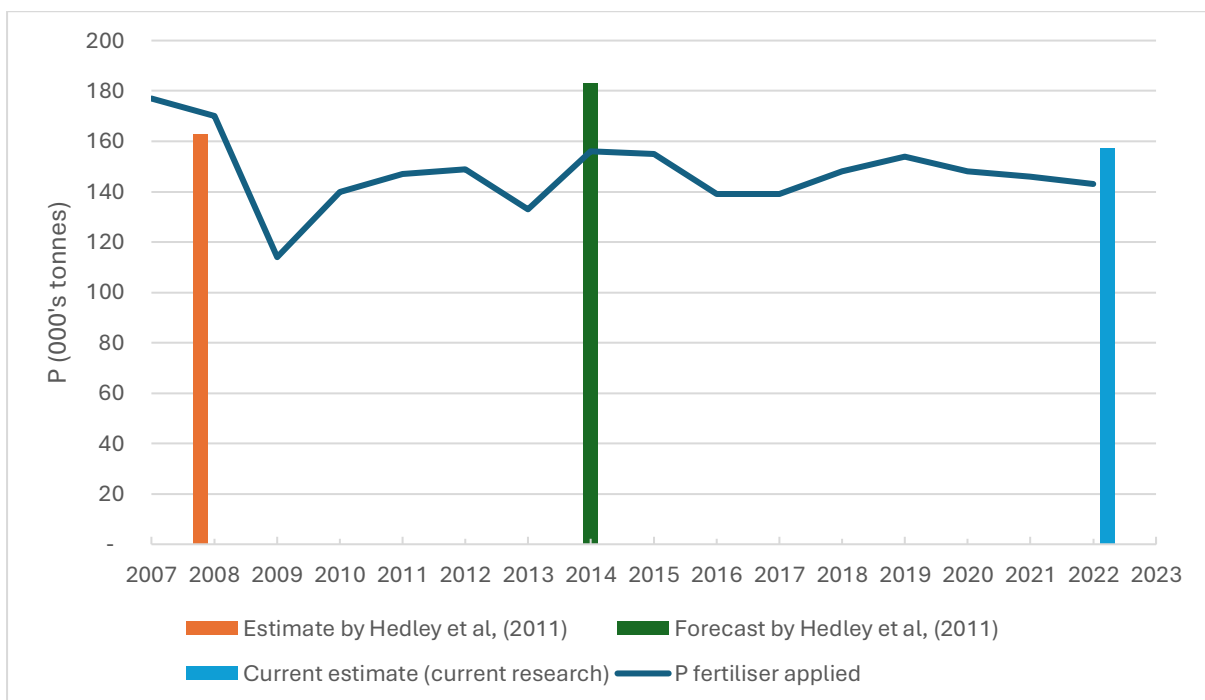


Figure 6.1. Quantities of total fertiliser P applied to the agricultural industry in New Zealand and the maintenance P requirements estimated (2008) and forecast (2014) by Hedley et al. (2011), and the current P maintenance and use estimate based on the 2021/2022 season (current study).

Since the report by Hedley et al. (2011), the total area under agriculture has decreased by 14%, from approximately 15.3 million hectares, to 13.2 million hectares in 2021/2022, influenced by a shift in land-use out of pastoral farming, towards urban development, exotic forestry (8.3%

increase), and native forest (42% increase) (Journeaux et al., 2017; Pers. Comms Stats NZ info-centre, 2025). Within the agricultural industry, the total area under sheep and beef production decreased by 14% with a 10% decrease in effective area from 2011/2012 to 2021/2022 (Table 4.11), likely due to a shift towards forestry on the steeper, less productive areas of the farms. A 3.5% decrease in arable area was also observed from 2011/2012 (Table 4.13). On the other hand, the dairy sector saw a 4% increase in effective area, from 1.64 million hectares in 2011/2012, to 1.7 million hectares in 2021/2022.

These changes in land area were forecast to shift slightly according to the June 2022 Situation and Outlook for the Primary Industries report released by the Ministry for Primary Industries (2022). A slight downward trend in the national dairy herd and land use area was expected to continue, along with static or decreasing areas under horticulture and arable production.

6.1 Soil test P values

Soil test P values and accumulation of P in soil is directly related to the ability of a soil to retain or lose P and to the amount of P applied, with continual application of excessive amounts of fertiliser P leading to over enriched soils, and soil test values beyond agronomic optimums (Chen et al., 2022; Sharpley & Tunney, 2000). Between 2002 to 2014, McDowell et al. (2019b) found that the mean annual Olsen P value for most regions in New Zealand (across all soil types) had increased slightly, with a decrease in the number of soil tests exceeding the target Olsen P values on volcanic and pumice soils, and increased soil enrichment on sedimentary and peat soils. In an analysis of the median Olsen P of soils across New Zealand over the 2001-2015 period, McDowell et al. (2020a) found that the median Olsen P values had increased by 1.2% . These increases in soil Olsen P are likely supported by the slight increase in P fertiliser sold over that period (Figure 2.2), and the increase in imported supplementary feed use, in particular PKE (Densley et al., 2023). According to the soil test results presented by the FANZ (2022f), the median soil Olsen P values have increased slightly from 2015 to 2021 for both dairy and sheep on volcanic and sedimentary soils, with the pumice and peat soil test values being much more varied annually.

The current study has shown that P fertiliser applications are likely matching the P maintenance requirements of the New Zealand dairy sector, however, there are environmental concerns with maintaining Olsen P levels above the target range as high Olsen P levels are associated with both

higher risk of P loss to freshwater, and long term legacy P losses to soil (Kleinman et al., 2011; McDowell et al., 2004; McDowell et al., 2020a; Nash et al., 2019; Stackpoole et al., 2019).

Within the sheep and beef sector, the estimated maintenance P requirement exceeded the fertiliser P applied for the 2021/2022 season and as a result, the Olsen P values (Table 4.10) are likely to decline overtime. However, as the average Olsen P values for the 2021/2022 season were within the target range (a weighted average of 22 to 26 mg/L) across all sheep and beef regions and production classes, it is unlikely that farm production would be negatively affected in the short term. Long term however, if the application of below maintenance rates of fertiliser P were to continue, soil P concentrations would likely reduce to below the target range, as the pasture and crops utilise the soil P reserves, negatively impacting pasture production and in turn animal production (Edmeades et al., 2006).

The elevated rate of P application to the 'other fruit and tree nut' horticultural land use, has likely contributed to the high weighted average Olsen P of 40mg P/L in the horticultural sector, with McDowell et al. (2020a) reporting a similar median Olsen P value of 39 mg P/L over the period from 2011 to 2020. It is likely that the high P application rates seen on land growing 'Other fruit + tree nuts', exceeded the soil maintenance requirements, with the increasing trend in soil Olsen P values (FANZ, 2022f) supporting the observation that P is accumulating under horticultural soils. By contrast, soil Olsen P values under arable land use are more stable, indicating that the maintenance P requirements are likely being met, through fertiliser P applied to rotational crops and pastoral areas receiving P from manure and supplementary feeds.

6.2 Opportunities for improved P maintenance management

Analysis conducted in the current study has shown that some areas within the pastoral sector are applying fertiliser P above the estimated maintenance requirements, whereas others are applying below, resulting in an accumulation of P and Olsen P values in some areas, and a depletion of P and decrease in Olsen P values in other areas. The Canterbury dairy region is one area where application of fertiliser P is greater than the maintenance requirements. According to the Dairybase (2024) data, the Canterbury region applied an average of 38 kg P/ha to all non-effluent areas (Table A.3), which is 6 kg P more than the estimated maintenance requirements of 32 kg P/ha/yr in the 2021/2022 season (Table 5.1). This would suggest that over time, the Canterbury region would observe an increase in soil Olsen P values. McDowell et al. (2023) found

lower fertiliser P application rates to dairy farms in the Waikakahi catchment (located in the Canterbury region) receiving an average of 26 kg P/ha between 2011 to 2020. It is possible that this average fertiliser application rate measured between 2011 and 2020 has increased over time in this region.

In contrast, the Waikato + Bay of Plenty and West Coast + Marlborough dairy regions were estimated to have applied 27 kg P/ha and 37 kg P/ha in the 2021/2022 season respectively, which is 15 kg P/ha and 14 kg P/ha less than the estimated P maintenance requirements of 42 kg P/ha/yr and 51 kg P/ha/yr, respectively. This suggests that the soils under dairying in the Waikato + Bay of Plenty region would see a decrease in soil Olsen P values over time. However this is unlikely to have a negative short term effect on farm production, as soils under dairy in the Waikato + Bay of Plenty and Westcoast + Marlborough regions tend to have Olsen P values above the target Olsen P range, with weighted average Olsen P values of 43 mg/L and 33 mg/L reported for the 2021/2022 season (Table 4.9).

Average rates of fertiliser P were also estimated for the Waiokura (22 kg P/ha) and Inchbonnie catchments (29 kg P/ha) (located in the Waikato + Bay of Plenty and West Coast + Marlborough catchments, respectively) by McDowell et al. (2023) over the period of 2011 to 2020 and indicate lower P applications than were measured in the current study.

Across the sheep and beef sectors, all average case study farms were estimated to have applied less fertiliser P per hectare than the estimated maintenance P requirements, which suggests a likely decrease in soil Olsen P values across the sector over time. The Marlborough + Canterbury sheep and beef region was estimated to apply the least fertiliser P/ha to pasture, with an average application rate of 6 kg P/ha/yr to pasture (across all production classes), which was 9 kg P/ha less than the estimated maintenance requirements of 15 kg P/ha/yr in the 2021/2022 season (Table C.2). Overall, the results indicate a mining of soil P to support pasture production across the sheep and beef industry. While this may be beneficial in the short term to the decrease soil Olsen P values (lowering soil P concentrations and thus the risk of P loss), there is the longer term risk that sub optimal fertiliser P application will compromise farm productivity and economic viability (Clark et al., 1990; Lambert et al., 1990).

Results from this study highlight the opportunity for both the dairy and sheep and beef sectors to improve P management to maintain economically optimum Olsen P values as well as reduce both short term effects on the environment and long term 'legacy' P sources, by increasing the P

use efficiency (PUE) of these livestock systems. On a global level, McDowell and Haygarth (2025) estimate that there is 0.32 – 0.43 Gt of plant available P and 3.0 – 3.83 Gt of non-readily available P reserves in global cropland and improved pastures, that are currently going un-used by agricultural production on these soils. McDowell and Haygarth (2025) suggest that the utilisation of these currently unused P stocks, and in turn improvement of global PUE can be achieved by decreasing soil Olsen P to meet optimal concentrations (in areas where soils are heavily enriched with P), increasing P application in areas where P is deficient and Olsen P is not optimal, using more efficient cultivars and crop types, and adaption of cropping locations (Cong et al., 2020; Jägermeyr et al., 2021; Manschadi et al., 2014; McDowell et al., 2024).

6.3 Overseer changes

When comparing maintenance P estimates from previous studies, it is important to understand that changes to the modelling software could have an influence on the results. The current research did not investigate changes in the P modelling software, or changes to calculations or assumptions made in the model, and so the effect of any changes to Overseer cannot be commented on. It should be acknowledged that the Overseer modelling software has undergone updates and changes since its use by Hedley et al. (2011), however the influence of these updates and changes is unknown. However, most of the differences in results between Hedley et al. (2011) and the current research can be explained by changes in land area, farming intensity and management practices, which suggest that changes to the Overseer model in the interim have not had significant influence on the current estimates.

6.4 Phosphorus balance

Phosphorus surpluses in agricultural budgets represent an excess of plant available P which could be used for plant uptake or lost to the environment, with large surpluses representing a high risk of P loss to the environment and an inefficient use of P (Scott et al., 2024). The P balances of the dairy and sheep and beef sectors (Table 5.2 & 5.4) are consistent with the estimated maintenance P requirement and average P application data previously discussed, with land under dairy likely accumulating P at an estimated rate of 3 kg P/ha/yr and land under sheep and beef likely depleting P (mining soil P reserves) at an estimated rate of -2 kg P/ha/yr. While there is room for error in the calculation of these P budgets (as regional average farm data was used and averaged to produce the national average values and any error in the amount of P

fertiliser applied to the case study farms will influence the P balance), the P budgets suggest that overall, the pastoral sector is applying fertiliser P at a rate that maintains the average national soil P concentrations, with minimal accumulation.

While there is limited research on agricultural P budgets in New Zealand, the estimated pastoral farming P balance in the current research is lower than the P balance of 5.6 kg P/ha estimated by Parfitt et al. (2008) for the 2001/2002 season, however, Parfitt et al. (2008) used a simple mass-balance approach to their nutrient budget, where there was no accounting for the change in soil pool P, and so it is unknown how much of the P was accumulating in the organic, inorganic mineral, and soil inorganic (plant available) pools. The estimated P balance for the individual dairy and sheep and beef sectors are similar to the lower end of the range of P balances estimated by Power et al. (2002) for the 1998/1999 season, where three mixed farming catchments from across New Zealand were used to determine a dairy P balance ranging from 4-31 kg P/ha and a sheep and beef balance from 1-10 kg P/ha.

Global P budgets estimate an average depletion of P at the rate of -6.6 kg P/ha under intensive grassland systems and -1.4 kg P/ha/yr under extensive grassland systems worldwide (Sattari et al., 2016). Phosphorus balances in Europe have been found to range from -10 kg P/ha/yr (deficit) to +30 kg P/ha/yr, with large surpluses seen in the Netherlands, Cyprus and Malta (Einarsson et al., 2020). A similarly large P surplus was estimated for land under intensive dairy across Australia, with Gourley et al. (2012) estimating a mean P surplus of +28 kg P/ha, with the balance ranging from a deficit of -7 kg P/ha to a surplus of +133 kg P/ha for the 2008/2009 season.

In Northern Ireland, Jordan et al. (2024) suggested a reduction in the national P budget surplus to +5.5 kg P/ha is required in order to reduce mean annual concentration of P in Lough Neagh, the largest freshwater lake in the UK and Ireland, and meet the lake water quality targets.

Table 6.1. Comparison of P budget research in New Zealand and globally, including the land use and country the P surplus/deficit relates to for agricultural land.

Land use	Details	Country	P balance	Reference
Dairy pasture	Intensive grazing	New Zealand	+3 kg P/ha	Current study
Sheep and beef pastures	Intensive and extensive grazing	New Zealand	-2 kg P/ha	Current study
Dairy pastures	Intensive grazing	Australia	+28 kg P/ha	Gourley et al. (2012)
Pastoral grazing	Mixed intensity	New Zealand	+5.6 kg P/ha	Parfitt et al. (2008)
Dairy grazing	Intensive grazing	New Zealand	+4-31 kg P/ha	Power et al. (2002)
Sheep and beef grazing	Mixed intensity grazing	New Zealand	+1-10 kg P/ha	Power et al. (2002)
Grassland	Intensive use	Global	+6.6 kg P/ha	Sattari et al. (2016)
Grassland	Extensive use	Global	-1.4 kg P/ha	Sattari et al. (2016)
Grassland + cropping	Cropping + mixed intensity grazing	Europe	-10 kg P/ha - +30 kg P/ha	Einarsson et al. (2020)
Grassland	Mixed intensity	Global	+0.4 kg P/ha	Lun et al. (2018)
Cropping		Global	4.7 kg P/ha	Lun et al. (2018)
Cropping	Intensive cropping	U.S & Canada	+3.2 kg P/ha	Williams et al. (2022)

Similarly to the maintenance P estimations, the P budgets vary regionally within the dairy and sheep and beef sectors with some regions observing high positive P balances (the Canterbury and Otago + Southland dairy regions), while other regions observed large negative P balances (the West Coast + Marlborough dairy region and the Marlborough + Canterbury sheep and beef region). These findings highlight the opportunity to improve P management through the use of nutrient budgets and soil testing. Some regions such as the Waikato + Bay of Plenty and West Coast + Marlborough dairy regions could benefit from decreasing P application in order to reduce accumulation of legacy P, while regions such as the Marlborough + Canterbury and Otago + Southland sheep and beef regions could benefit from increasing the amount of P applied to replace the P removed via crop and supplement harvest and possibly even increase soil test P values to better maintain pasture production. The use of nutrient budgets and soil testing play a key role in this process, as nutrient budgets allow for the tracking of P movement within the farm system, and can be used to inform P applications to improve the overall farm P use efficiency.

No P budget has been determined for the arable and horticultural sectors, although Journeaux (2024) estimated that 6-36 kg P is removed from the soil by the grain and cereal crops in the arable sector and that 2-13 kg P/ha and 7-37 kg P/ha is removed from the soil by fruit and vegetable

crops respectively, in the horticultural sector. With the average application of P to the arable and horticultural sectors being 27 kg P/ha and 36 kg P/ha respectively, it is likely that these sectors are applying enough fertiliser P to maintain soil test P levels, resulting in either balanced or positive P budgets.

In comparison to previous studies both in New Zealand and internationally (Table 6.1), the low estimated P balances (+3 kg P/ha and -2 kg P/ha) determined for the dairy and sheep and beef sectors (respectively) in the current study, is likely attributed to an increased uptake and application of BMP's on dairy and sheep and beef farms over the last 20 years (McDowell et al., 2023). In a study of 5 catchments across New Zealand, dominated by dairy farming, McDowell et al. (2023) were able to show that extensive efforts to promote BMP's on dairy farms from 2001 to 2010 resulted in a 37% reduction in P fertiliser use. Although the relative increase in Olsen P values seen from 1988 to 2015 across most soil types (McDowell et al., 2020a), does not reflect this reduction in P fertiliser use, the increase in imported supplementary feed and stocking rate have likely assisted in the maintenance of the soil Olsen P values. This suggests that at a national level, the agricultural industry of New Zealand is generally utilising non-renewable P resources efficiently to achieve soil test P values that support near optimal pasture and crop production, while seeing minimal accumulation of P in the inorganic soil pool.

6.5 Future P requirements

While no modelled estimations have been made regarding the future P requirements of New Zealand's agricultural industry, the current P use, estimated maintenance requirements, estimated P budget and trends in soil test data can provide useful insight into the likely future trends for P use. Figure 6.1 shows that the estimated current P maintenance/use requirements of the agricultural industry in the 2021/2022 season were larger than amount of P applied in the same season. With the purchase and use of fertiliser P being strongly influenced by pastoral farming profit, the expected increase in farm profit is likely to have a positive influence on fertiliser P purchased. A forecast increase in red meat prices for the sheep and beef 2024/2025 season is likely to have a positive influence on fertiliser purchases, with the sheep and beef farm profit before tax (FPBT) forecast to bounce back from a difficult 2023/2024 season (a 61% increase expected from a low FPBT of \$56,400, to approximately \$106,500) (B+LNZ, 2025d). While farm profit is still low (in comparison to past seasons) it is likely that fertiliser P purchases and application will increase. This will in turn reduce the amount of P mined from the soil to

support production, as the P applied (69,988 tonnes P) did not meet the maintenance P requirements (86,877 tonnes P) in the current season (2021/2022).

The milk payout is forecast to remain stable from the 2024/2025 season, with a payout of \$10/kg MS forecast for the opening of the 2025/2026 season, alongside an 11% increase in dairy farm profit after tax (FPAT) of \$1,158,000 dollars. This increase in profit could suggest an increase in fertiliser purchases in the dairy sector in the 2025/2026 season. With the averaged total amount of fertiliser P applied to the dairy sector (59,988 tonnes P) already meeting the maintenance requirements (59,579 tonnes P) in the current (2021/2022) season, an increase in P fertiliser purchases would result in an over application of P to the dairy sector, on average. While some regions and farm systems may benefit from increased P application, the dairy sector on average could pose a higher risk of environmental P loss if P purchased/applied were to increase dramatically.

6.5.1 Dairy maintenance P under a target Olsen P value

With the Olsen P values of the dairy sector being higher than the target Olsen P values required to support biologically optimum production, there is room to reduce Olsen P values, and in turn reduce the estimated maintenance P requirements. To assess the effect that different Olsen P values would have on the maintenance P requirements and nutrient budgets in the dairy sector and on the national maintenance requirements, a secondary analysis of the dairy sector was conducted, where the Olsen P values for all regions was entered as 30 mg/L [the highest target value recommended by Roberts and Morton (2023)].

Setting the Olsen P value at 30 mg/L in the current study resulted in the average national dairy maintenance P requirement decreasing from 35 kg P/ha/yr to 31 kg P/ha/yr (11% decrease), with regional requirements ranging from 25 kg P/ha/yr in the 'Otago + Southland' region to 49 kg P/ha/yr in the 'West Coast + Marlborough' region. The change in Olsen P values had the largest effect on the estimated maintenance P requirements of the 'Waikato + Bay of Plenty' region, decreasing maintenance P requirements from 42 kg P/ha/yr to 34 kg P/ha/yr (19% decrease). The total dairy maintenance P requirement as a result of changing Olsen P values to 30 mg/L was estimated to be 53,073 tonnes of P for the 2021/2022 season (Table 6.2), which is a 6,506 ton decrease in total maintenance P requirements for the dairy sector (calculated as 59,579 tonnes under the current weighted average Olsen P).

With the estimated maintenance requirements of the sheep and beef, arable and horticultural sectors remaining the same, and using the 'target Olsen P' dairy maintenance P requirement of 53,073 tonnes P, the estimated national maintenance P requirements decreased from 157,259 tonnes to 150,753 tonnes for the 2021/2022 season (Table 6.3). If the average soil Olsen P value for all dairy regions were 30 mg/L, the amount of fertiliser P applied in the 2021/2022 season would only have to increase by 7,924 tonnes across the total agricultural industry in order to meet the maintenance requirements.

6.5.2 Dairy P budgets under a target Olsen P value

The P budgets generated by the target Olsen P case study farms showed that if the Olsen P value for all dairy soils were set at 30mg/L, the amount of P being added to dairy systems in fertiliser and imported supplementary feeds was too high, resulting in a large P surplus for most dairying regions (ranging from a surplus of +3 kg P/ha/yr in the Taranaki region to +9 kg P/ha/yr in the Waikato + Bay of Plenty region) (Table 6.3). The only region to show a deficit was the West Coast + Marlborough region with a deficit of -2 kg P/ha/yr. Using the target soil Olsen P value of 30 mg/L across the dairy sector, resulted in an estimated average P surplus of +7 kg P/ha/yr in the 2021/2022 season. No changes were made to the production of the dairy regions as the Olsen P values were above the target value, meaning that biological optimum production was already being achieved on average, in all regions. This large P surplus across most of the dairy regions emphasises the opportunity for the dairy industry to reduce P inputs to achieve soil Olsen P values within the target range, without experiencing any short-term negative effects on production.

Table 6.2. The weighted average dairy farm maintenance P requirements (kg P/ha) for each dairy production region in New Zealand, using a target Olsen P value of 30 mg P/L for all dairy regions, showing the average block maintenance requirements (kg P/ha), and the total maintenance P requirements at the block, farm, regional and national level (kg P and tonnes P) for the 2021/2022 season. Modelled using Overseer, v6.5.9.

	Northland + Auckland	Waikato + Bay of Plenty	Taranaki	East Coast + Lower North Island	Westcoast + Marlborough	Canterbury	Otago + Southland	Nationally
Area (ha)								
Farm effective area	132	170	109	189	162	235	217	
Effluent block	18	24	20	30	23	68	40	
Non-effluent	86.7	74.5	52	128.3	99.4	122.6	107.4	
Silage block	27.3	71.5	37	30.7	39.6	44.4	69.5	
Support block	42	60	30	51	45	85	65	
Block maintenance requirements (kg P/ha)								
Effluent block	0	0	0	0	10	0	0	
Non-effluent	15	21	26	20	39	30	16	
Silage block	33	37	42	39	56	48	34	
Support block	26	26	24	20	35	21	20	
Total block P requirement (kg P)								
Effluent	0	0	0	0	230	0	0	
Milking platform	1,301	1,565	1,352	2,566	3,877	3,678	1,718	
Non-effluent	901	2,646	1,554	1,197	2,218	2,131	2,363	
Support block	1,097	1,555	720	1,010	1,575	1,785	1,300	
Total farm maintenance P requirement (kg P)	3,299	5,765	3,626	4,773	7,899	7,594	5,381	
Total regional maintenance P requirements (tonnes P)	3,641	18,751	5,495	3,814	4,566	9,041	7,765	53,073
Total regional effective area (ha)	145,698	552,952	165,198	151,006	93,644	279,765	313,117	1,701,380
Weighted average maintenance P requirements (kg P/ha)	25	34	33	25	49	32	25	31

Table 6.3. Phosphorus (P) budgets for the regionally representative case study dairy farms (using the target Olsen P value of 30mg P/L for each region), showing the farm average inputs, outputs and change in soil pools (kg P/ha) and the national weighted averages (kg P/ha), for the 2021/2022 season.

Inputs/Outputs (kg P/ha/yr)	Northland + Auckland	Waikato + Bay of Plenty	Taranaki	East Coast + Lower North Island	West Coast + Marlborough	Canterbury	Otago + Southland	National mean
P added								
Fertiliser, lime and other	19	24	28	21	31	27	24	25
Supplements	8	13	11	8	7	8	11	10
P removed								
Leaching, runoff and direct losses	1.4	1	0.8	1.1	3.2	1	0.7	1
As product	9	11	12	11	9	16	13	12
Change in pools								
Organic pool	9	8	7	9	21	8	10	9
Standing plant material	-2	-3	-2	-2	-3	-2	-2	-2
Inorganic mineral	2	6	12	2	3	2	2	4
Change in supplement storage	1	2	2	3	4	3	2	2
Root and stover residuals	6	9	3	5	3	6	8	2
Inorganic soil pool (surplus/deficit)	6	9	3	5	-2	6	8	7
Total farm P loss (kg P)	185	170	87	208	518	235	152	189

Table 6.4. Estimated total national agricultural fertiliser phosphorus (P) maintenance requirements for the sheep and beef, dairy (using target Olsen P values of 30 mg P/L for all dairy regions), arable, and horticultural sectors for the 2021/2022 season.

	Sheep and beef	Dairy	Total pastoral	Arable	Horticulture	Total
Area (ha)	4,816,520	1,701,380		227,594	127,000	
P maintenance (kg P/ha)	18	31		27	36	
P maintenance (000's tonnes)	86,877	53,073	139,950	6,210	4,593	150,7539

Table 6.5. Average regional, North Island, South Island and national maintenance phosphorus (P) requirements (kg P/ha) for the dairy sector under current soil test levels (weighted average Olsen P value for each region) and under the sector target Olsen P value (30 mg/L for all regions), with the change in maintenance P requirement, as a result of the change in Olsen P value (%), shown. The national dairy maintenance value estimated by Hedley et al (2011) has also been included.

	Estimated maintenance P requirements (kg P/ha)			
	Based on weighted average Olsen P	Based on target Olsen P value (30 mg P/L)	Percentage change (%)	2007/2008 estimation*
Northland + Auckland	27	25	-9	
Waikato + Bay of Plenty	42	34	-19	
Taranaki	39	33	-14	
East Coast + Lower North Island	27	25	-6	
North Island	37	31	-16	
West Coast + Marlborough	51	49	-4	
Canterbury	32	32	0	
Otago + Southland	26	25	-4	
South Island	32	31	-3	
Nationally	35	31	-11	42

*2007/2008 estimation was made by Hedley et al. (2011) at a national level only.

Chapter 7 Conclusion

Phosphate rock is a non-renewable resource that is mined globally and relied on heavily by New Zealand's agricultural industry. With about 90% of total fertiliser P use being applied to the dairy and sheep and beef sectors, it is important to understand the maintenance requirements of these sectors to plan for the efficient and sustainable P use. There has been limited studies determining the total P fertiliser maintenance requirements of the pastoral sector, with no national assessments made in over a decade. Having an improved and current assessment is important because land use changes and the adoption of different management practices over time can affect farm P fertiliser requirements. This research has determined the current maintenance P requirements, using the maintenance requirements and P budgets, to provide insights into the future P demands of the agricultural industry.

This study estimated that the national average maintenance P fertiliser requirements for the dairy and the sheep and beef sectors to be 35 and 18 kg P/ha, respectively, for the 2021/2022 season. This compares to values of 42 and 12 kg P/ha, respectively, estimated by Hedley et al. (2011). While variation in methodologies will have contributed some of the differences observed between these studies, changes in nutrient management in these sectors will also be a factor. For example, the greater adoption of land treatment of farm dairy effluent and increased use of imported supplementary feed will have contributed to lower per hectare maintenance P fertiliser requirements on dairy farms.

The total national P fertiliser maintenance requirement for the pastoral sector in the 2021/2022 season was estimated to be 146,456 tonnes P/yr, which is about 12% higher the estimated average P fertiliser used. This difference is likely to mainly be influenced by a shortfall in P use by the sheep and beef sector, with requirement and use being better matched for the dairy sector. With the forecast financial outlook for the dairy and sheep and beef sectors indicating an increase in farm profitability, it is likely that discretionary expenditure will increase, allowing farmers to apply more fertiliser P. This could reduce the level of soil P mining or meet maintenance requirements completely on sheep and beef farms, but could further elevate soil Olsen P values on dairy farms, enhancing the risk of environmental P loss. However, with the volatility of sheep and beef farm profitability, it will be important for farmers to maintain economically optimal soil P levels for pasture and livestock production into the future.

This research highlighted the need for a greater level of detail in reported farm management data in the arable and horticultural sector in order to gain a more accurate understanding of P use and potential P demand, in order to fully understand efficiency of P use in these sectors.

Appendices

Appendix A

Table A.1. Difference in total number of herds, total effective area and total milk solids produced, reported by Dairybase/Baseline and the Livestock Improvement Corporation (LIC) New Zealand dairy statistics census data for the 2021/22 season. Percentage values show the Dairybase/Baseline data as a proportion of the Livestock Improvement Corporation (LIC) New Zealand dairy statistics census data.

Dairy Regions	Total number of herds per region*			Total effective (ha)			Total milk solids produced (kg MS)		
	Dairybase	LIC	%	Dairybase	LIC	%	Dairybase	LIC	%
Northland/Auckland	122	1,059	12	24,309	145,698	17	20,448,334	111,715,896	18
Waikato/Bay of Plenty	686	4,105	17	123,320	552,952	22	142,196,324	581,217,749	24
Taranaki	236	1,515	16	32,687	165,198	20	38,196,884	181,057,008	21
Manawatū/Whanganui	157	953	16	31,823	151,006	21	33,010,972	155,438,208	21
Marlborough/Westcoast	105	552	19	21,818	93,644	23	18,330,486	73,013,892	25
Canterbury	336	1,189	28	93,089	279,765	33	1,417,70,103	405,996,118	35
Southland/Otago	218	1,423	15	54,788	313,117	17	68,112,538	3,58,926,041	19
New Zealand	1,860	10,796	17	381,834	1,701,380	22	462,065,641	1,867,364,912	25

*Number of herds is used as a proxy for the number of farms per region.

Table A.2. Difference in average effective farm area (ha), average stocking rate (cows/ha) and the area weighted average milk production (kg MS/ha) produced on farm as reported in the Dairybase data and the Livestock Improvement Corporation (LIC) New Zealand dairy statistics census data for the 2021/22 season. Percentage values are the percentage difference between the Dairybase data and LIC data for average effective area, weighted average milk solids produced and average stocking rate.

Dairy Regions	Average effective area (ha)			Weighted average milk solids produced (kg MS/ha)			Average stocking rate (cows/ha)		
	Dairybase	LIC	%	Dairybase	LIC	%	Dairybase	LIC	%
Northland/Auckland	172	132	26	841	767	9	2.39	2.52	5
Waikato/Bay of Plenty	180	170	6	1,153	1,051	9	2.97	2.77	7
Taranaki	139	109	24	1,169	1,096	6	2.81	2.79	0.7
Manawatū/Whanganui	201	189	6	1,037	1,029	0.8	2.63	2.69	2
Marlborough/Westcoast	208	162	25	840	780	7	2.48	2.49	0.4
Canterbury	277	235	16	1,523	1,451	5	3.60	3.42	5
Southland/Otago	251	217	15	1,243	1,146	8	2.85	2.80	2
New Zealand	203	173	19	1,210	1,097	7	2.99	2.80	3.2

Table A.3 Regionally representative dairy farm case study data, used in Overseer (v6.5.9), including physical farm data (effective area, climate, herd size, soil order and ASC) production data (milk solids production per cow, per effective hectare, and annual average), and farm management data (fertiliser application rates, irrigation and effluent management, forage cropping, and other supplementary feed) for the 2021/2022 season.

2021/22 season	Northland + Auckland	Waikato + Bay of Plenty	Taranaki	East Coast + Lower North Island	West Coast + Marlborough	Canterbury	Otago + Southland
Regional effective area	145,698	552,952	165,198	151,006	93,644	279,765	313,117
Average temperature	15	13	13	14	12	11	10
Rainfall (annual average) (mm)	1,330	1,400	1,766	1,162	3,083	719	908
effective area	132	170	109	189	161.5	235	217
Herd size	310	464	304	507	395	805	607
Replacement %	25%	24%	22%	24%	25%	25%	24%
Replacement cow numbers	78	109	67	119	99	201	143
Average stocking rate (cows/ha)	2.52	2.77	2.79	2.69	2.49	3.42	2.8
Average annual milk solids production (kg MS)	105,613	158,100	119,561	182,747	132,198	338,915	250,531
Milk solids produced per cow (kg MS)	342	343	394	362	335	421	412
Milk-solids produced per effective hectare (kg MS/ha)	767	1,051	1,096	1,029	780	1,451	1,146
Area harvested for hay/silage (ha)	27	71	37	31	40	44	70
Summer crop grazed [crop type and area (ha)]	15 (turnips)	14 (turnips)	8(Turnips)	12.26(turnips) 8.4 (Fodder Beet + Kale)	11.2 (Turnips) 16(Swedes & Fodder beet)	10.3 (Turnips) 15.13 (Fodder beet & Kale)	13.3 (Turnips) 13.9 (Fodder beet & Swedes)
Winter crop grazed [crop type and area (ha)]	0	15.2 (fodder beets)	4.8(Fodder beet)				
<u>Feed fed from storage (t DM)</u>							
Maize silage	159	123	71	89	0	61	108
Pasture silage	35	53	30	40	29	59	158
Hay	10	13	3	13	15	0	33

Imported feeds (t DM)

PKE	142	237	137	187	112	149	268
Maize silage	72	92	30	130	14	40	6
Barley grain	0	0	3	9	63	179	146
Brewers grain	21	15	5	0	3	25	43
Lucerne silage	0	15	0	4	6	0	0
Maize grain	0	10	8	26	0	0	6
Molasses	0	5	10	22	3	10	12
Prolig	0	0	15	0	0	5	0
Cereal Straw	0	0	3	0	20	10	6
Concentrates	0	39	10	13	57	20	55
Other	35	73	30	43	9	60	67
Total	271	484	250	435	287	498	608

Other inputs

Average pasture potential (t DM/ha)	12	14	15	13	11	17	13
Days of season irrigated	0	109	0	77	54	106	103
Irrigation interval (Days)	0	16	0	12	8.5	6.4	7
Irrigation (total area) (ha)	0	137	0	117	86	266	255
Irrigation type	-	centre-pivot	-	centre pivot	k-line	centre pivot	centre pivot
Annual irrigation water applied (mm)	0	220	0	245	254	355	268
weighted average soil Olsen P (FANZ)	37	43	39	34	33	30	32

Fertiliser

Nitrogen applied (kg N/ha)	122	114	131	84	155	170	135
Phosphorus applied (kg P/ha)	21	27	27	24	37	38	27

Potassium applied (kg K/ha)	35	47	52	22	56	26	33
Lime (kg /ha)	629	654	400	569	1127	344	599
Effluent application depth	Best practice followed, shallow application depth						
Effluent area	best practice followed, with area adjusted to match 150kg N						
Dominant soil orders	Brown, Ultic	Allophanic, Granular & Pumice	Allophanic	Pallic, Brown	Brown, Podzol	Pallic, Brown, Recent	Pallic, Brown
Default ASC (in order of dominant soil orders)	43, 26	83, 49, & 49	83	21, 43	43, 32	21, 43, 23	21, 43

Table A.4. Regionally representative North Island sheep and beef farm case study data used in Overseer (v6.5.9), including physical farm data (effective area, climate, stocking rates, soil order and ASC) production data (greasy wool production per head), and farm management data (fertiliser application rates, forage cropping, and hay/silage harvest area) for the 2021/2022 season.

	Northland + Waikato + Bay of Plenty			Taranaki + Manawatū			Gisborne + Hawkes Bay + Wairarapa		
	Class 3 Hard Hill	Class 4 Hill	Class 5 Finishing	Class 3 Hard Hill	Class 4 Hill	Class 5 Finishing	Class 3 Hard Hill	Class 4 Hill	Class 5 Finishing
Number of farms in North Island production classes	225	1665	240	275	565	255	420	825	550
Regional average rainfall (mm)		1423			1211			1177	
Average total area (ha)	953	452	300	1210	582	253	1404	705	438
Effective area	723	361	251	927	488	207	948	592	392
New Grass area	4	4	12	10	8	8	4	8	6
Cash crop area	0	0	8	0	0	6	0	0	7
Hay/silage	4	17	35	8	12	23	4	8	20
Summer forage crop (area under leafy turnips)	2	3	3	11	7	5	6	12	6
Winter forage crop (area under kale and swedes)	2	4	13	24	11	7	7	7	13
Trees and scrub area	230	91	49	283	94	46	456	113	46
Topography of effective area									
Flat	16	22	24	10	19	23	11	10	34
Rolling	24	9	8	28	15	54	19	26	60
Easy Hill	246	209	146	130	135	82	204	272	218
Steep hill	430	100	19	741	298	17	704	269	54
Animal production									
Open Sheep (SU)	3072	1085	629	4880	2819	976	4602	3085	1472
Open Cattle (SU)	2470	2334	2614	2497	1754	1351	3122	2112	2006

Stocking rate (SU/ha)	8	10	13	8	10	11	8	9	9
Wool shorn (kg greasy)	15399	5221	2720	25457	15085	3300	21118	15409	6802
Fertiliser applied (kg /ha)									
Pasture N	7	16	24	10	11	15	13	10	8
Pasture P	17	17	19	14	16	15	12	14	12
Pasture K	4	11	14	1	4	9	0	1	2
Pasture S	24	23	28	23	23	21	21	19	20
Crop N	90	103	235	31	60	107	78	51	48
Crop P	61	55	48	32	41	31	48	42	27
Crop K	4	40	179	13	27	41	23	12	20
Crop S	13	25	30	25	16	19	16	17	21
Ag-Lime	86	144	318	39	64	203	83	44	13
Dominant soil orders	Brown, Allophanic, Granular	Brown, Allophanic, Granular	Ultic, Granular	Brown, Allophanic	Brown, Allophanic	Brown, Pallic, Gley	Pumice, Brown, Pallic	Pumice, Brown, Pallic	Brown, Pallic
Default ASC values	43, 83, 49	43, 83, 49	26, 49	43, 83,	43, 83,	43,21, 43	49, 43, 21	49, 43, 21	43, 21

Table A.5. Regionally representative South Island sheep and beef farm case study data used in Overseer (v6.5.9), including physical farm data (effective area, climate, stocking rates, soil order and ASC) production data (greasy wool production per head), and farm management data (fertiliser application rates, forage cropping, and hay/silage harvest area) for the 2021/2022 season.

	R4: Marlborough, Canterbury			R5: Otago, Southland		
	Class 2 Hill	Class 6 Finishing/Breeding	Class 8 Mixed Finishing	Class 2 Hill	Class 6 Finishing/Breeding	Class 7 Finishing
Number of farms in South Island production classes	395	1210	465	225	610	1040
Rainfall (mm)		710			978	
Average total area (ha)	1575	564	418	1619	730	303
Effective area	1414	490	386	1454	600	272
New Grass area	22	20	3	24	29	14
Cash crop area	0	19	137	0	1	8
Hay/silage	45	48	38	24	22	28
Summer forage crop (area under leafy turnips)	15	11	2	15	3	2
Winter forage crop (area under kale and swedes)	39	42	51	39	38	18
Trees and scrub area	161	74	32	165	130	31
Topography of effective area						
Flat	43	39	17	218	11	38
Rolling	110	126	119	266	62	80
Easy Hill	223	185	62	432	327	107
Steep hill	969	53	10	490	150	5
Animal production						
Open Sheep (SU)	3959	2151	1432	4658	3926	2545
Open Cattle (SU)	1982	1534	1251	2131	1064	392
Stocking rate (SU/ha)	4	8	7	5	8	11
Wool Shorn (kg greasy)	18296	10920	5010	21459	17754	11280

Fertiliser applied (kg /ha)

Pasture N	2	14	11	3	11	16
Pasture P	4	11	5	5	12	19
Pasture K	1	3	3	2	3	18
Pasture S	11	23	8	12	21	31
Crop N	43	86	202	52	63	89
Crop P	24	29	28	41	47	41
Crop K	6	13	38	20	17	27
Crop S	14	20	40	20	21	30
Ag-Lime	47	127	182	65	164	222
Dominant soil orders	Brown, Pallic	Pallic, Brown, Recent	Pallic, Brown, Recent	Brown	Brown, Pallic	Brown, Pallic
Default ASC values	43, 21	21, 43, 23	21, 43, 23	43	43, 21	43, 21

Appendix B

Table B.1. Average proportion of land area in flat/rolling (low), easy hill (medium), and steep hill (high) slope classes for each farm production class. Adapted with permission, from Saggar et al. (2015).

Production class	Low Slope (<12°) %	Medium Slope (12-24°) %	High Slope (>24°) %
Northland + Waikato + Bay of Plenty			
3	6.5	34	59.5
4	14.5	57.9	27.6
5	34.3	58	7.7
Taranaki + Manawatū			
3	6.0	14.0	79.9
4	11.2	27.7	61.1
5	52.1	39.4	8.4
Gisborne + Hawkes Bay + Wairarapa			
3	4.1	21.5	74.3
4	8.7	45.9	45.5
5	30.5	55.6	13.9
Marlborough + Canterbury			
2	15.6	15.8	68.5
6	51.5	37.7	10.8
8	81.4	16.2	2.5
Otago + Southland			
2	36.6	29.7	33.7
6	20.5	54.5	25.0
7	59.0	39.4	1.7

Table B.2. The average amount of imported supplementary feeds used by the regionally representative case study farms of New Zealand's dairy sector (t DM), for each of the main supplementary feeds in the 2021/2022 season.

	Northland + Auckland	Waikato+ Bay of Plenty	Taranaki	East Coast + Lower North Island	Westcoast + Marlborough	Canterbury	Otago + Southland
PKE	142	237	137	187	112	149	268
Maize silage	72	92	30	130	14	40	6
Barley grain	0	0	2	9	63	179	146
Brewers grain	21	15	5	0	3	25	43
Lucerne silage	0	15	0	4	6	0	0
Maize grain	0	10	7	26	0	0	6
Molasses	0	5	10	22	3	10	12
Proliq	0	0	15	0	0	5	0
Cereal Straw	0	0	2	0	20	10	6
Concentrates	0	39	10	13	57	20	55
Other	35	73	30	43	9	60	67
Total	271	483	250	434	287	497	608

Source: with permission, Dairybase (2024)

Table B.3. Total amount of imported supplementary feeds used (t DM) in the 2021/2022 season, by dairy production region and according to supplementary feed type. Amounts were calculated by multiplying the average tonnes imported per representative farm (Table A.2) by the number of herds in each production region according to the LIC (2022) data.

	PKE	Maize silage	Barley grain	Brewers grain	Lucerne silage	Maize grain	Molasses	Proliq	Cereal Straw	Concentrates	Other
Northland + Auckland	150,331	76,583	0	22,691	0	0	0	0	0	0	36,874
Waikato + Bay of Plenty	972,512	377,096	0	59,542	59,542	39,694	19,847	0	0	158,777	297,708
Taranaki	208,219	45,430	3,786	7,572	0	11,357	15,143	22,715	3,786	15,143	45,430
East Coast + Lower North Island	178,053	124,223	8,282	0	4,141	24,845	20,704	0	0	12,422	41,408
North Island total	1,509,115	623,333	12,067	89,805	63,682	75,896	55,694	22,715	3,786	186,343	421,419
Westcoast + Marlborough	61,821	7,926	34,873	1,585	3,170	0	1,585	0	11,096	31,703	4,755
Canterbury	177,455	47,321	212,946	29,576	0	0	11,830	5,915	11,830	23,661	70,982
Otago + Southland	380,815	8,655	207,717	60,584	0	8,655	17,310	0	8,655	77,894	95,204
South Island total	620,091	63,902	455,536	91,745	3,170	8,655	30,725	5,915	31,581	133,258	170,941
National total	2,129,206	687,235	467,604	181,550	66,853	84,551	86,420	28,630	35,367	319,601	592,360

Source: With permission, Dairybase (2024)

Appendix C

Table C.1. The average production class and average regional maintenance P requirements of the sheep and beef production regions (for the 2021/2022 season) showing the block and farm average maintenance P requirement (kg P/ha) total farm and total regional P requirements (kg P) for the North Island production regions.

Averaged parameters (2021/22 season)	Northland, Waikato, Bay of Plenty			Taranaki-Manawatū			Gisborne, Hawkes Bay, Wairarapa		
	Class 3 Hard Hill	Class 4 Hill	Class 5 Finishing	Class 3 Hard Hill	Class 4 Hill	Class 5 Finishing	Class 3 Hard Hill	Class 4 Hill	Class 5 Finishing
Total effective area	162675	601065	60240	254925	275720	52785	398160	488400	215600
Farm effective area	723	361	251	927	488	207	948	592	392
block area (ha)									
Flat	16	22	31	10	19	23	11	10	34
Rolling	24	9	8	28	15	54	19	26	60
Easy	246	209	146	130	135	82	204	272	218
Steep	430	100	19	741	298	17	704	269	54
New Pasture (flat)	4	4	12	10	8	8	4	8	6
Hay/silage (flat or rolling)	4	17	35	8	12	23	4	8	20
Maintenance P requirements (kg P/ha)									
Flat	21	21	22	21	21	17	20	20	16
Rolling	22	23	25	22	22	19	23	20	18
Easy	19	21	24	20	21	18	20	19	17
Steep	22	20	25	19	19	18	19	19	16
New Pasture	21	21	22	21	21	17	20	20	16
Hay/silage	39	41	45	38	29	32	37	36	32
Total farm P requirement (kg P)	15,233	7,836	6,699	18,000	9,746	4,064	18,363	11,439	6,930
Weighted farm P requirements (kg P/ha)	21	22	27	19	20	20	19	19	18
Total P requirement per production class (kg P)	3,427	13,047	1,608	4,950	5,506	1,050	7,712	9,437	3,811
Total P requirements (kg P)			18,082			11,506			20,961
Weighted P maintenance requirement (kg P/ha)			22			20			19

Table C.2. The average production class and average regional maintenance P requirements for the sheep and beef production regions (for the 2021/2022 season), showing the block and farm average maintenance P requirement (kg P/ha) total farm and total regional P requirements (kg P), for the South Island production regions and the New Zealand total

Averaged parameters 2021/22 season	Marlborough, Canterbury			Otago, Southland			New Zealand
	Class 2 Hill	Class 6 Finishing/Breeding	Class 8 Mixed Finishing	Class 2 Hill	Class 6 Finishing/Breeding	Class 7 Finishing	
Total effective area	530,250	524,300	179,490	327,150	366,000	282,880	4,719,640
Farm effective area (ha)	1,414	490	386	1,454	600	272	
Block area (ha)							
Flat	43	58	116	218	11	38	
Rolling	110	126	157	266	62	80	
Easy	223	185	63	432	327	107	
Steep	969	53	10	490	150	5	
New Pasture (flat)	22	20	3	24	29	14	
Hay/silage (flat or rolling)	45	48	38	24	22	28	
Maintenance P requirement (kg P/ha)							
Flat	16	15	15	15	16	16	
Rolling	16	15	15	15	16	18	
Easy	14	15	12	13	16	18	
Steep	12	12	12	12	18	22	
New Pasture	16	15	15	15	16	16	
Hay/silage	32	33	33	31	34	32	
Total farm P requirement (kg P)	19,000	8,055	6,263	19,860	10,296	5,207	
Weighted farm P requirements (kg P/ha)	13	16	16	14	17	19	
Total P requirement per production class (t P)	7,505	9,747	2,912	4,469	6,281	5,415	
Total Regional P requirement (t P)			20,164			16,164	
Total National P requirement (t P)							86,877
Weighted regional maintenance P requirement (kg P/ha)			15			17	
Weighted national maintenance P requirement (kg P/ha)							18

Table C.3. Sheep and beef phosphorus (P) budgets showing the nutrients added, removed and changes in soil pools for the production classes in the North Island sheep and beef regions.

	Northland + Waikato + Bay of Plenty			Taranaki + Manawatū			Gisborne + Hawkes Bay + Wairarapa		
	Class 3	Class 4	Class 5	Class 3	Class 4	Class 5	Class 3	Class 4	Class 5
Nutrients added									
Fertiliser, lime and other	12	14	17	11	13	14	8	12	12
Nutrients removed									
Leaching, runoff and direct losses	1.4	1.3	4	0.4	0.4	0.9	0.4	0.4	0.3
As product	1	2	3	1	2	3	1	2	2
As supplement	0	0	0	0	0	0	0	0	0
Change in pools									
Standing plant material	0	0	-1	-1	-1	-1	0	-1	-1
Organic pool	7	7	8	6	6	8	8	10	9
Inorganic mineral	3	3	2	3	4	1	1	1	1
Inorganic soil pool	-0.4	1	-1	1	2	1	-2	-1	-1
Change in supplement storage	0	0	1	0	0	0	0	0	1
Root and stover residuals	0	0	1	1	0	1	0	1	1
Total farm P loss (kg P)	1,012	469	1,004	371	195	186	379	237	118

Table C.4. Sheep and beef phosphorus (P) budgets showing the nutrients added, removed and changes in soil pools for the production classes in the South Island sheep and beef regions.

	Marlborough, Canterbury			Otago + Southland		
	Class 2	Class 6	Class 8	Class 2	Class 6	Class 7
Nutrients added						
Fertiliser, lime and other	3	11	6	5	12	18
Nutrients removed						
Leaching, runoff and direct losses	0.1	0.1	1	0.1	0.1	0.1
As product	1	2	18	1	2	3
As supplement	0	0	4	0	0	0
Change in pools						
Standing plant material	-1	-1	-2	-1	-1	-1
Organic pool	9	7	2	8	8	9
Inorganic mineral	1	1	1	2	1	1
Inorganic soil pool	-8	-0.1	-21	-6	1	5
Change in supplement storage	0	0	0	0	0	0
Root and stover residuals	1	2	3	1	1	1
Total farm P loss (kg P)	141	49	386	145	60	27

Table C.5. Correlation matrix of all variables related to the dairy sector estimated maintenance and modelled Overseer nutrient budgets.

Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	
Farm effective area (ha)	1	1																																			
Effluent block (ha)	2	0.85	1.00																																		
Non-effluent block (ha)	3	0.82	0.63	1.00																																	
Silage block (ha)	4	0.42	0.19	-0.09	1.00																																
Support block (ha)	5	0.93	0.90	0.65	0.46	1.00																															
Average temperature	6	-0.64	-0.62	-0.29	-0.53	-0.53	1.00																														
Rainfall (annual average) NIWA 30 yr average	7	-0.51	-0.56	-0.33	-0.22	-0.58	0.05	1.00																													
Total milk solids produced (herd annual average) (kg MS)	8	0.91	0.98	0.65	0.33	0.93	-0.68	-0.62	1.00																												
Milk solids produced per cow (kg MS)	9	0.52	0.75	0.21	0.22	0.52	-0.67	-0.61	0.77	1.00																											
Milk solids produced per effective hectare (kg MS/ha)	10	0.64	0.90	0.31	0.25	0.71	-0.64	-0.60	0.89	0.92	1.00																										
Average stocking rate (cows/ha)	11	0.63	0.91	0.32	0.21	0.78	-0.48	-0.62	0.88	0.79	0.96	1.00																									
weighted average soil Olsen P (FANZ)	12	-0.66	-0.68	-0.78	0.20	-0.49	0.59	0.13	-0.66	-0.50	-0.48	-0.38	1.00																								
Average ASC	13	-0.69	-0.48	-0.90	0.10	-0.57	0.18	0.24	-0.49	-0.04	-0.09	-0.11	0.74	1.00																							
Effluent block maintenance requirements (kg P/ha)	14	-0.11	-0.22	0.05	-0.14	-0.22	-0.21	0.90	-0.27	-0.47	-0.41	-0.42	-0.24	-0.14	1.00																						
Non-effluent block maintenance requirements (kg P/ha)	15	-0.19	-0.05	-0.25	-0.05	-0.13	-0.20	0.74	-0.14	-0.23	-0.03	0.03	0.08	0.36	0.71	1.00																					
Silage block maintenance requirements (kg P/ha)	16	-0.13	-0.02	-0.19	-0.02	-0.09	-0.25	0.73	-0.10	-0.22	-0.01	0.04	0.03	0.31	0.72	1.00	1.00																				
Support block maintenance requirements (kg P/ha)	17	-0.45	-0.49	-0.33	-0.14	-0.42	0.14	0.93	-0.57	-0.70	-0.62	-0.55	0.19	0.13	0.87	0.70	0.68	1.00																			
Effluent total block P requirement (kg P)	18	-0.11	-0.22	0.05	-0.14	-0.22	-0.21	0.90	-0.27	-0.47	-0.41	-0.42	-0.24	-0.14	1.00	0.71	0.72	0.87	1.00																		
Non-effluent block total P requirement (kg P)	19	0.46	0.45	0.56	-0.13	0.40	-0.37	0.39	0.38	-0.06	0.19	0.26	-0.55	-0.43	0.67	0.66	0.70	0.39	0.67	1.00																	
Silage block total P requirement (kg P)	20	0.29	0.15	-0.20	0.89	0.39	-0.50	0.10	0.23	0.04	0.19	0.21	0.28	0.25	0.15	0.39	0.42	0.18	0.15	0.17	1.00																
Support block total P requirement (kg P)	21	0.67	0.59	0.44	0.43	0.78	-0.44	0.00	0.58	0.03	0.31	0.44	-0.33	-0.49	0.33	0.33	0.37	0.24	0.33	0.68	0.57	1.00															
Total farm P requirement (kg P)	22	0.29	0.14	0.11	0.43	0.35	-0.21	0.35	0.14	-0.32	0.00	0.13	0.15	0.01	0.46	0.68	0.71	0.44	0.46	0.66	0.74	0.71	1.00														
Total effective regional area (ha)	23	0.32	0.19	-0.15	0.85	0.50	-0.14	-0.42	0.29	0.10	0.25	0.34	0.46	0.19	-0.42	-0.10	-0.08	-0.25	-0.42	-0.21	0.79	0.42	0.48	1.00													
Total regional maintenance P requirements (tonnes P)	24	0.03	-0.07	-0.36	0.71	0.24	0.08	-0.14	-0.01	-0.19	0.00	0.13	0.70	0.40	-0.25	0.14	0.14	0.02	-0.25	-0.16	0.79	0.33	0.61	0.93	1.00												
Weighted average regional maintenance P (kg P/ha)	25	-0.60	-0.55	-0.65	0.04	-0.49	0.24	0.72	-0.60	-0.57	-0.43	-0.34	0.66	0.69	0.47	0.79	0.76	0.71	0.47	0.16	0.41	0.00	0.58	0.13	0.47	1.00											
Fertiliser (kg P/ha)	26	0.01	0.17	-0.19	0.13	0.01	-0.61	0.60	0.12	0.17	0.26	0.19	-0.20	0.30	0.65	0.87	0.88	0.51	0.65	0.59	0.44	0.32	0.48	-0.12	-0.03	0.51	1.00										
Supplements (kg P/ha)	27	-0.11	-0.18	-0.57	0.76	0.00	-0.09	-0.27	-0.06	0.15	0.11	0.07	0.68	0.63	-0.48	-0.13	-0.14	-0.27	-0.48	-0.59	0.65	-0.13	0.12	0.80	0.78	0.26	-0.06	1.00									
Leaching, runoff and direct losses (kg P/ha)	28	-0.20	-0.32	0.08	-0.32	-0.27	0.07	0.87	-0.39	-0.66	-0.57	-0.52	-0.16	-0.24	0.94	0.60	0.60	0.90	0.94	0.62	-0.03	0.31	0.40	-0.47	-0.26	0.44	0.42	-0.60	1.00								
As product (kg P/ha)	29	0.67	0.90	0.32	0.30	0.74	-0.62	-0.66	0.90	0.91	1.00	0.96	-0.44	-0.10	-0.46	-0.08	-0.06	-0.66	-0.46	0.15	0.22	0.32	0.01	0.32	0.06	-0.45	0.19	0.16	-0.62	1.00							
Organic pool (kg P/ha/yr)	30	-0.12	-0.33	0.02	-0.01	-0.25	-0.18	0.89	-0.35	-0.55	-0.52	-0.55	-0.14	-0.15	0.97	0.61	0.63	0.87	0.97	0.56	0.22	0.31	0.47	-0.32	-0.15	0.47	0.55	-0.36	0.92	-0.57	1.00						
Standing plant material (kg P/ha)	31	0.11	0.33	0.22	-0.38	0.06	0.01	-0.66	0.32	0.64	0.45	0.34	-0.39	-0.17	-0.65	-0.66	-0.68	-0.77	-0.65	-0.41	-0.68	-0.50	-0.85	-0.35	-0.57	-0.76	-0.44	-0.18	-0.62	0.44	-0.71	1.00					
Inorganic mineral (kg P/ha/yr)	32	-0.70	-0.46	-0.90	0.07	-0.56	0.17	0.27	-0.48	-0.03	-0.07	-0.09	0.72	1.00	-0.11	0.40	0.35	0.16	-0.11	-0.39	0.24	-0.47	0.02	0.16	0.38	0.70	0.34	0.59	-0.21	-0.08	-0.13	-0.17	1.00				
Change in supplement storage (kg P/ha)	33	-0.21	-0.16	-0.53	0.43	-0.16	-0.37	0.56	-0.16	-0.06	0.04	0.01	0.36	0.66	0.43	0.80	0.80	0.47	0.43	0.24	0.73	0.17	0.62	0.30	0.47	0.79	0.81	0.45	0.21	0.01	0.42	-0.66	0.67	1.00			
Root and stover residuals (kg P/ha)	34	0.53	0.49	0.58	-0.05	0.38	-0.50	0.19	0.47	0.19	0.38	0.37	-0.53	-0.26	0.42	0.53	0.59	0.04	0.42	0.86	0.17	0.41	0.56	-0.15	-0.15	0.07	0.55	-0.38	0.28	0.35	0.32	-0.19	-0.25	0.29	1.00		
Inorganic soil pool (kg P/ha/yr) (surplus/deficit)	35	0.67	0.61	0.59	0.20	0.66	-0.16	-0.91	0.67	0.54	0.50	0.48	-0.41	-0.60	-0.67	-0.82	-0.79	-0.81	-0.67	-0.24	-0.17	0.15	-0.37	0.26	-0.07	-0.91	-0.62	0.02	-0.62	0.55	-0.65	0.63	-0.62	-0.72	-0.14	1.00	
Total P lost (kg P)	36	0.09	-0.06	0.32	-0.20	0.00	-0.12	0.74	-0.12	-0.51	-0.37	-0.31	-0.35	-0.42	0.93	0.60	0.62	0.78	0.93	0.80	0.07	0.51	0.53	-0.38	-0.25	0.31	0.47	-0.64	0.95	-0.41	0.90	-0.61	-0.39	0.19	0.49	-0.47	1

Table C.6. Correlation matrix of all variables related to the sheep and beef sector estimated maintenance and modelled Overseer nutrient budgets.

Factors	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35			
Rainfall (mm)	1	1.00																																				
Average total area (ha)	2	-0.21	1.00																																			
Effective area	3	-0.30	0.98	1.00																																		
New Grass area	4	-0.52	0.33	0.43	1.00																																	
Cash crop area	5	-0.48	-0.28	-0.24	-0.26	1.00																																
Summer forage crop (area under leafy turnips)	6	-0.39	0.67	0.74	0.44	-0.29	1.00																															
Winter forage crop (area under kale and swedes)	7	-0.88	0.24	0.35	0.62	0.54	0.33	1.00																														
Trees and scrub area	8	0.17	0.74	0.60	-0.10	-0.31	0.23	-0.18	1.00																													
Open Sheep (SU)	9	-0.21	0.87	0.82	0.40	-0.33	0.55	0.22	0.74	1.00																												
Open Cattle (SU)	10	0.53	0.48	0.38	-0.35	-0.31	0.24	-0.41	0.67	0.24	1.00																											
Stocking rate (SU/ha)	11	0.59	-0.79	-0.85	-0.38	-0.13	-0.64	-0.59	-0.34	-0.63	-0.11	1.00																										
Wool Shorn (kg greasy)	12	-0.15	0.84	0.79	0.36	-0.38	0.57	0.17	0.74	0.99	0.28	-0.59	1.00																									
Average ASC	13	0.63	0.17	0.11	-0.35	-0.35	-0.01	-0.47	0.32	0.21	0.44	0.05	0.31	1.00																								
Flat maintenance requirement (kg P/ha)	14	0.85	-0.07	-0.18	-0.54	-0.38	-0.22	-0.76	0.34	-0.06	0.63	0.49	0.03	0.72	1.00																							
rolling maintenance requirement (kg P/ha)	15	0.88	-0.13	-0.26	-0.58	-0.39	-0.33	-0.81	0.33	-0.14	0.63	0.59	-0.07	0.62	0.96	1.00																						
easy maintenance requirement (kg P/ha)	16	0.85	-0.29	-0.40	-0.43	-0.49	-0.34	-0.81	0.16	-0.22	0.45	0.74	-0.14	0.53	0.90	0.95	1.00																					
Steep maintenance requirement (kg P/ha)	17	0.82	-0.38	-0.47	-0.36	-0.40	-0.58	-0.76	0.07	-0.22	0.20	0.78	-0.17	0.39	0.77	0.83	0.89	1.00																				
New Pasture maintenance requirement (kg P/ha)	18	0.85	-0.07	-0.18	-0.54	-0.38	-0.22	-0.76	0.34	-0.06	0.63	0.49	0.03	0.72	1.00	0.96	0.90	0.77	1.00																			
Hay/silage maintenance requirement (kg P/ha)	19	0.64	-0.12	-0.21	-0.31	-0.14	-0.34	-0.42	0.21	-0.24	0.58	0.42	-0.20	0.27	0.68	0.71	0.65	0.64	0.68	1.00																		
Flat (Total block requirements (kg P))	20	-0.40	0.31	0.41	0.31	0.35	0.34	0.56	-0.16	0.11	-0.09	-0.50	0.05	-0.18	-0.53	-0.53	-0.61	-0.57	-0.53	-0.31	1.00																	
rolling (Total block requirements (kg P))	21	-0.69	0.36	0.48	0.50	0.34	0.45	0.74	-0.17	0.24	-0.32	-0.65	0.16	-0.40	-0.80	-0.81	-0.85	-0.76	-0.80	-0.55	0.90	1.00																
easy (Total block requirements (kg P))	22	0.34	0.44	0.43	0.30	-0.58	0.25	-0.21	0.35	0.41	0.44	-0.25	0.42	0.20	0.19	0.13	0.13	0.13	0.19	0.23	0.07	-0.03	1.00															
Steep (Total block requirements (kg P))	23	0.10	0.84	0.74	-0.03	-0.35	0.45	-0.11	0.88	0.80	0.62	-0.49	0.83	0.46	0.35	0.28	0.11	-0.01	0.35	0.09	-0.17	-0.13	0.27	1.00														
New Pasture (Total block requirements (kg P))	24	-0.41	0.31	0.40	0.98	-0.33	0.42	0.54	-0.09	0.39	-0.28	-0.27	0.36	-0.27	-0.39	-0.44	-0.28	-0.23	-0.39	-0.20	0.22	0.37	0.32	0.00	1.00													
Hay/silage (Total block requirements (kg P))	25	-0.54	-0.24	-0.12	0.42	0.36	0.06	0.60	-0.56	-0.44	-0.34	-0.02	-0.47	-0.59	-0.47	-0.42	-0.33	-0.35	-0.47	0.00	0.31	0.37	-0.37	-0.50	0.41	1.00												
Fertiliser P, lime and other added Leaching, runoff and direct losses	26	0.59	-0.76	-0.79	-0.23	-0.29	-0.60	-0.59	-0.38	-0.52	-0.23	0.92	-0.46	0.16	0.43	0.51	0.70	0.80	0.43	0.37	-0.50	-0.60	-0.10	-0.49	-0.15	-0.08	1.00											
As product	27	0.55	-0.38	-0.39	-0.30	0.09	-0.44	-0.31	-0.19	-0.56	0.36	0.57	-0.54	0.12	0.55	0.60	0.58	0.58	0.55	0.78	-0.08	-0.39	-0.04	-0.24	-0.18	0.29	0.42	1.00										
As supplement	28	-0.40	-0.36	-0.32	-0.30	0.99	-0.37	0.46	-0.37	-0.38	-0.35	-0.03	-0.44	-0.32	-0.32	-0.33	-0.42	-0.31	-0.32	-0.11	0.31	0.28	-0.58	-0.40	-0.35	0.33	-0.21	0.14	1.00									
Standing plant material	29	-0.43	-0.20	-0.17	-0.29	0.99	-0.28	0.51	-0.24	-0.25	-0.26	-0.17	-0.31	-0.27	-0.33	-0.35	-0.48	-0.38	-0.33	-0.13	0.35	0.32	-0.52	-0.26	-0.35	0.27	-0.34	0.07	0.98	1.00								
Organic pool	30	0.62	0.25	0.13	-0.24	-0.64	-0.14	-0.68	0.57	0.18	0.57	0.08	0.21	0.47	0.54	0.59	0.52	0.46	0.54	0.45	-0.37	-0.47	0.53	0.41	-0.23	-0.50	0.19	0.09	-0.65	-0.61	1.00							
Inorganic mineral	31	0.21	0.14	0.16	0.32	-0.79	0.30	-0.40	0.06	0.15	0.08	0.12	0.15	-0.21	0.04	0.09	0.23	0.25	0.04	0.03	-0.25	-0.15	0.52	0.07	0.34	-0.12	0.23	-0.12	-0.77	-0.80	0.37	1.00						
Inorganic soil pool	32	0.57	0.07	0.04	-0.28	-0.25	-0.07	-0.36	0.14	0.07	0.36	0.09	0.18	0.95	0.66	0.57	0.50	0.37	0.66	0.23	-0.07	-0.33	0.14	0.29	-0.19	-0.39	0.20	0.24	-0.23	-0.20	0.34	-0.30	1.00					
Change in supplement storage	33	0.53	-0.20	-0.26	0.10	-0.83	-0.10	-0.61	0.05	0.03	-0.01	0.53	0.10	0.32	0.40	0.44	0.63	0.62	0.40	0.15	-0.54	-0.52	0.27	0.00	0.17	-0.34	0.72	-0.02	-0.79	-0.86	0.53	0.61	0.26	1.00				
Root and stover residuals	34	0.33	-0.34	-0.32	-0.13	-0.06	-0.20	-0.20	-0.30	-0.48	0.23	0.42	-0.46	-0.21	0.12	0.27	0.33	0.28	0.12	0.33	-0.06	-0.21	0.04	-0.33	-0.07	0.28	0.32	0.57	-0.04	-0.10	-0.10	0.22	-0.09	0.07	1.00			
	35	-0.72	-0.23	-0.14	0.19	0.78	0.07	0.77	-0.46	-0.24	-0.48	-0.18	-0.28	-0.63	-0.65	-0.67	-0.65	-0.57	-0.65	-0.25	0.40	0.55	-0.51	-0.44	0.13	0.64	-0.27	-0.06	0.74	0.72	-0.84	-0.45	-0.54	-0.64	0.03	1.00		

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