# Final Technical Results Report

# 2025

**Assessment of organic phosphorus sources**


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## REPORT SENSITIVITY

Does the report have any of the following sensitivities?

| | |
|---|---|
| Intended for journal publication | YES ☒ NO ☐ |
| Results are incomplete | YES ☐ NO ☒ |
| Commercial/IP concerns | YES ☐ NO ☒ |
| Embargo date | YES ☒ NO ☐<br>If Yes, Date: 28 March 2027 |

# Contents

# ABSTRACT

The addition of mineral-based fertilisers to soil has been an important strategy to improve soil phosphorus (P) fertility and crop growth. However, the price of P fertilisers has been highly variable and continues to increase. Livestock manures are a source of P that could offset mineral-based fertilisers in many cropping regions. The overall aim of this project was to assess the crop response of P from chicken manure (CM) and monoammonium phosphate (MAP) at multiple rates and over two growing seasons. In general, concentrations of total P in dry manures were relatively low (0.3 – 2.5 %), and inorganic forms were predominant (on average 85 % of total P). Crop responses to CM and MAP were generally similar across all rates, growing seasons, and crop types. A large portion of P from CM and MAP accumulated in the 0 – 10 cm soil layer as inorganic forms. Crop recovery of 'fresh' MAP in 2024 was around 40 % (canola) and 32 % (wheat) in the year of application, and was unaffected by previous applications of CM or MAP. Chicken manure was estimated to be the most economic type of fertiliser P for improved crop growth if obtained relatively close to the source.

# EXECUTIVE SUMMARY


Phosphorus (P) is an essential macronutrient for grain crops. In general, crop growth is limited due to low soil P fertility in many grain growing regions of Australia. Historically, mineral-based fertilisers, such as monoammonium phosphate (MAP), have been an important option to improve soil P fertility and reduce the likelihood of a crop P deficiency. The problem with this is that mineral-based fertilisers are primarily derived from phosphate rock, which is a non-renewable resource and often located in geopolitically unstable regions of the world. Consequently, the price of fertiliser P from mineral-based sources continues to increase and is highly variable. Alternative sources of P, such as livestock manure, have gained much attention and have the potential to partially offset mineral-based fertilisers. This research aimed to evaluate the potential of livestock manure, i.e., chicken manure (CM), as an alternative source of P than MAP in supplying P to two winter crops (canola and wheat) over two growing seasons (2022 and 2023). The study focused on four main objectives:

- Assessing the concentrations and forms of P in various livestock manures collected across NSW and QLD.
- Evaluating crop responses to increasing rates of P supplied as either chicken manure or MAP under field conditions.
- Investigating the fate of P from CM and MAP in soil over time.
- Determining the crop recovery of a ‘fresh’ addition of MAP in soils that had previously been fertilised with either CM or MAP.

Concentrations of total P across all dry manures ranged from 0.3 % to 2.5 % P, and were relatively low compared to that of mineral-based fertilisers (typically 8 % to 23 % P). Pig manure had the highest average concentration of P (2.0 %), followed by chicken manure (1.1 %) and beef/dairy manure (~ 0.7%). On average, 78 % of total P in ‘fresh’ manures was present as inorganic forms, which increased to 86 % of total P in dry manures. Pools of organic P in all manures were relatively low, with the predominant form of organic P being phytate or RNA mononucleotides. Therefore, the P forms in manure are not too dissimilar to those in many mineral-based fertilisers and are likely to be highly water soluble and readily plant-available.

In 2022 and 2023, canola and wheat yield significantly increased with the addition of fertiliser P as CM or MAP. In 2022, canola seed yield ranged from 2.7 to 4.0 t/ha, whereas wheat grain yield ranged from 6.7 to 8.0 t/ha. In 2023, crop yields were generally lower, but followed a similar pattern than the previous year. There was no significant difference in crop yield or crop P offtake between CM and MAP in 2022 or 2023. Therefore, the addition of fertiliser P is vital to improve crop yields in soils of low P fertility, and that CM and MAP are viable options in supplying P to crops.

A soil P audit revealed that concentrations of ‘plant-available’ P (Colwell-P) in the 0 – 10 cm soil layer increased with the addition of fertiliser P application. Concentrations of Colwell-P in the 0 – 10 cm layer ranged from 25 to 60 mg P/kg in 2022. Overall, concentrations of Colwell-P were similar between CM and MAP, except at the highest fertiliser rates. Concentrations of Colwell-P across all treatments generally declined after each growing season, and differences between the CM and MAP treatments decreased over time. Furthermore, a large portion of the P from CM and MAP was found in pools of inorganic P in the 0 – 10 cm soil later. In contrast, concentrations of organic P in soil, and also P in the 10 – 30 cm soil layer, remained largely unchanged in 2022 and 2023. This is consistent with previous results (P analyses on manures and crop responses) and suggests that the P in CM behaved similarly to that of MAP when added to soil.

In 2024, crop responses to fresh MAP applications were generally consistent across plots with prior fertilisation histories (CM and MAP). The proportion of crop P uptake derived from the added fresh MAP was slightly higher in non-fertilised plots (i.e., 31 % for wheat and 21 % for canola) compared to the previously fertilised plots at the 90 kg P/ha rate (i.e., 25 % for wheat and 16 % for canola). Overall, the majority of crop P uptake was derived from the soil P reserves, with soil P contributing an average of 72 % for wheat and 82 % for canola. Furthermore, crop recovery of P from the fresh MAP was on average 32 % for wheat and 40 % for canola in the year of application. Therefore, previous applications of CM to soil (up to 90 kg P/ha) do not significantly improve the availability of fresh additions of mineral-based fertilisers.

In 2022, the addition of fertiliser P (and basal nutrients) resulted in about 1.09 t/ha of extra wheat grain yield and 1.26 t/ha of canola seed yield compared to the non-fertilised control. In 2023, there was about 0.59 t/ha of extra wheat grain yield and 0.80 t/ha of canola seed yield compared to the non-fertilised control. Therefore, the addition of fertiliser P resulted in an extra 1.68 t/ha of wheat grain yield and 2.06 t/ha of canola seed yield across the two years.

A target rate of 50 kg P/ha was used for economic calculations, which would require 2.85 t/ha of CM (dry-weight basis). This equates to 5.07 $m^3$/ha of CM (fresh-weight basis) when taking into account the water content. The overall cost of CM (fresh-weight basis) supplied, delivered, and applied is estimated at $172.50/ha or $3.45/kg P. In contrast, the overall cost of MAP supplied, delivered, and applied is estimated at $281.03/ha or $5.62/kg P. Therefore, the most economic option of supplying P to the field is CM under the aforementioned conditions. Assuming a price of $350/t for wheat and $550/t for canola, the extra yield alone would result in an increased return of $588/ha and $1133/ha for wheat and canola, respectively. The return on the extra yield alone is considerably more than the overall cost of CM and MAP. The extra yield is likely to further increase in the third (and possibly fourth) year due to the residual value of the fertiliser.

This project shows that livestock manure can be used to offset mineral-based fertilisers, and may be the most economic option of P in certain regions. Furthermore, this project shows that the majority of P in livestock manure was that of inorganic P, and behaved in similar manner when added to soil compared to that of MAP. Since there was no significant difference in crop responses to CM and MAP, growers have flexibility on choosing CM or MAP as a source of fertiliser P. Fertiliser decisions can be more easily made on the cost of each fertiliser type based on $/kg P needed to meet a target P rate.

## BACKGROUND

Australia is a major producer of grain crops and is estimated to generate around $19 billion in revenue each year. However, crop yields are often limited due to low soil phosphorus (P) fertility. The use of mineral-based fertilisers has typically been an important strategy to increase soil P fertility and reduce the likelihood of a crop P deficiency.

Mineral-based fertilisers are predominantly used across the grains industry, particularly that of monoammonium phosphate (MAP) and diammonium phosphate (DAP). The majority of mineral-based fertilisers are derived from naturally occurring phosphate rock, which is a non-renewable resource and often located in geopolitically unstable regions of the world. Australia has very limited reserves of phosphate rock, and therefore needs to import approximately 214 kt of P each year, which a large portion is used for agriculture. Furthermore, the cost of P fertiliser has been highly volatile and predicted to increase in the future (Bovill, Huang et al. 2013). It is essential that alternative sources of P be developed/investigated and assessed if they can offset the use of mineral-based fertilisers in supplying P to crops.

In Australia, it is estimated that around 635 kt of P as livestock manure is produced annually. Intensive livestock enterprises (e.g., cattle feedlots, piggeries, and poultry sheds) have the potential to offset a significant portion of the P requirements of crops that are currently being met by mineral-based fertilisers. There is also increasing demand for organic amendments as an alternative P source due to mineral-based fertilisers. However, there is limited information on the forms of P present in livestock manures, and their fate in soil to improve soil P fertility and meet crop P demand.

In general, concentrations of total P in livestock manure tend to be much lower than that of mineral-based fertilisers. The forms of P in livestock manure could either be ‘organic’, i.e., associated with carbon (e.g., phytate), or ‘inorganic’, i.e., associated with a cation (e.g., calcium phosphate). Studies outside of Australia show that a large portion of the P in livestock manure is that of inorganic forms, but chicken manure can contain a higher proportion of its total P as organic forms (largely as phytate). However, the ratio of inorganic to organic P in livestock manure is highly variable and can depend on the type of animal, its diet, and the processing/storage of manure. The significance of this is that the predominant forms of P in livestock manure are likely to affect its fate in soil and availability to crops.

# PROJECT OBJECTIVES

The first main aim was to assess the forms of P in a variety of livestock manures collected in eastern Australia. The second main aim was to determine the crop responses to increasing rates of fertiliser P supplied as either CM or MAP under field conditions. The third main aim was to assess the fate of fertiliser P in soil supplied as either CM or MAP. The fourth main aim was to determine the crop recovery of a 'fresh' addition of MAP in the year of application to soils that had been previously fertilised with either CM or MAP under field conditions. Lastly, a brief economic assessment was carried out on CM and MAP as a source of P to crops.

# METHODOLOGY

The experimental work comprised of four main parts.

## Part One – Phosphorus in Fertilisers

*Sample collection and preparation*

Fresh manure samples were collected from a variety of locations across New South Wales (NSW) and Queensland (QLD). A total of 24 samples were collected, which included nine chicken manures, eight cattle manures, three dairy manures, and four pig manures. Chicken manures were obtained from broiler chickens and poultry layers, cattle manures were obtained from grassfed, feedlot, and dairy operations, and pig manures were obtained from a piggery.

At least 2 kg of each manure sample was collected and then stored at 4 °C. A subsample was taken and dried at low temperature until constant weight (35 °C for 14 days). Dried manure samples were then ground to powder (< 2 mm) prior to analysis.

*Sample analysis*

A subsample of each fresh manure sample was analysed for gravimetric water content. Gravimetric water content was calculated using Equation 1.

$$\theta_m \ (g/g) = \left(\frac{M_{fm}}{M_{dm}} - 1\right) \qquad \text{(Equation 1)}$$

, where ‘$\theta_m$’ refers to the gravimetric water content (g water / g of dry material), ‘$M_{fm}$’ refers to the mass of fresh manure (g), and ‘$M_{dm}$’ refers to the mass of dry manure (g).

A diversity of chemical analyses was carried out on all manure samples. Manure pH was measured at a 1:5 soil to solution ratio in water. Concentrations of total carbon (C) and nitrogen (N) were determined by dry combustion using a LECO Combustion Analyser. Concentrations of total aluminium (Al), calcium (Ca), iron (Fe), potassium (K), magnesium (Mg), sulfur (S), and P were obtained by digestion (nitric-perchloric) followed by inductively coupled plasma-optical emissions spectroscopy (ICP-OES). Concentrations of inorganic and organic P were determined using the NaOH-EDTA extraction technique. The chemical composition of organic P in NaOH-EDTA extracts were determined using solution $^{31}$P nuclear magnetic resonance (NMR).

*Chicken manure and MAP used in the field experiment*

A subsample of the two fertilisers used in the field experiment was analysed, i.e., a commercially available monoammonium phosphate (MAP) and a chicken manure (CM) sourced from a farm near Temora (NSW). Pictures of the fertilisers are shown in Figure 1.


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**Figure 1. A picture of the monoammonium phosphate (MAP) granules (left) and chicken manure (CM) (right) before addition to the field. The MAP was sourced from a commercial supplier and the CM was sourced from a farm near Temora (NSW).**

**Part Two – Crop Responses to CM and MAP**

*Site details and experimental design*

Two field experiments including four replicates and arranged into a randomised block design were established at the Wongarbon site in the 2022 winter season. Each plot size was 12 m × 2 m and arranged in a randomised complete block design with four replicates. Treatments included eight fertiliser rates (0, 5, 10, 15, 30, 50, 70, and 90 kg P/ha) and two fertiliser types (chicken manure and MAP). The first field experiment included a canola (2022)/wheat (2023) rotation, and the second field experiment included a wheat (2022)/canola (2023) rotation. Phosphorus fertilisers were supplied as a broadcast and mixed into the surface 0 – 10 cm soil layer in 2022. Pictures of the field experiments at approximately 30 DAS are shown in Figure 2.

**Figure 2. A picture of the canola field experiment at 29 DAS (left) and the adjacent wheat field experiment at 30 DAS (right) in 2022. The two field experiments were located on a property near Wongarbon (NSW).**

Basal additions of N were applied each year to ensure that N was not limiting crop growth. In 2022, the estimated supply of available N to canola and wheat in the 90 kg P/ha plots as CM was 388 kg N/ha and 244 kg N/ha, respectively. This also assumed an estimated supply of 60 kg N/ha from the soil, 43 Kg N/ha as MAP at planting, and that 50 % of the N in the added CM would be plant-available in the year of application. Therefore, all plots received regular additions of N as urea or UAN throughout the growing season, which resulted in each plot having a total available N of 388 kg N/ha for canola and 244 kg N/ha for wheat. In 2023, all plots received regular additions of N that resulted in a total available N of 115 kg N/ha for canola and 137 kg N/ha for wheat. Basal additions of K and S as sulfate of potash to supply 80 kg K/ha and 33 kg S/ha were applied in 2022. Micronutrients were applied throughout the duration of the field experiments in 2022 and 2023 when needed.

*Harvest*

A subset of plots was selected for dry matter cuts. This included both crop types and fertiliser treatments at the 0, 30, and 90 kg P/ha rates. Briefly, three lots of one meter lengths of row was identified and the aboveground biomass collected from each within the plot. In 2022, this occurred on the 27$^{th}$ of July, which corresponded to 93 DAS for canola and 63 DAS for wheat. In 2023, this occurred on the 27$^{th}$ of July, which corresponded to 90 DAS for canola and wheat. The aboveground biomass was placed in an oven at 65 °C until constant weight, weighed, passed through a mulcher, and then ground to pass through a 1 mm sieve.

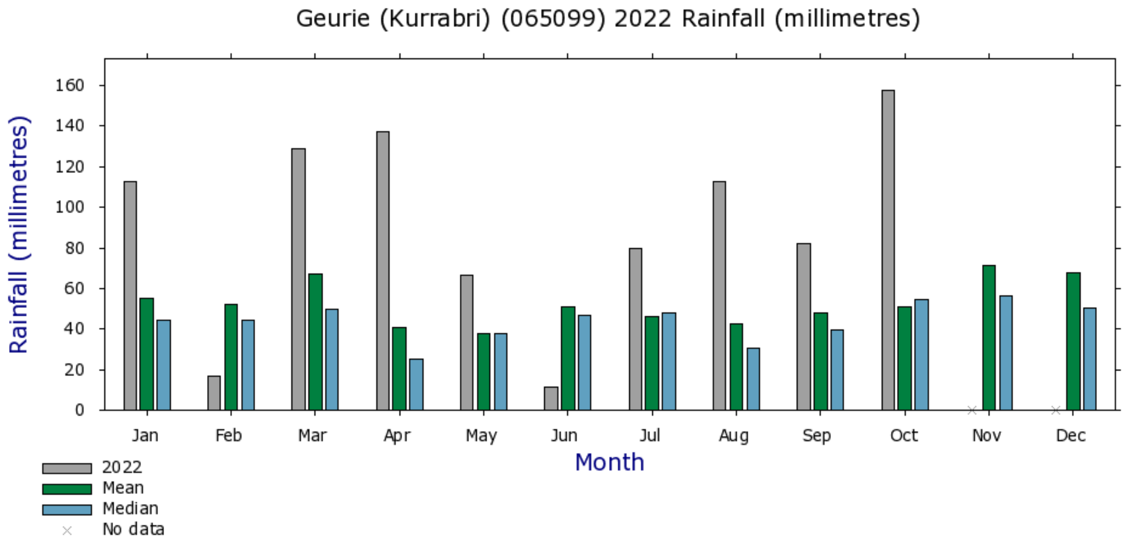
Canola seed and wheat grain yield data were obtained at the end of the growing season. A subsample of canola seed and wheat grain were also obtained from each plot. Canola seed and wheat grain were ground to pass through a 1 mm sieve prior to chemical analyses.

*Climate*

Figure 3 shows the rainfall data at the nearest weather station (Geurie, NSW) to the Wongarbon field site. The average (long-term) rainfall data at this site is about 611 mm/yr. In 2022, rainfall was recorded to be 967 mm which is well above the long-term average. In contrast, in 2023, rainfall was recorded to be 137 mm which is well below the long-term average.

*Analyses*

All plant material were analysed for total elements. Concentrations of total P were obtained by digestion (nitric-perchloric) followed by ICP-OES. Crop P uptake in aboveground biomass and crop P offtake in seed/grain were determined by multiplying dry matter or seed/grain yield with the concentration of total P. Values were converted to an area basis (i.e., kg P/ha).



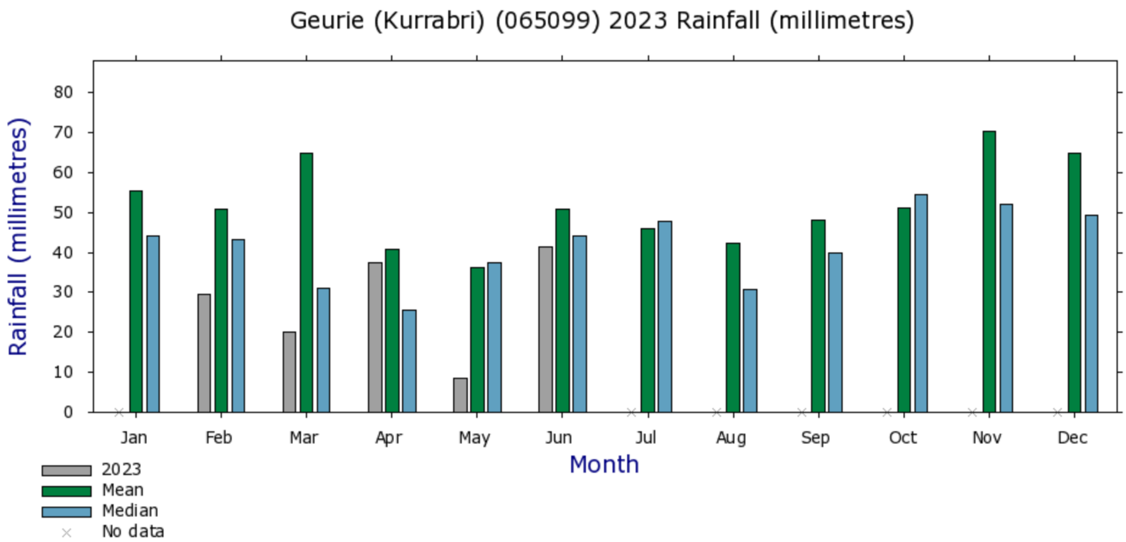




**Figure 3. The average long-term rainfall data and the rainfall data for 2022 (top) and 2023 (bottom) at the nearest weather station (Geurie, NSW) to the Wongarbon field site. The data was taken from the Bureau of Meteorology.**

## Part Three – Fate of CM and MAP in Soil

*Soil collection and preparation*

Soil samples were collected on the 24th of May in 2022, which corresponded to one day before sowing in the wheat experiment and 29 days after sowing (DAS) in the canola experiment. In addition, soil samples were collected on the 25th of May in 2023, which corresponded to 27 DAS (canola and wheat), and 414 days since the initial fertiliser application in 2022. A subset of plots was sampled from the 10 – 30 cm soil layer. All soil samples were placed in an oven at 40 °C until constant weight, and then ground to pass through a 2 mm sieve. Soil samples were then analysed for a range of chemical properties and measures of "plant-available" P.

*Soil analyses*

A diversity of chemical analyses was carried out on all samples from the 0 – 10 cm soil layer. Soil pH and EC were measured at a 1:5 soil to solution ratio in water. Concentrations of 'plant-available P' as estimated by the Colwell and DGT methods. Concentrations of inorganic and organic P were determined using the NaOH-EDTA extraction technique. Measures of mineral N ($NH_4^+$ and $NO_3^-$) were obtained using 2 M KCl.

**Part Four – Crop Responses to $^{33}$P-labelled MAP**

*Microplots and $^{33}$P-labelled MAP*

In 2024, a field 'microplot' experiment was established within the existing plots of the two field experiments near Wongarbon (NSW). A subset of treatments was selected, which included the 0, 30, and 90 kg P/ha rates for both crops and fertiliser types. Three of the four field replicates were chosen and each experimental plot contained two microplots.

Analytical grade MAP solution was dissolved in water and then a carrier-free $^{33}$P radionuclide was added. Briefly, a 30 cm long microplot was identified just after germination (21 DAS for canola and 13 DAS for wheat) where there was a consistent plant stand along the row (Figure 4). A total of eight (9 mm diam.) stainless steel tubes with a removeable stainless steel rod insert were inserted into the soil about 2 – 3 cm adjacent from the planting row to a depth of 8 cm below the soil surface. The rod insert was removed and an 8 Gauge needle placed within each tube and a known volume of the $^{33}$P-labelled MAP solution injected into the soil, which supplied about 13 kg P/ha. A small volume of water was then added to rinse the needle, and the tubes left for several minutes to allow the solution to diffuse into the soil. The tubes were then removed, and the hole backfilled with topsoil.

**Figure 4. A picture showing how the $^{33}$P labelled MAP solution was injected within the 30 cm microplot. Eight tubes were inserted along the row to supply MAP as a 'band' about 8 cm below the soil surface to supply 13 kg P/ha (left). A picture also shows how the plants were harvested within the microplot (pink), including an adjacent buffer zone (blue). Plants were harvested at 132 DAS for canola and 124 DAS for wheat (right).**

*Harvest*

Aboveground biomass was harvested 132 DAS for canola and 124 DAS for wheat. All plants within the microplot row (30 cm length) and the adjacent front and back rows (each 30 cm in length) were collected for analysis. At the time of harvesting, wheat was at booting stage and canola was at flowering stage. The harvested biomass was then dried in an oven at 65°C until constant weight. Plant samples were then weighed and ground to pass through a 1 mm sieve.

*Analyses*

All plant material were analysed for total elements. Concentrations of total P were obtained by digestion (nitric-perchloric) followed by ICP-OES. Crop P uptake in aboveground biomass was determined by multiplying dry matter with the concentration of total P. In addition, plant digests were analysed for $^{33}P$ activity using a liquid scintillation counter.

## LOCATION

Where field trials have been conducted, provide the following location details in the table below: latitude and longitude, or nearest town. (Add additional rows as required.)

| Site # | Latitude (decimal degrees) | Longitude (decimal degrees) | Nearest town |
|---|---|---|---|
| Trial Site #1 | -32.320417 | 148.789361 | Wongarbon (NSW) |

If the research results are applicable to a specific GRDC region/s (e.g. North/South/West) or GRDC agro-ecological zone/s, indicate which in the table below:

| Research | Benefiting GRDC region (select up to three) | Benefitting GRDC agro-ecological zone | |
|---|---|---|---|
| Assessment of organic phosphorus sources | Northern Region<br>Choose an item.<br>Choose an item. | ☐ Qld Central<br>☐ NSW NE/Qld SE<br>☐ NSW Vic Slopes<br>☐ Tas Grain<br>☐ SA Midnorth-Lower Yorke Eyre<br>☐ WA Northern<br>☐ WA Eastern<br>☐ WA Mallee | ☒ NSW Central<br>☐ NSW NW/Qld SW<br>☐ Vic High Rainfall<br>☐ SA Vic Mallee<br>☐ SA Vic Bordertown-Wimmera<br>☐ WA Central<br>☐ WA Sandplain |

## RESULTS

**Part One – Phosphorus in Fertilisers**

*Animal manures*

Chemical properties varied among and within manure types (Table 1). Manure pH ranged from 6.4 to 8.8 across all samples. On average, CM and pig manure was near neutral pH, cattle manure was slightly alkaline, and dairy manure was moderately alkaline. Concentrations of total N were highest in the chicken and pig manure and lowest in the cattle and dairy manure. The C:N ratio for all manure types was low (< 25). Concentrations of calcium were the dominant cation in CM and pig manure, whereas cattle and dairy manure had elevated concentrations of calcium, iron, and potassium.

**Table 1. Some chemical properties of dried animal manures collected across NSW and QLD. The average values for each manure type are reported with minimum and maximum values provided in parentheses. The number (n) of samples that was collected for each manure type is shown.**

| Parameter | Chicken manure (n = 9) | Cattle manure (n = 8) | Dairy manure (n = 3) | Pig manure (n = 4) |
|---|---|---|---|---|
| $pH_{w\ (1:5)}$ | 6.7 (6.4 - 7.2) | 7.6 (7.1 - 8.4) | 8.1 (7.4 - 8.8) | 7.2 (7.1 - 7.5) |
| Total C (%) | 34.1 (15.1 - 42.6) | 34.0 (25.2 - 40.5) | 16.6 (13.2 - 21.4) | 41.3 (38.1 - 42.6) |
| Total N (%) | 4.4 (2.2 - 6.2) | 1.9 (1.3 - 2.7) | 1.2 (0.9 - 1.5) | 3.8 (3.4 - 4.5) |
| C/N Ratio | 8 (6 - 14) | 18 (14 - 25) | 14 (10 - 17) | 11 (9 - 12) |
| Total Al (%) | 0.3 (0.0 - 1.0) | 0.6 (0.1 - 1.0) | 1.1 (0.6 - 1.7) | 0.1 (0.0 - 0.1) |
| Total Ca (%) | 3.9 (1.1 - 8.8) | 1.7 (0.7 - 2.6) | 1.6 (1.3 - 2.1) | 3.7 (2.7 - 5.9) |
| Total Fe (%) | 0.5 (0.1 - 1.8) | 1.1 (0.1 - 2.5) | 1.6 (1.0 - 2.3) | 0.1 (0.1 - 0.2) |
| Total K (%) | 1.9 (0.8 - 2.6) | 1.0 (0.4 - 2.1) | 1.4 (1.2 - 1.6) | 1.1 (0.7 - 1.4) |
| Total Mg (%) | 0.6 (0.4 - 1.3) | 0.6 (0.4 - 0.8) | 1.0 (0.8 - 1.3) | 0.9 (0.9 - 1.0) |
| Total S (%) | 0.4 (0.2 - 0.6) | 0.3 (0.1 - 0.6) | 0.3 (0.3 - 0.3) | 0.4 (0.4 - 05) |
| Total P (%) | 1.1 (0.7 - 1.5) | 0.6 (0.3 – 0.9) | 0.8 (0.6 - 1.0) | 2.0 (1.7 - 2.5) |

Concentrations of total P differed greatly among and within dry manure types ranging from 0.3 – 2.5 % P across all samples (Table 1). In general, pig manure had the highest concentration of total P (average of 2.0 % P) followed by chicken manure (average of 1.1 % P), and beef/dairy manure (average of ~ 0.7 % P). The largest variability in concentrations of total P was found among chicken manure (0.7 – 1.5 % P) and pig manure (1.7 – 2.5 % P) samples. The majority of P in fresh/moist manures was present as inorganic forms (on average 78 % of total P), which generally increased after drying (on average 85 % of total P).

Table 2. **Concentrations of phosphorus in alkali (NaOH-EDTA) extracts on dried animal manures collected across eastern Australia. The average values for each manure type are reported with minimum and maximum values provided in parentheses. The number (n) of samples that was collected for each manure type is shown.**

| Parameter | Chicken manure (n = 9) | Cattle manure (n = 8) | Dairy manure (n = 3) | Pig manure (n = 4) |
|---|---|---|---|---|
| Total P (g P/kg) | 11.2 (6.9 - 14.8) | 5.7 (3.2 - 9.2) | 7.6 (6.2 - 9.7) | 19.8 (16.7 - 24.9) |
| Inorganic P (% of total P) | 82 (64 - 96) | 86 (77 - 94) | 92 (86 - 97) | 85 (70 - 92) |
| Organic P (% of total P) | 18 (4 - 36) | 14 (6 - 23) | 8 (3 - 14) | 15 (8 - 30) |

The chemical composition of organic P in alkali (NaOH-EDTA) extracts on dry manures was carried out using solution $^{31}P$ NMR spectroscopy. The predominant class of organic P detected across all manure types was that of monoesters. Important forms of monoester identified in the majority of manure samples included *myo*-inositol hexakisphosphate (*myo*-$IP_6$), RNA mononucleotides, and α- and β-glycerophosphate.

**Table 3. The chemical composition of organic phosphorus in dried animal manures as determined by solution $^{31}P$ nuclear magnetic resonance (NMR) on alkali (NaOH-EDTA) extracts. The average values for each manure type are reported with minimum and maximum values provided in parentheses. The number (n) of samples that was collected for each manure type is shown.**

| Parameter | Chicken manure (n = 9) | Cattle manure (n = 8) | Dairy manure (n = 3) | Pig manure (n = 4) |
|---|---|---|---|---|
| Monoesters (% of organic P) | 90 (77 - 99) | 87 (75 - 93) | 93 (92 - 94) | 92 (86 - 99) |
| Diesters (% of organic P) | 10 (1 - 23) | 13 (7 - 25) | 7 (6 - 8) | 8 (1 - 14) |
| Phosphonates (% of organic P) | 0.0 (0.0 - 0.1) | 0.0 (0.0 - 0.0) | 0.0 (0.0 - 0.0) | 0.0 (0.0 - 0.0) |

*Chicken manure and MAP – field experiment*

Some chemical and physical properties of the CM and MAP fertilisers are shown in Table 1. The gravimetric water content of the CM at collection was 0.9 g/g (or 44 %). The pH of a water suspension of the MAP and CM fertilisers at a 1:5 material to water ratio was 4.5 and 6.6, respectively. The C to N ratio of the CM was 7.2 on a dry-weight basis. The majority (about 94 %) of N in the CM was non-extractable with 2 M KCl and presumably bound in an organic form. Concentrations of P in the CM and MAP fertilisers were 1.8 % and 22.1 %, respectively. Calcium was the predominant cation measured in the CM.

**Table 4. Some chemical properties of the dried chicken manure and monoammonium phosphate (MAP) that was used in the field experiment.**

| Parameter | Chicken manure | MAP |
|---|---|---|
| GWC (g/g) | 0.9 | 0.0 |
| $pH_{w\ (1:5)}$ | 6.6 | 4.5 |
| Total C (%) | 39.6 | - |
| Total N (%) | 5.5 | 10.5 |
| C/N Ratio | 7.2 | - |
| Total Al (%) | 0.03 | 1.25 |
| Total Ca (%) | 5.83 | 0.77 |
| Total Fe (%) | 0.02 | 1.48 |
| Total K (%) | 2.08 | 0.43 |
| Total Mg (%) | 0.73 | 0.94 |
| Total P (%) | 1.75 | 22.14 |
| Total S (%) | 0.60 | 1.91 |

The concentration of alkali (NaOH-EDTA) extractable P in the chicken manure was 14.52 g P/kg material, which was about 83 % of the total P in the CM by acid digestion. Concentrations of alkali soluble inorganic P (orthophosphate) was the predominant pool of P in the CM, which accounted for 81 % of total extractable P. Pools of organic P were a relatively minor pool, which accounted for about 19 % of total extractable total P. Phytate (*myo*-$IP_6$) was the most abundant pool of organic P in the CM (1293 mg P/kg), followed by other monoesters (894 mg P/kg).

**Table 5. Concentrations of phosphorus in the dried chicken manure that was used in the field experiment.**

| Parameter | Chicken manure |
|---|---|
| Total P (%) | 1.75 |
| NaOH-EDTA extractable total P (g P/kg) | 14.52 |
| Orthophosphate (g P/kg) | 11.80 |
| Organic P (g P/kg) | 2.70 |
| *myo*-$IP_6$ (mg P/kg) | 1293 |
| *scyllo*-$IP_6$ (mg P/kg) | 36 |
| RNA mononucleotides (mg P/kg) | 231 |
| $\alpha$- and $\beta$-Glycerophosphate (mg P/kg) | 164 |
| Other monoester (mg P/kg) | 894 |
| Other diester (mg P/kg) | 60 |
| DNA (mg P/kg) | 24 |
| Pyrophosphate (mg P/kg) | 21 |

**Part Two – Crop Responses to CM and MAP**

*Soil*

Some chemical and physical properties of the soil at the Wongarbon site prior to the field experiment is shown in Table 6. The site has a clay loam topsoil (0 – 10 cm) over a clay subsoil (10 – 30 cm), and both soil layers have an acidic pH (pH 4.9 and 5.5, respectively). Soil organic C is low and there does not appear to be any major soil chemical constraints. The concentration of extractable mineral N in the topsoil is moderate (41 mg N/kg), but dominated by nitrate-N and strongly concentrated in the top 10 cm of the soil profile. The concentrations of Colwell-P are similarly stratified, with the relatively low concentration in the 0 – 10cm layer (19 mg P/kg) indicating that crops would be responsive to the addition of fertiliser P at this site.

**Table 6.** Some chemical properties of a soil sample collected from the 0 – 10 cm and 10 – 30 cm layers at the field site near Wongarbon (NSW). The data was taken from GOA based on initial soil tests.

| **Parameter** | **Unit** | **0 – 10 cm** | **10 – 30 cm** |
|---|---|---|---|
| Field texture | – | Clay loam | Clay |
| $pH_{CaCl2\ (1:5)}$ | – | 4.9 | 5.5 |
| $pH_{w\ (1:5)}$ | – | 5.7 | 6.5 |
| $EC_{w\ (1:5)}$ | dS/m | 0.08 | 0.08 |
| $EC_{w\ (se)}$ | dS/m | 0.6 | 0.2 |
| Organic C | g/kg | 13.0 | 4.0 |
| Extractable $NO_3^-$ | mg/kg | 36.0 | 4.2 |
| Extractable $NH_4^+$ | mg/kg | 4.9 | 1.1 |
| Colwell-P | mg/kg | 19.0 | 5.0 |
| BSES-P | mg/kg | 30.0 | 5.0 |
| PBI | – | 62.0 | 84.0 |
| KCl40-S | mg/kg | 6.0 | 5.0 |
| CEC | cmol(+)/kg | 6.4 | 7.8 |
| ESP | % | 1.0 | 1.0 |
| DTPA-Zn | mg/kg | 0.6 | <0.02 |
| DTPA-Cu | mg/kg | 1.2 | 0.8 |
| DTPA-Fe | mg/kg | 48.0 | 10.0 |
| DTPA-Mn | mg/kg | 110.0 | 34.0 |

Measures of soil pH (1:5 in water) in the 0 – 10 cm soil layer largely ranged from 5.4 – 5.6 across all fertiliser rates and did not significantly differ between the MAP and CM treatments (Figure 5). However, there was a negative slope between soil pH and increasing addition of fertiliser P at both field sites. Measures of soil EC (1:5 in water) in the 0 – 10 cm soil layer ranged from 0.10 – 0.15 dS/m in the canola experiment, which was greater than that in the wheat experiment ranging from 0.05 – 0.1 dS/m. There was also a significant increase in soil EC for CM compared to MAP in the wheat field experiment at higher P rates.

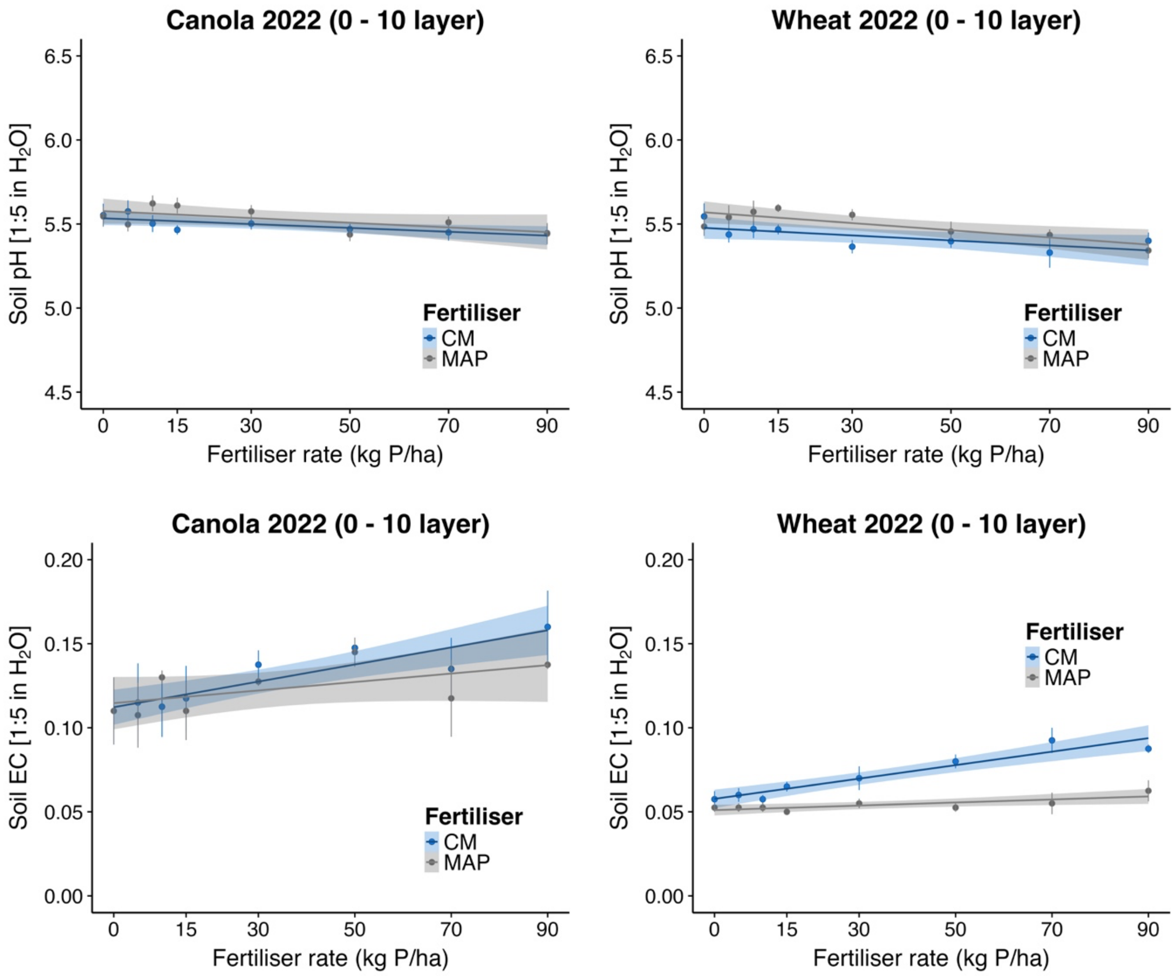



**Figure 5. Measures of soil pH (top) and EC (bottom) in the 0 – 10 cm soil layer for the canola (29 DAS) and wheat (-1 DAS) field experiments in 2022 with increasing addition of fertiliser P as MAP or CM. This corresponds to 48 days after the initial application of fertiliser P on the 6$^{th}$ of April 2022.**

In general, pools of "plant-available" P (Colwell and DGT) in the 0 – 10 cm soil layer increased with increasing fertiliser additions for the MAP and CM treatments in both experiments at the time of sampling (Figure 6). Pools of Colwell-P increased from around 30 – 55 mg P/kg with the addition of fertiliser P, and were generally higher in the MAP treatments compared to the CM treatments at high fertiliser rates. Measures of DGT followed similar patterns to that of Colwell.

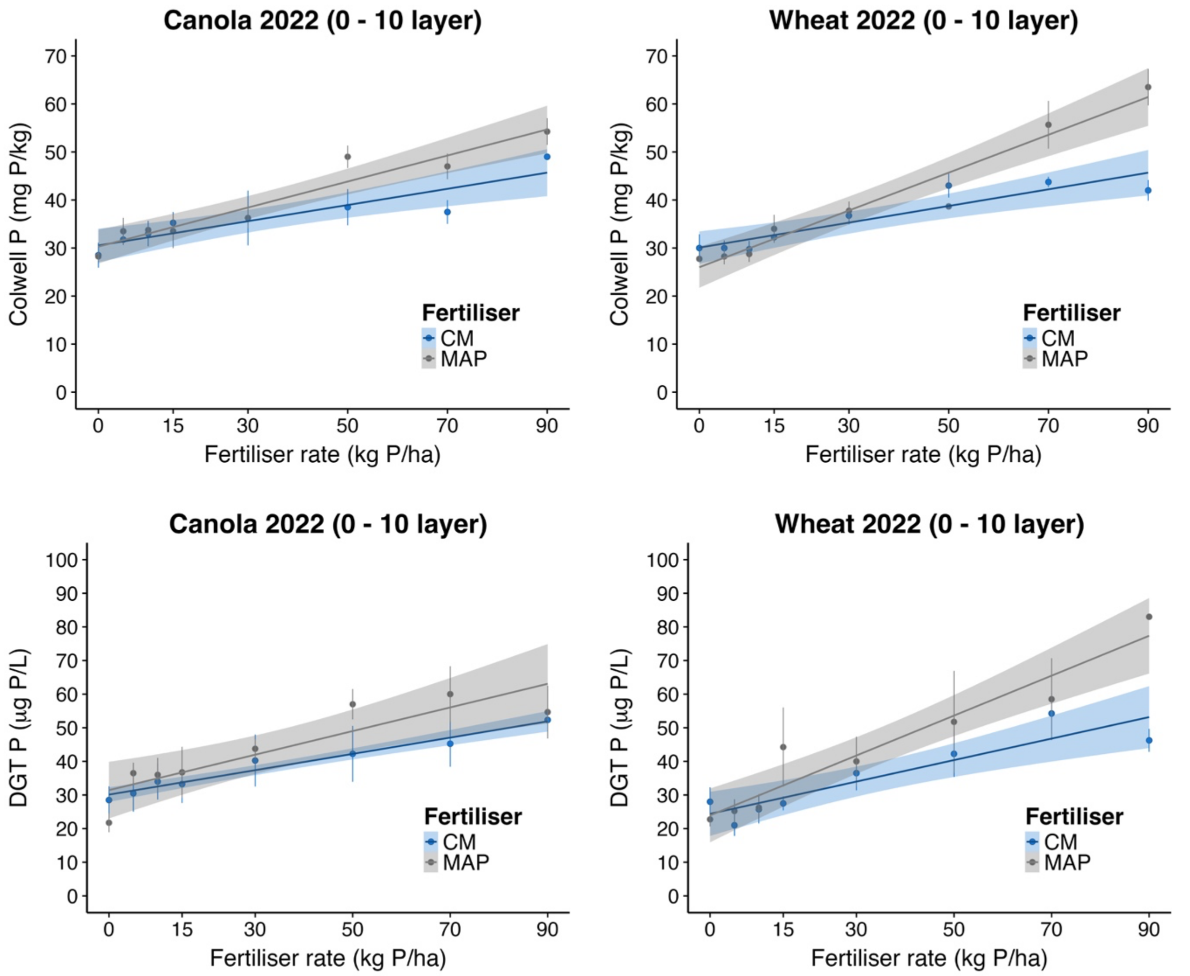



**Figure 6. Measures of "plant-available" P as determined by the Colwell method (top) and DGT method (bottom) in the 0 – 10 cm soil layer of the canola (29 DAS) and wheat (-1 DAS) experiments in 2022 with increasing addition of fertiliser P as MAP or CM. This corresponds to 48 days after the initial application of fertiliser P on the 6th of April 2022.**

*Biomass*

Dry matter in both field experiments increased with the addition of fertiliser P (Figure 7). However, differences were small between the 0 and 30 kg P/ha rates in canola, and the 30 and 90 kg P/ha rates in wheat. In general, dry matter was not significantly different between the MAP and CM treatments for canola and wheat at 93 DAS and 63 DAS, respectively.

Biomass cuts of wheat and canola were taken on the 27th of July corresponding to 90 DAS. A subset of plots was sampled including the 0, 30, and 90 kg P/ha fertiliser rates of the two fertilisers and crop types. Three rows of one metre length were taken from each plot, bulked, dried, ground, and then measured for a range of chemical analyses.

Canola aboveground dry matter ranged from on average 4393 – 8920 kg/ha across both fertiliser types (Figure 14). Canola aboveground dry matter increased with the addition of fertiliser P, which resulted in a 103 % increase in canola dry matter when comparing the 0 and

90 kg P/ha fertiliser rates. There was a significant difference in canola aboveground dry matter between each of the fertiliser rates (i.e., 0, 30, and 90 kg P/ha).

Wheat aboveground dry matter ranged from on average 5808 – 8670 kg/ha across both fertiliser types (Figure 14). Wheat aboveground dry matter increased with the addition of fertiliser P, which resulted in a 49 % increase in wheat dry matter when comparing the 0 and 90 kg P/ha fertiliser rates. There was no significant difference in wheat aboveground dry matter between the 0 and 30 kg P/ha fertiliser rates, but there was a significant difference between the 0 and 90 kg P/ha, and 30 and 90 kg P/ha, fertiliser rates.

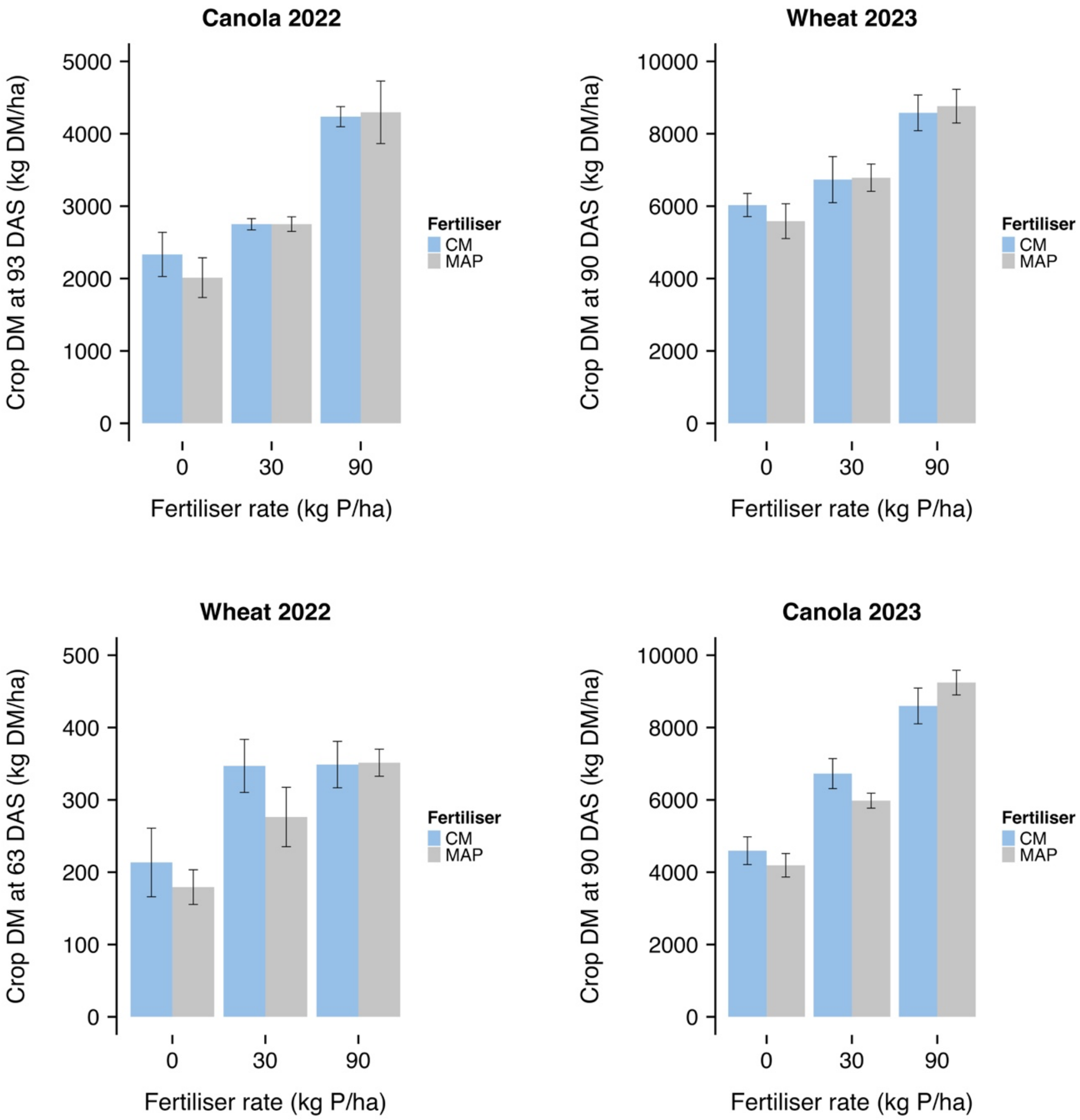



**Figure 7. Measures of dry matter (kg DM/ha) for the canola (2022)/wheat (2023) field experiment (top), and the wheat (2022)/canola (2023) field experiment (bottom). In 2022, samples were taken on the 27th of July corresponding to 63 DAS in the wheat experiment and 93 DAS in the canola experiment (left). In 2023, samples were also taken on the 27th of July corresponding to 90 DAS in the wheat and canola field experiments (right).**

In general, concentrations of N and P in aboveground biomass for canola and wheat increased with the addition of fertiliser P (Table 7). Concentrations of P across all treatments were very low in 2023. Concentrations of P in aboveground biomass of wheat and canola were generally similar between the CM and MAP fertilisers.

**Table 7. The phosphorus (P) concentration (% P in aboveground biomass) of wheat and canola. In 2022, wheat was harvested at 63 DAS and canola was harvested at 93 DAS. In**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**2023, wheat and canola were harvested at 90 DAS. Values in parentheses are standard errors.**

| Crop | Fertiliser Rate (kg P/ha) | 2022 | | 2023 | |
|---|---|---|---|---|---|
| | | CM | MAP | CM | MAP |
| Wheat | 0 | 0.32 (0.02) | 0.28 (0.01) | 0.09 (0.00) | 0.08 (0.00) |
| | 30 | 0.39 (0.02) | 0.35 (0.01) | 0.10 (0.01) | 0.09 (0.00) |
| | 90 | 0.42 (0.03) | 0.49 (0.02) | 0.10 (0.01) | 0.10 (0.01) |
| Canola | 0 | 0.31 (0.04) | 0.27 (0.01) | 0.07 (0.00) | 0.06 (0.01) |
| | 30 | 0.39 (0.02) | 0.40 (0.01) | 0.08 (0.01) | 0.06 (0.00) |
| | 90 | 0.49 (0.02) | 0.52 (0.02) | 0.11 (0.00) | 0.12 (0.02) |

In 2022, crop P uptake in aboveground biomass at 93 DAS ranged from 5 – 21 kg P/ha for canola, whereas for wheat at 63 DAS this ranged from 0.5 – 1.7 kg P/ha (Figure 8). In 2023, crop P uptake in aboveground biomass at 90 DAS ranged from 2 – 11 kg P/ha for canola, whereas for wheat at 90 DAS this ranged 4 – 9 kg P/ha. In general, crop P uptake in aboveground biomass was similar between the CM and MAP treatments at all rates. However, there was a significant increase in canola P uptake in 2023 for CM compared to MAP.

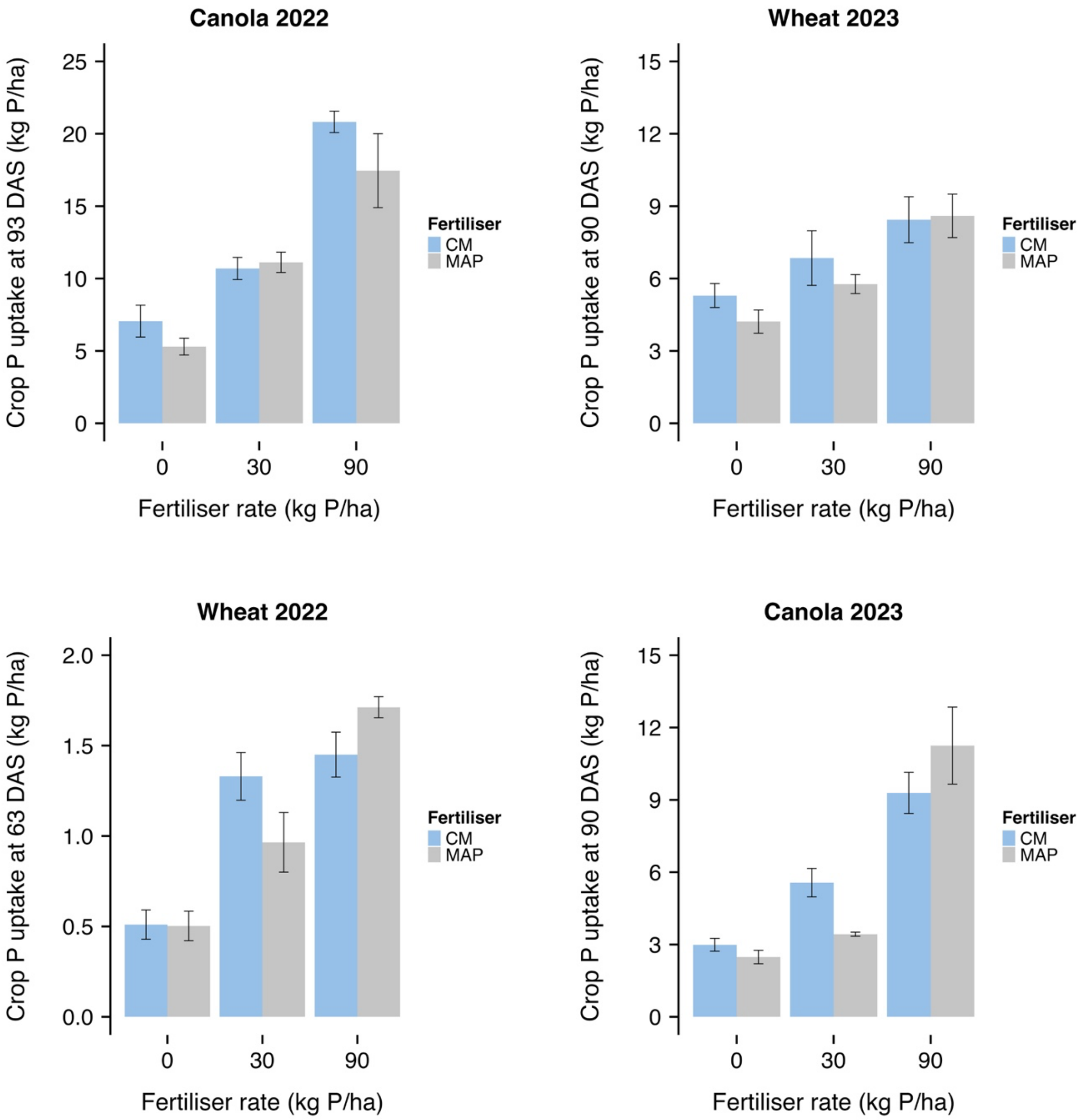


**Figure 8. Measures of crop P uptake for the canola (2022)/wheat (2023) field experiment (top), and the wheat (2022)/canola (2023) field experiment (bottom). In 2022, samples were taken on the 27th of July corresponding to 63 DAS in the wheat experiment and 93 DAS in the canola experiment (left). In 2023, samples were also taken on the 27th of July corresponding to 90 DAS in the wheat and canola field experiments (right).**

*Grain/Seed*

Overall, grain/seed yield increased with the addition of fertiliser P (Figure 9). In 2022, canola seed yield was relatively high ranging from 2.7 – 4.0 t/ha and wheat grain yield was very high ranging from 6.7 – 8.0 t/ha. However, there was no significant difference in crop grain/seed P offtake between the CM and MAP treatments. In 2023, canola yield ranged from 0.9 – 1.8 t/ha, which was on average 61 % lower than that in 2022. Similarly, wheat yield ranged from 2.2 – 3.0 t/ha and was on average 64 % lower than that in 2022.

Overall, canola seed yield increased with the addition of fertiliser P in 2023 (Figure 9). On average, there was an additional 0.8 t/ha of canola seed yield at the highest rates of fertiliser P compared to the non-fertilised treatment. However, canola seed yield was not significantly different between the CM and MAP treatments. Canola was strongly responsive to the addition of fertiliser P in 2023. Although, the response of canola to the addition of fertiliser P in 2023 was on average ~ 36 % less than that in 2022.

Overall, wheat grain yield increased with the addition of fertiliser P in 2023 (Figure 9). On average, there was an additional 0.6 t/ha of wheat grain yield at the highest rates of fertiliser P compared to the non-fertilised treatment. Similarly, wheat grain yield was not significantly different between the CM and MAP treatments. There was a relatively small wheat response to the addition of fertiliser P in 2023, which was on average ~ 46 % less than that in 2022.

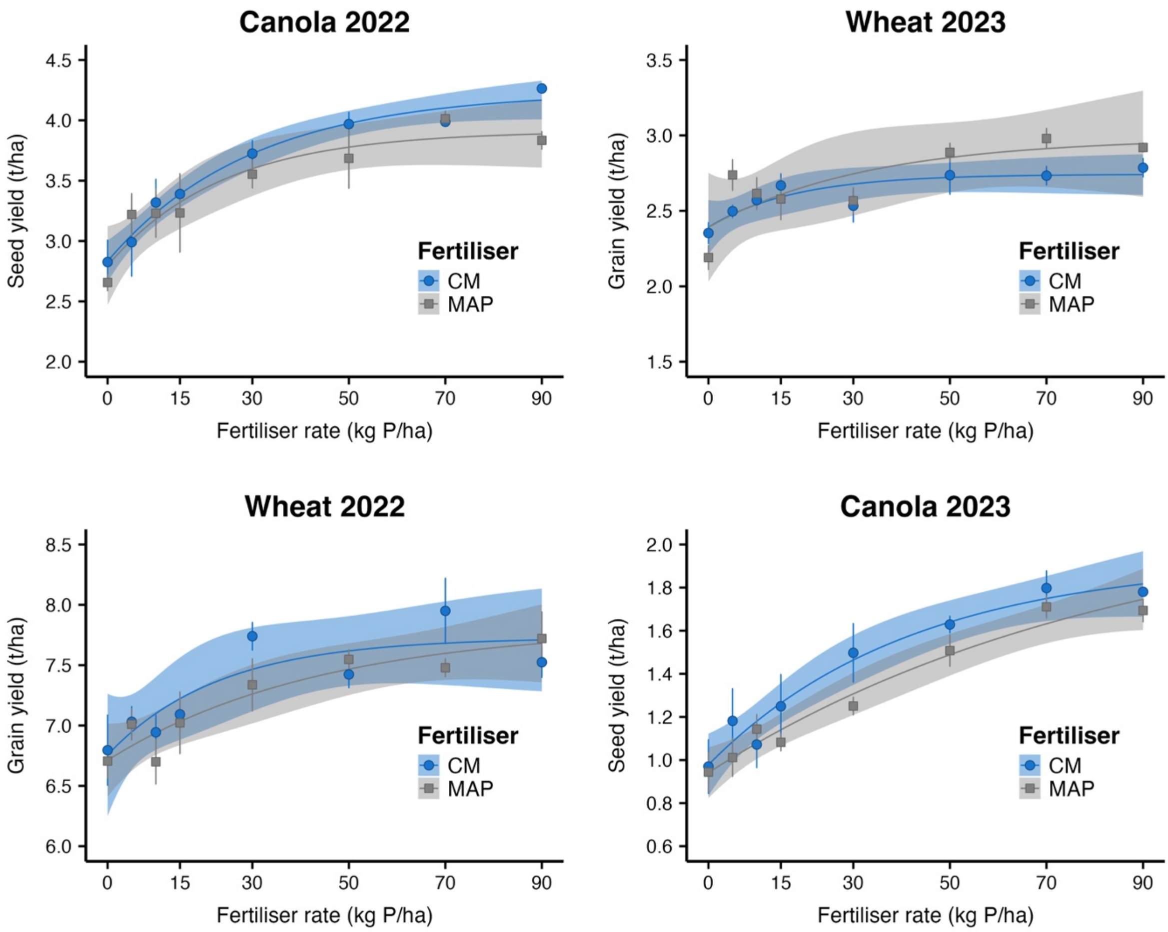


**Figure 9. Canola seed (2022) and wheat grain (2023) yield data for the first field experiment (top), and wheat grain (2022) and canola seed (2023) yield data for the second field experiment (bottom). Fertiliser treatments include type (MAP vs CM) and rate (0, 5, 10, 15, 30, 50, 70, and 90 kg P/ha), which was applied in 2022. A randomised complete block design with four replicates was established. A Mitscherlich model has been fitted to the data.**

Concentrations of P in canola seed/wheat grain increased with the addition of fertiliser (Table 8). In 2022, concentrations of P in canola seed increased at a greater rate with fertiliser input compared to that in wheat grains. In contrast, in 2023, concentrations of P in wheat grain increased at a greater rate with fertiliser input compared to that in canola seeds.

**Table 8. The phosphorus (P) concentration (% P in grain/seed) of wheat and canola. Values in parentheses are standard errors.**

| Crop | Fertiliser Rate (kg P/ha) | 2022 | | 2023 | |
|---|---|---|---|---|---|
| | | CM | MAP | CM | MAP |
| Wheat | 0 | 0.28 (0.00) | 0.27 (0.01) | 0.33 (0.03) | 0.32 (0.01) |
| | 5 | 0.28 (0.01) | 0.29 (0.01) | 0.34 (0.03) | 0.33 (0.02) |
| | 10 | 0.27 (0.01) | 0.28 (0.01) | 0.36 (0.03) | 0.36 (0.01) |
| | 15 | 0.28 (0.01) | 0.29 (0.01) | 0.33 (0.00) | 0.36 (0.04) |
| | 30 | 0.30 (0.01) | 0.29 (0.00) | 0.41 (0.03) | 0.39 (0.02) |
| | 50 | 0.30 (0.01) | 0.32 (0.00) | 0.44 (0.02) | 0.48 (0.01) |
| | 70 | 0.30 (0.01) | 0.32 (0.01) | 0.52 (0.01) | 0.47 (0.02) |
| | 90 | 0.33 (0.01) | 0.32 (0.01) | 0.62 (0.02) | 0.53 (0.01) |
| Canola | 0 | 0.33 (0.03) | 0.32 (0.01) | 0.28 (0.01) | 0.27 (0.01) |
| | 5 | 0.34 (0.03) | 0.33 (0.02) | 0.30 (0.02) | 0.28 (0.02) |
| | 10 | 0.36 (0.03) | 0.36 (0.01) | 0.29 (0.02) | 0.28 (0.01) |
| | 15 | 0.33 (0.00) | 0.36 (0.04) | 0.29 (0.01) | 0.28 (0.01) |
| | 30 | 0.41 (0.03) | 0.39 (0.02) | 0.34 (0.01) | 0.29 (0.01) |
| | 50 | 0.44 (0.02) | 0.47 (0.01) | 0.36 (0.02) | 0.31 (0.01) |
| | 70 | 0.52 (0.01) | 0.47 (0.02) | 0.41 (0.02) | 0.37 (0.01) |
| | 90 | 0.62 (0.02) | 0.53 (0.01) | 0.40 (0.00) | 0.40 (0.02) |

Canola seed P offtake increased from about 9 kg P/ha to 22 kg P/ha with increasing addition of fertiliser P, whereas wheat grain P offtake increased from about 19 kg P/ha to 25 kg P/ha (Figure 10). Therefore, strong crop responses to the addition of fertiliser P were observed at this site. However, differences in crop seed/grain P offtake was not significantly different between the CM and MAP treatments. The exception was at the 30 kg P/ha rate for canola in 2023, where CM was greater than MAP.

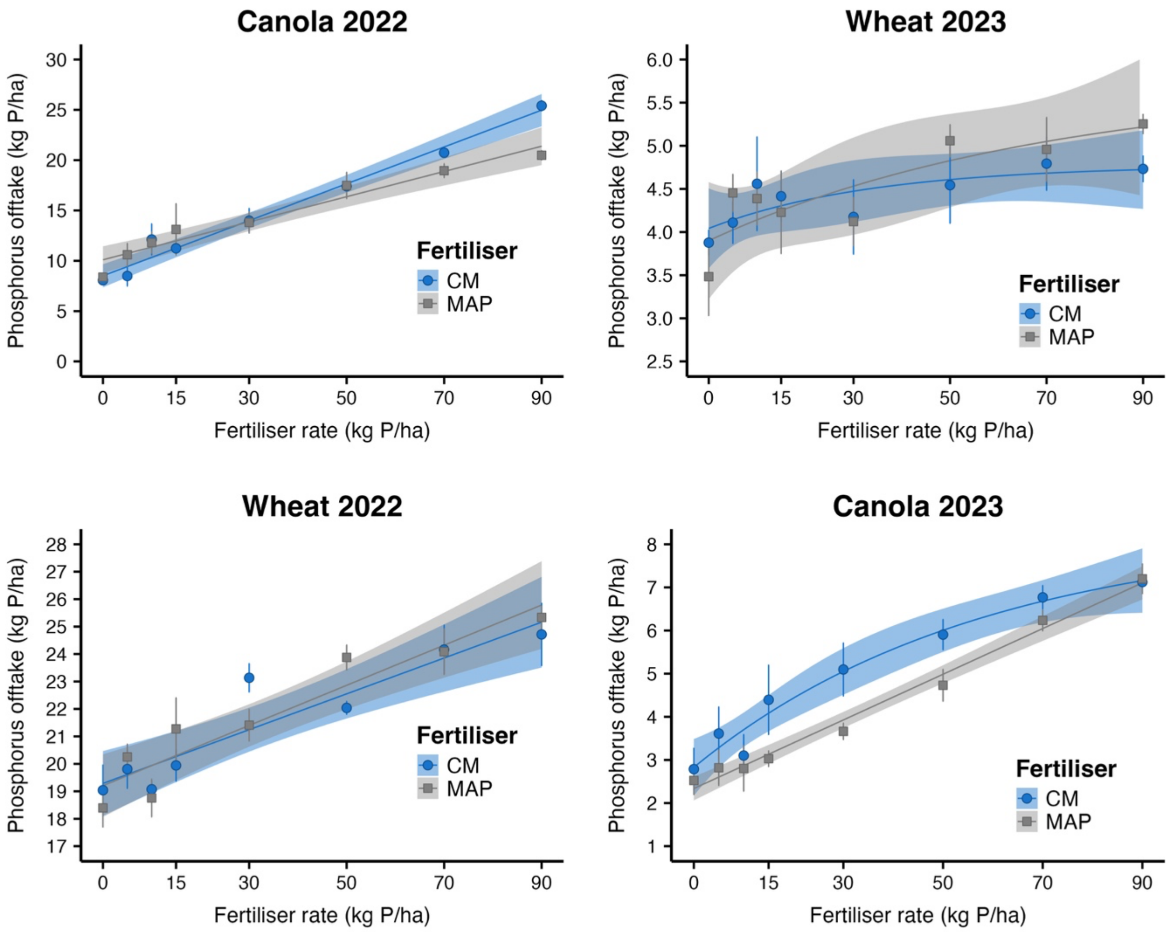


**Figure 10. Canola seed (2022) and wheat grain (2023) P offtake for the first field experiment (top), and wheat grain (2022) and canola seed (2023) yield data for the second field experiment (bottom). Fertiliser treatments include type (MAP vs CM) and rate (0, 5, 10, 15, 30, 50, 70, and 90 kg P/ha), which was applied in 2022. A randomised complete block design with four replicates was established. A Mitscherlich model has been fitted to the data.**

Figure 1 shows the cumulative crop P offtake for the canola (2022)/wheat (2023) field experiment, and the wheat (2022)/canola (2023) field experiment. Cumulative crop P offtake ranged from about 12 to 30 kg P/ha over two growing seasons. There was no significant difference in cumulative crop P offtake between the CM and MAP treatments.

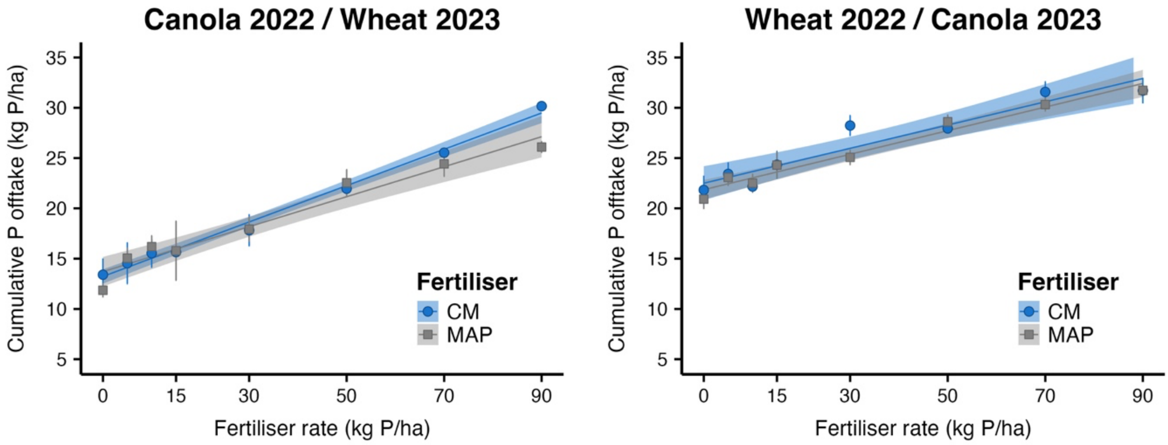


**Figure 11. The cumulative P offtake for the canola (2022)/wheat (2023) field experiment, and the wheat (2022)/canola (2023) field experiment. Fertiliser treatments include type (MAP vs CM) and rate (0, 5, 10, 15, 30, 50, 70, and 90 kg P/ha), which was applied in 2022. A randomised complete block design with four replicates was established. A linear model has been fitted to the data as the best fit.**

**Part Three – Fate of CM and MAP in Soil**

In general, concentrations of plant-available P (Colwell-P) in the 0–10 cm soil layer increased with the addition of fertiliser P for both the CM and MAP treatments, which ranged from 25 to 60 mg P/kg in 2022 (Figure 12). Concentrations of Colwell-P were typically higher in the MAP treatments compared to the chicken manure treatments at the highest fertiliser rates. Furthermore, concentrations of Colwell-P in the 0 – 10 cm soil layer generally decreased over time in fertilised soil (i.e., for both CM and MAP), which ranged from 20 to 40 mg P/kg in 2024.

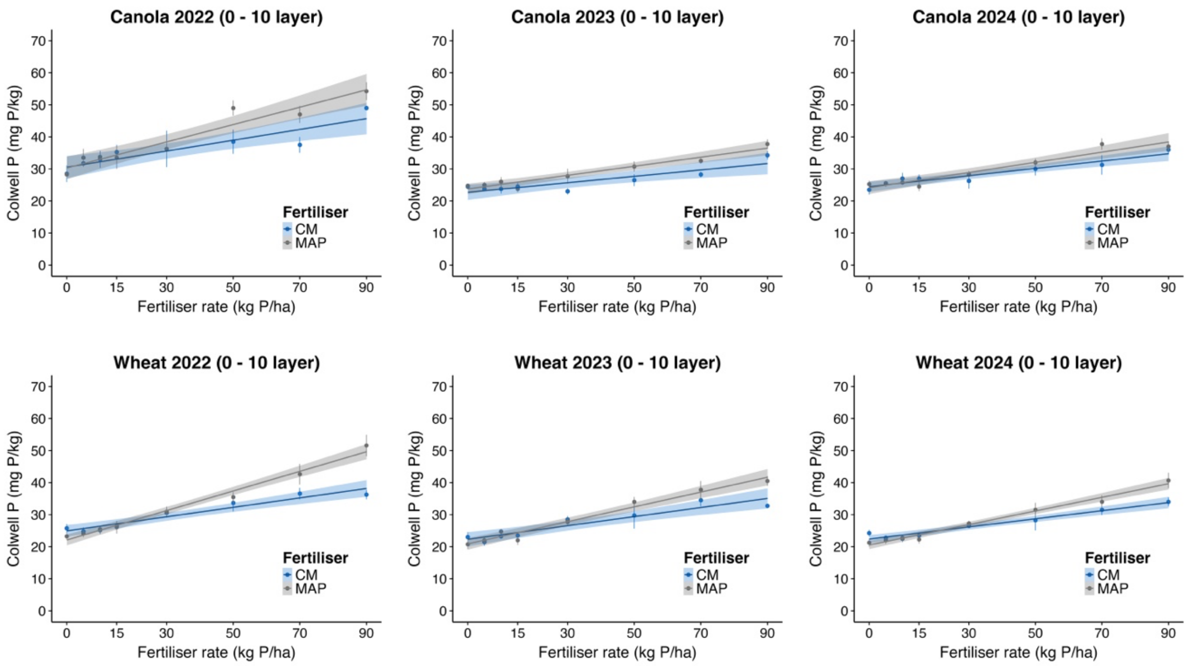


**Figure 12. Measures of "plant-available" P as determined by the Colwell method after each growing season for the canola (2022)/wheat (2023)/canola (2024) field experiment (top) and the wheat (2022)/canola (2023)/wheat (2024) field experiment (bottom) in the 0 – 10 cm soil layer.**

In general, concentrations of extractable inorganic P in the 0 – 10 cm soil layer increased with the addition of fertiliser P for both the CM and MAP treatments ranging from about 75 to 145 mg P/kg in 2022 (Figure 13). There was no difference in the concentration of extractable inorganic P between the chicken manure and MAP treatments across all growing seasons. Furthermore, concentrations of extractable organic P in the 0 – 10 cm soil layer remained unchanged with the addition of fertiliser P, but did tend to decrease overall by about 15 mg P/kg after each growing season.

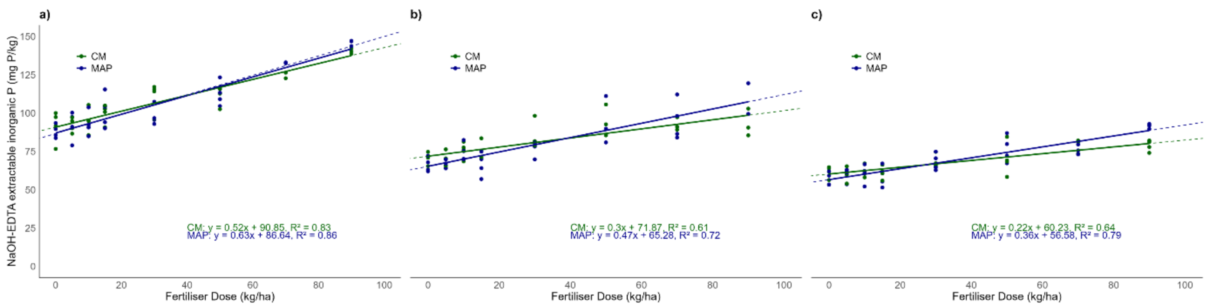


**Figure 13. Measures of soil inorganic P as determined by the alkali (NaOH-EDTA) extraction technique after each growing season for the canola (2022)/wheat (2023)/canola (2024) field experiment (top) and the wheat (2022)/canola (2023)/wheat (2024) field experiment (bottom) in the 0 – 10 cm soil layer.**

Samples from the 10 – 30 cm soil layer were obtained from the 0, 30, and 90 kg P/ha rates for the MAP and CM treatments (three of the four replicates). In general, measures of extractable mineral N ($NH_4^+$ and $NO_3^-$) and “plant-available” P in the 10 – 30 cm layer were considerably lower compared to that in the 0 – 10 cm layer (Table 9). Measures of Colwell-P in the 10 – 30 cm layer are similar between the CM and MAP treatments. Furthermore, measures of Colwell-P in the 10 – 30 cm layer remained largely unchanged between 2022 and 2023.

**Table 9. Pools of extractable mineral N ($NH_4^+$ and $NO_3^-$) and “plant-available” P in the 10 – 30 cm layer of select plots at 27 days after sowing (or 414 days after the initial application) for the 2023 winter growing season. Treatments sampled include fertiliser type (MAP vs CM) and rate (0, 30, and 90 kg P/ha) with three of the four replicates.**

| Crop | Fertiliser rate (kg P/ha) | MAP | | CM | |
|---|---|---|---|---|---|
| | | Mineral N (mg/kg) | Colwell P (mg/kg) | Mineral N (mg/kg) | Colwell P (mg/kg) |
| Wheat (2022) / Canola (2023) | 0 | 19 | 6 | 22 | 5 |
| | 30 | 23 | 7 | 19 | 7 |
| | 90 | 24 | 13 | 22 | 8 |
| Canola (2022) / Wheat (2023) | 0 | 26 | 7 | 27 | 7 |
| | 30 | 24 | 7 | 25 | 5 |
| | 90 | 23 | 10 | 26 | 8 |

**Part Four – Crop Responses to $^{33}$P-labelled MAP**

In general, crop responses to the addition of ‘fresh’ MAP in 2024 were largely consistent among treatments that had received fertiliser P as either chicken manure or MAP in 2022 (Table 2). However, crop responses tended to be higher in the 90 kg P/ha fertilised plots compared to the non-fertilised plots. Overall, crop responses were more variable for canola compared to wheat.

The proportion of crop P uptake that was derived from the added fresh $^{33}$P-laballed MAP (Pdff %) tended to be higher in the non-fertilised plots (31 % for wheat and 21 % for canola) compared to the 90 kg P/ha plots (on average 25 % for wheat and 16 % for canola). Therefore, pools of soil P were the most important source of P for crop growth (on average 72 % for wheat and 82 % for canola). Crop recovery of fresh MAP in the year of application was around 32 % for wheat and 40 % for canola and was similar among treatments based on previous additions of fertiliser type and rate.

**Table 10. Crop responses to the addition of 'fresh' $^{33}P$-labelled MAP in 2024. The $^{33}P$-labelled MAP was applied to field plots that had originally received CM or MAP in 2022 at 0, 30, or 90 kg P/ha. Values in parentheses are standard errors. Pdff = proportion of crop P uptake derived from the 'fresh' $^{33}P$-labelled MAP. Pdfs = proportion of crop P uptake derived from the soil. Fertiliser recovery refers to the percentage of applied fertiliser (i.e., 'fresh' $^{33}P$-labelled MAP) that was recovered in the aboveground biomass for canola and wheat in 2024.**

| Crop | Field plot treatment established in 2022 | Rate of 'fresh' $^{33}P$-labelled MAP added in 2024 (kg P ha$^{-1}$) | Dry matter (g microplot$^{-1}$) | Crop P uptake (mg P microplot$^{-1}$) | Pdfs (%) | Pdff (%) | Crop recovery of 'fresh' $^{33}P$-labelled MAP (% applied) |
|---|---|---|---|---|---|---|---|
| Wheat (2024) | Control (0 kg P ha$^{-1}$) | 13 | 67.2 (4.8) | 95.1 (7.4) | 68.7 (1.6) | 31.3 (1.6) | 29.5 (1.3) |
| | MAP (30 kg P ha$^{-1}$) | 13 | 68.4 (3.0) | 105.3 (8.9) | 68.2 (1.5) | 31.8 (1.5) | 33.2 (1.3) |
| | MAP (90 kg P ha$^{-1}$) | 13 | 76.9 (4.3) | 127.7 (6.4) | 73.9 (1.9) | 26.1 (1.9) | 33.4 (2.0) |
| | CM (30 kg P ha$^{-1}$) | 13 | 74.4 (6.5) | 120.0 (7.2) | 73.6 (1.8) | 26.4 (1.8) | 32.0 (2.8) |
| | CM (90 kg P ha$^{-1}$) | 13 | 71.3 (3.8) | 127.6 (11.0) | 75.5 (1.9) | 24.5 (1.9) | 30.6 (0.7) |
| Canola (2024) | Control (0 kg P ha$^{-1}$) | 13 | 140.2 (12.4) | 224.4 (30.7) | 79.3 (2.8) | 20.7 (2.8) | 43.6 (1.5) |
| | MAP (30 kg P ha$^{-1}$) | 13 | 158.6 (20.0) | 273.9 (44.6) | 84.8 (2.4) | 15.2 (2.4) | 38.0 (3.0) |
| | MAP (90 kg P ha$^{-1}$) | 13 | 145.2 (24.6) | 302.7 (55.3) | 84.7 (2.7) | 15.3 (2.7) | 41.0 (1.5) |
| | CM (30 kg P ha$^{-1}$) | 13 | 113.9 (13.8) | 182.9 (25.2) | 78.1 (3.0) | 21.9 (3.0) | 37.1 (2.0) |
| | CM (90 kg P ha$^{-1}$) | 13 | 133.6 (11.9) | 261.5 (39.8) | 82.7 (2.4) | 17.3 (2.4) | 42.6 (3.0) |

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# DISCUSSION OF RESULTS

### Part One – Phosphorus in Fertilisers

Concentrations of total P in manure samples were relatively low, but consistent with previous studies. Therefore, higher volumes of manure will need to be applied when targeting particular rates on a kg P/ha basis. The fresh CM also had a high moisture content, and this needs to be taken into account when calculating P requirements. The pH of manures was around slightly acidic to moderately alkaline with low C:N ratios, which suggest the manures will be rapidly decomposed by microbes.

There is limited insight on the chemical composition of manures in Australia. Pools of inorganic P were the predominant form of P in manures. Furthermore, the relatively high concentrations of Ca in manures suggest that the likely forms of inorganic P are those of calcium phosphate minerals. However, soil-based data shows that much of the P in manures is readily labile and dissolves into the soi.

Pools of organic P were relatively low in manures. This is consistent with beef manure in studies outside Australia. However, it would be expected that pools of organic P be higher in the manure of chickens and pigs because these animals do not produce enough phytase to break hydrolyse the phytate in seed. However, the reason for much lower concentrations in the analysed samples is that farms may have added a phytase supplement to their feed to aid phytate hydrolysis. The relatively low concentrations of organic P in the manures suggests that abiotic processes (e.g., adsorption/desorption and precipitation/dissolution) may be more important than biotic processes (e.g., mineralisation/immobilisation) for P in manures. It could also suggest that the P in manures behaves more like the P in mineral-based fertilisers than previously thought.

There was a range of total P values across and within all manures. In addition, the effect of drying/storage/processing also increased the concentration of inorganic P in manures. It is unclear if the drying/storage/processing steps could alter plant-availability. Nevertheless, it is important to understand how much P (and water) is in the manure, and how it has been treated.

### Part Two – Crop Responses to CM and MAP

Crops were responsive to the addition of fertiliser at both field sites. In general, crop growth, grain/seed yield, crop P uptake, and crop P offtake all increased with the addition of fertiliser P (CM and MAP). This is consistent with previous studies on the effect of fertiliser P on crop growth in Australia. However, crop responses to CM were not significantly different to that of MAP. This suggests that crops were accessing a similar pool of soluble P from the CM to that of MAP. It is possible that the very wet growing season in 2022 promoted the dissolution of P in CM.

These findings suggest that a more direct comparison can be made with manures (CM) and MAP in terms of P requirements and price. The P in manure appears to be highly plant-available similar to that of MAP. There also was a lack of evidence supporting improved P availability from manure over time compared to MAP.

### Part Three – Fate of CM and MAP in Soil

Increasing concentrations of plant-available P in the 0 – 10 cm soil layer with the addition of fertiliser P for CM and MAP, support the rapid dissolution of P in CM after addition to soil. It is already known that MAP is highly water soluble. The values of Colwell P decreased after each growing season. This is likely due to some removal of P via seed/grain export, and the onging soil reactions of P adsorption that reduces the plant-availability of added P over time.

Furthermore, the majority of P from the CM and MAP appears to be in the pool of inorganic P in soil. In contrast, pools of organic P remained unchanged and even slightly decreased after each growing season. This is consistent with earlier findings that much of the P in CM was that of inorganic P. Furthermore, the reduction in organic P is likely due to mineralisation processes that can be promoted with soil disturbance after each growing season.

Pools of plant-available P in deeper layers of the soil profile were low and did not change with the addition of fertiliser P. Therefore, the majority of added P is not lost but rather accumulates in the soil layer of placement over the duration of this experiment.

**Part Four – Crop Responses to $^{33}$P-labelled MAP**

Soil was the primary source of P for canola and wheat and residual pools of soil P from CM did not appear to be more plant-available than that of MAP. The proportion of P in canola and wheat derived from the fertiliser (pdff %) was slightly higher in the control compared to the fertilised plots. This is likely due to a greater reliance on the added fertiliser P at low soil P fertility. Furthermore, there was no significant difference pdff % between plots that had received CM or MAP.

Crop recovery of fertiliser P was around 32 % of added P for the wheat and 40 % of added P for the canola. There is limited data assessing the crop recovery of fertiliser P using direct methods (i.e., radioactive isotopes). However, previous studies suggest a value of around 30 % is relatively consistent. It is unclear why canola had higher recoveries of added P, but could be due to better root access or rhizosphere processes that mobilise P. Clearly, further increases in crop recovery of fertiliser P is needed to improve P use efficiency.

**Economics**

An economic analysis was carried out based on information provided from the aforementioned field experiments, in consultation with primary producers, and a chicken manure supplier. Two scenarios were investigated, including one where only P was considered, and the other where P and N was taken into account to balance the N added in the chicken manure. Furthermore, since the application of chicken manure is typically applied at a high rate once every 4 – 5 years, a target rate of 50 kg P/ha was used for calculations. The distance from the source for chicken manure is also an important consideration, and here we assume that a farm was located within 50 km from the source.

A target P input of 50 kg P/ha would require 2.85 t/ha of chicken manure (dry-weight basis). This equates to 5.07 $m^3$/ha of chicken manure (wet-weight basis). The cost of chicken manure (wet-weight basis) supplied and delivered to the farm is estimated at \$27/$m^3$ within a 50 km radius of the of chicken manure. The application of chicken manure to the field is estimated at \$7/$m^3$, which equates to a cost of \$35.52/ha. Therefore, the overall cost is \$172.50/ha or \$3.45/kg P. A target P input of 50 kg P/ha would require 225.86 kg/ha of MAP. The cost of MAP supplied and delivered to the farm is estimated at \$1200/t. The application of MAP to the field as a broadcast is estimated at $10/ha. Therefore, the overall cost is $281.03/ha or $5.62/kg P.

The most economic option of supplying P to the field appears to be chicken manure under the aforementioned conditions. Indeed, the cost of chicken manure (wet-weight basis) supplied and delivered to the farm would need to increase to $\$48.39/m^3$ to be similar to the overall cost of MAP. Alternatively, if the cost of MAP decreased to $719.50/t[1] then the overall cost would approximate that of chicken manure. Furthermore, distances greater than 50 km from the source would also significantly increase the overall cost of chicken manure.

The addition of N in the CM was also taken into consideration. At a target P input of 50 kg P/ha chicken manure and MAP would also provide 157.45 kg N/ha and 23.63 kg N/ha, respectively. Therefore, an additional 133.83 kg N/ha is required to supplement the N in the MAP and balance the N added in the chicken manure. If the additional N was added as urea, then 290.93 kg/ha of urea would be required. The cost of urea supplied and delivered to the farm is estimated at $850/t. The application of urea to the field as a broadcast is estimated at $30/ha (i.e., $10/ha x three passes). Therefore, the overall cost for MAP (and urea) is $558.31/ha or $11.17/kg P.

In 2022, the addition of fertiliser P (and basal nutrients) resulted in about 1.09 t/ha extra wheat grain yield and 1.26 t/ha canola seed yield compared to the non-fertilised control. In 2023, there was about 0.59 t/ha extra wheat grain yield and 0.80 t/ha canola seed yield compared to the non-fertilised control. Therefore, the addition of fertiliser P resulted in an extra 1.68 t/ha of wheat grain yield and 2.06 t/ha of canola seed yield across the two years.

Assuming a price of $350/t for wheat and $550/t for canola, the additional yield alone would result in an increased return of $588/ha and $1133/ha for wheat and canola, respectively. The return on the extra yield alone is considerably more than the overall cost of chicken manure, and still more than the overall cost of MAP (and urea). Further research is needed to better understand crop responses to the residual value of fertiliser P (animal manures and mineral-based fertiliser) over longer timeframes. For the latter, this is being investigated as part of GRDC investment UOQ2303-005RTX.

## CONCLUSION

Mineral-based fertilisers (e.g., MAP) are an important source of P for crop production in Australia. However, prices for mineral-based fertiliser P are forecast to rise and price volatility is expected to increase in the future. Livestock manure is an alternative source of P that has the potential to significantly offset the input of mineral-based fertiliser in some regions. Overall, concentration of total P in livestock manure can vary considerably and is typically much lower than that of mineral-based fertilisers. The majority of P in livestock manure is that of inorganic forms, which appears to be readily soluble.

Crop responses increased with the addition of fertiliser P across multiple years, with little difference between chicken manure and MAP. This suggests that chicken manure can be used to offset P inputs from mineral-based fertilisers with similar results in crop yield, providing that other nutrients are non-limiting. Furthermore, grain growers can more directly compare the cost of using chicken manure to that of MAP on a P-basis. Finally, the residual value of chicken manure appears to be similar to that of MAP, with crop recoveries of 'fresh' additions of MAP being similar in the year of application regardless of fertiliser history at this site.

# IMPLICATIONS

- The elemental concentrations (and water content) of manures varies widely, which has implications for correct P inputs
- Understanding the chemical composition of P in manures helped predict the likely fate of P manures when added to soil and their availability to plants.
- Chicken manure is a P source that leads to improved crop growth.
- Grain growers have more options for reliable sources of P for crop production.
- The addition of manure and mineral-based fertiliser significantly improved crop growth
- Past fertiliser history did not have a strong effect on the crop response to a fresh addition of MAP.
- Much of the P in MAP and CM rapidly entered the soil solution and started to sorb into soil mineral surfaces. Over time, the sorbed P became less plant-available after each growing season.

## RECOMMENDATIONS

Grain growers should investigate what animal manures are potentially accessible in their region and obtain as much information as possible on the material. This includes total concentrations of P and moisture content. Grain growers should consider the P in CM to be similar to that of MAP, which was consistent over multiple growing seasons. However, manure drying/storage/processing may affect these results. Another consideration is the N (and other elements) in the manure.

A more extensive investigation of animal manures (and other sources of P) is needed to better understand the main chemical characteristics of manures that could be related to plant-availability. Furthermore, improved understanding on the manure P-soil interactions would be welcomed to better understand their transformations in soil. There was evidence to suggest that sorption-desorption processes are important in governing the supply of P at this site. This would help identify the main sink pathways of fertiliser P and give insight on how to improve P use efficiency.

It is unclear if the crop recoveries of added P by canola and wheat were low or high, as data is limited. There is much scope to improve the crop recovery of added P in these systems. It is possible that crop recoveries of fertiliser P could be improved based on soil hydrology, fertiliser rate, and fertiliser placement.

# GLOSSARY AND ACRONYMS

Below is a sample abbreviations and acronyms list. Be sure to include all abbreviations and acronyms that appear in the report.

| | |
|---|---|
| CM | chicken manure |
| DAP | diammonium phosphate |
| ICP-OES | inductively coupled plasma-optical emissions spectroscopy |
| MAP | monoammonium phosphate |
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## REFERENCES


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