

BIOECONOMY
SCIENCE
INSTITUTE



Plant & Food[®]
Research
Rangahau Ahumāra Kai



PFR SPTS No. 27786

Tapping into legacy P stocks on highly fertile cropping soils: final science report

Norris M, Cummins M, Wise B, Arnold N

September 2025

Report for:

Horticulture New Zealand Incorporated

DISCLAIMER

The New Zealand Institute for Bioeconomy Science Limited does not give any prediction, warranty or assurance in relation to the accuracy of or fitness for any particular use or application of, any information or scientific or other result contained in this report. Neither the New Zealand Institute for Bioeconomy Science Limited nor any of its employees, students, contractors, subcontractors or agents shall be liable for any cost (including legal costs), claim, liability, loss, damage, injury or the like, which may be suffered or incurred as a direct or indirect result of the reliance by any person on any information contained in this report.

LIMITED PROTECTION

This report may be reproduced in full, but not in part, without the prior written permission of the New Zealand Institute for Bioeconomy Science Limited. To request permission to reproduce the report in part, write to: The Science Publication Office, Plant & Food Research – Postal Address: Private Bag 92169, Victoria Street West, Auckland 1142, New Zealand; Email: SPO-Team@plantandfood.co.nz.

PUBLICATION DATA

Norris M, Cummins M, Wise B, Arnold N. September 2025. Tapping into legacy P stocks on highly fertile cropping soils: final science report. A Bioeconomy Science Institute report prepared for: Horticulture New Zealand Incorporated. Milestone No. 105678. Contract No. 44127. Job code: P/442124/01. PFR SPTS No. 27786.

KEYWORDS: Phosphorus, mixed cropping, vegetable production, Olsen P, P retention

Report prepared by:

Matt Norris
Scientist/Researcher, Land Use Impacts
September 2025

Report approved by:

Penny Tricker
Science Group Leader, Cropping Systems and Environment
September 2025

Contents

Executive summary	1
1 Introduction	1
2 Component 1: Legacy P field trial	2
2.1 Methods	2
2.1.1 Site location	2
2.1.2 Experimental design	2
2.1.3 Crop management and fertiliser treatments	3
2.1.4 Measurements	3
2.1.5 Data analysis	4
2.2 Results	5
2.2.1 General weather conditions	5
2.2.2 Baseline fertility	6
2.2.3 Crop development	7
2.2.1 Biomass production	8
2.2.2 Nutrient concentrations and uptake in biomass	9
2.2.1 Nitrogen mass balances	10
2.3 General discussion and conclusions	11
3 Component 2: Regional STP scoping study	13
3.1 Methods	13
3.1.1 Sampling sites	13
3.1.2 Sampling approach	13
3.1.3 Measurements	13
3.2 Results	17
3.3 General discussion and conclusions	18
4 Evidence-based guidance for optimising P management in high P retention soils	22
5 Summary and next steps	24
6 Acknowledgements	24
7 References	25
Appendix 1. Lettuce production data for Standard and Zero P treatments. Values in parentheses are standard errors of the mean	27
Appendix 2. Lettuce nutrient concentration and update data across Standard and Zero P treatments. Values in parentheses are standard errors	27

Executive summary

Tapping into legacy P stocks on highly fertile cropping soils: final science report

Norris M, Cummins M, Wise B, Arnold N
Plant & Food Research Group, Bioeconomy Science Institute

September 2025

This report presents findings from a short-term study funded by Horticulture New Zealand Incorporated, on opportunities to better utilise soil phosphorus (P) stocks on moderate to high P-retention cropping soils of the northern and eastern Waikato and south Auckland regions. The study evaluated the effects of withholding P fertiliser on winter lettuce grown in a granular soil with elevated Olsen P (Component 1), and mapped the regional distribution of Olsen P concentrations that exceed agronomic optimums in high P-retention cropping blocks (Component 2). The research was driven by dual objectives: economically, to reduce fertiliser costs, and environmentally, to mitigate the risk of water quality degradation from P loss.

Key findings from Component 1: Legacy P field trial

- The field trial, run at Te Ahikawariki: The Vegetable Industry Centre of Excellence (VICE) research farm at Pukekohe, tested the hypothesis that withholding P fertiliser from a granular soil (P retention ~ 58%) with high Olsen P (70–80 mg/L) would not negatively affect winter lettuce crop yields. The results strongly corroborated this hypothesis: Production metrics were comparable or even increased in the Zero P treatment compared to the Standard P treatment, which received P fertiliser. Specifically, total fresh weight yields were significantly higher in the Zero P treatment (32 t FW/ha) compared to the Standard P treatment (25 t FW/ha), and head size diameters were also greater in the Zero P treatment (11.3 cm versus 10.6 cm). Yields in the Zero P treatment were also comparable to what would typically be expected for winter iceberg lettuce sown at 51,000 plants/ha in the Pukekohe area (~30 t FW/ha whole plant yield).
- Plant nutrient uptake data indicated that lower yields in the Standard treatment were likely due to lower soil P supply in this treatment zone, suggesting that fertiliser applied at planting (surface banded) did not affect Olsen P within the rootzone. Across the trial site, optimal Olsen P concentration (0-15 cm) appeared to be around 75 mg/L, beyond which fresh weight yields did not substantially increase. This finding aligns with existing recommendations suggesting that maintenance P is not required for lettuce above 70 mg/L Olsen P.
- Overall nitrogen (N) use efficiency was low with crop N uptake estimated at 21% of N applied in fertiliser. In the Standard treatment, P export in product was estimated at 8% of fertiliser applied highlighting the basic mechanism behind soil P enrichment which occurs when P inputs in fertiliser exceed P export in product.

Key findings from Component 2: Regional Soil Test P (STP) scoping study

A regional scoping study of 30 cropping sites across the northern and eastern Waikato and south Auckland regions revealed widespread P saturation:

- Many sites had Olsen P concentrations exceeding agronomic optimums. The median Olsen P across all sites was 81 mg/L, with concentrations in the granular soils (median 112 mg/L, n = 17) about double those of the allophanic soils (62–66 mg/L; n = 13).
- Olsen P concentrations were above optimal ranges (35–70 mg/L) at 60% of sites while 37% of sites had excessively high Olsen P (> 100 mg/L).
- Strong correlations were observed between water-extractable P (WEP) and Olsen P ($y = 0.0022x - 0.025$; $r = 0.90$) and between WEP and P saturation (Olsen P/P Retention; $y = 0.1x + 0.02$; $r = 0.94$). Water-extractable P is a good surrogate measure for dissolved reactive P in surface runoff, and hence these relationships are useful for assessing environmental risk associated with topsoil P loading.
- Importantly, an Olsen P 'change point' between 40–50 mg/L (and 0.40 for Olsen P/P Retention) was identified, above which WEP rapidly increased. This suggests that above an Olsen P of about 50 mg/L (and P saturation of about 0.45), P sorption sites are largely saturated, making P more susceptible to loss.
- Using the WEP relationships derived in this study, we estimate that reducing Olsen P from 100 mg/L to 50 mg/L (i.e. midpoint target range for vegetable crops) in moderate to high P-retention soils (> 50%) could reduce DRP (dissolved reactive P) concentrations in overland flow by up to 55%.

Recommendations:

- An Olsen P of around 50 mg/L appears to be suitable for maintaining soil P supply for most vegetable crops (based on current evidence-based recommendations), and up to 75 mg/L for high demanding crops. This represents a good balance between maintaining soil P supply and minimising environmental risks associated with P loss in surface runoff from moderate to high P-retention cropping soils. There is no reasonable basis for applying additional P when Olsen P > 75 mg/L, even on high P retention soils.
- For crops with higher P demand or higher Olsen P thresholds (e.g. lettuce), management strategies should be employed to improve P uptake efficiency; for example, banding starter fertiliser close to the plant root zone. Broadcasting or banding of P fertiliser on the surface should be avoided as this has a very limited effect on available P for the immediate crop, and also carries a considerable risk of loss through runoff events.
- For sites with high Olsen P > 80 mg/L, focused attention should be given to reducing soil P reserves to within target agronomic ranges. Continued P application to high Olsen P soils is likely a waste of economic resource and an unacceptable environmental risk.

To support long-term improvements in phosphorus management for vegetable and mixed crop production, we recommend initiating a research programme with the following objectives:

1. Quantify the impact of phosphorus drawdown on crop yield, specifically, to determine the threshold below which yield penalties occur, and how this varies across different vegetable crops. It should be noted that yield - Olsen P response curves are already established for many crops, and the conventional approach has been to apply fertiliser to reach these target soil test values. A key project objective, therefore, would be to demonstrate to growers that *reducing* soil phosphorus levels to the established targets does not compromise yield.
2. Reassess agronomic phosphorus optimums for vegetable crops grown in high phosphorus-retention soils, and evaluate how these optimums align with environmental risk thresholds.
3. Evaluate and refine management practices to enhance phosphorus use efficiency in intensive cropping systems. Potential strategies include targeted fertiliser placement, cover cropping, soil health improvements, and the use of phosphorus-solubilising amendments to mobilise recalcitrant phosphorus reserves.
4. Investigate whether starter P fertiliser is required for vegetable production in cold soil conditions, even if soil test P values are adequate.

Findings would be used to inform best management practices for phosphorus use, aiming to enhance the long-term sustainability of vegetable production in Aotearoa New Zealand. Grower involvement and field days will be important, so that this research leads to knowledge transfer and practice change.

For further information please contact:

Matt Norris
Plant & Food Research Group, Bioeconomy Science Institute Ruakura
Private Bag 3230
Waikato Mail Centre
Hamilton 3240
NEW ZEALAND
Tel: +64 7 959 4430

Email: matt.norris@plantandfood.co.nz

1 Introduction

Phosphorus (P) is a crucial nutrient for crop growth and is applied to agricultural fields through fertilisers to keep soil P levels at optimal concentrations for crop production. In the northern and eastern Waikato and South Auckland regions of New Zealand, many cropping sites have a long history of P application reflecting, in part, high soil fertility requirements to sustain intensive vegetable production. However, for P nutrition, there is also a long-standing belief that soil test P (STP) levels need to be maintained at higher than target recommendations on the high P-retention soils which characterise these regions. For example, target Olsen P ranges for many vegetable crops typically fall within the 40 – 60 mg/L range (Reid & Morton, 2019), however, STP data from regional field trials frequently return values > 100 mg/L. It is true that high P-retention soils require higher P inputs to achieve a target STP level, however, as demonstrated by Reid et al. (2020) and Reid et al. (2024), target STP values to achieve maximum production do not increase with soil P retention.

There are two key issues associated with excessive P applications to cropping soils. Firstly, overapplying P increases fertiliser costs without proportional yield benefits. Geopolitical uncertainty and an overall decline in global P stocks continue to drive up costs, making it crucial to use P fertilisers more efficiently. Secondly, environmental impacts associated with over-application of P are well documented, resulting in water quality degradation as excess P is transferred to receiving water bodies. Research within New Zealand and globally has demonstrated that the risk of P loss in subsurface and overland flow from soils is related directly to STP (i.e. Olsen P concentration), with the risk of losses deemed higher above a critical change point, which is often soil type dependent (Heckrath et al. 1995; McDowell & Sharpley 2001; McDowell et al. 2003). Consequently, there exists a dual incentive to reduce P applications on soils with high STP concentrations. From an economic perspective, drawing down on legacy P reserves means that less P fertiliser needs to be applied (i.e. reduced cost input), while from an environmental perspective, reducing STP levels reduces the risk of diffuse P transfer into receiving waterways.

With a view to improved P management across the granular and allophanic cropping soils of the northern and eastern Waikato and south Auckland regions, Horticulture New Zealand Incorporated funded a short-term study to assess:

1. The effects of withholding P to a winter lettuce crop established on a high STP granular soil
2. The regional extent to which Olsen P concentrations are in excess of agronomic optimums on high P-retention cropping blocks, and the potential for addressing high STP levels through a P drawdown approach.

An aligned objective of the project was to establish a baseline for the development of a longer-term research programme focused on legacy P stocks in highly fertile cropping soils.

This report provides a summary of key findings from each research component, a discussion of evidence-based guidance for optimising P management in high P-retention soils and recommendations on future work in this area.

2 Component 1: Legacy P field trial

2.1 Methods

2.1.1 Site location

The trial site was located at Te Ahikawariki: The Vegetable Industry Centre of Excellence (VICE) research farm at Pukekohe. Soil type is a Puni clay which is a Mottled Orthic Granular Soil with moderate P retention (Manaaki Whenua 2025).

2.1.2 Experimental design

The experimental design consisted of two management zones (Standard and Zero P) separated by a grass buffer strip (Figure 1). Each management zone was 14 beds wide by 30 m long (~0.08 ha). Soil and crop measures were taken from five monitor plots (2 beds x 5 m) located within zone.

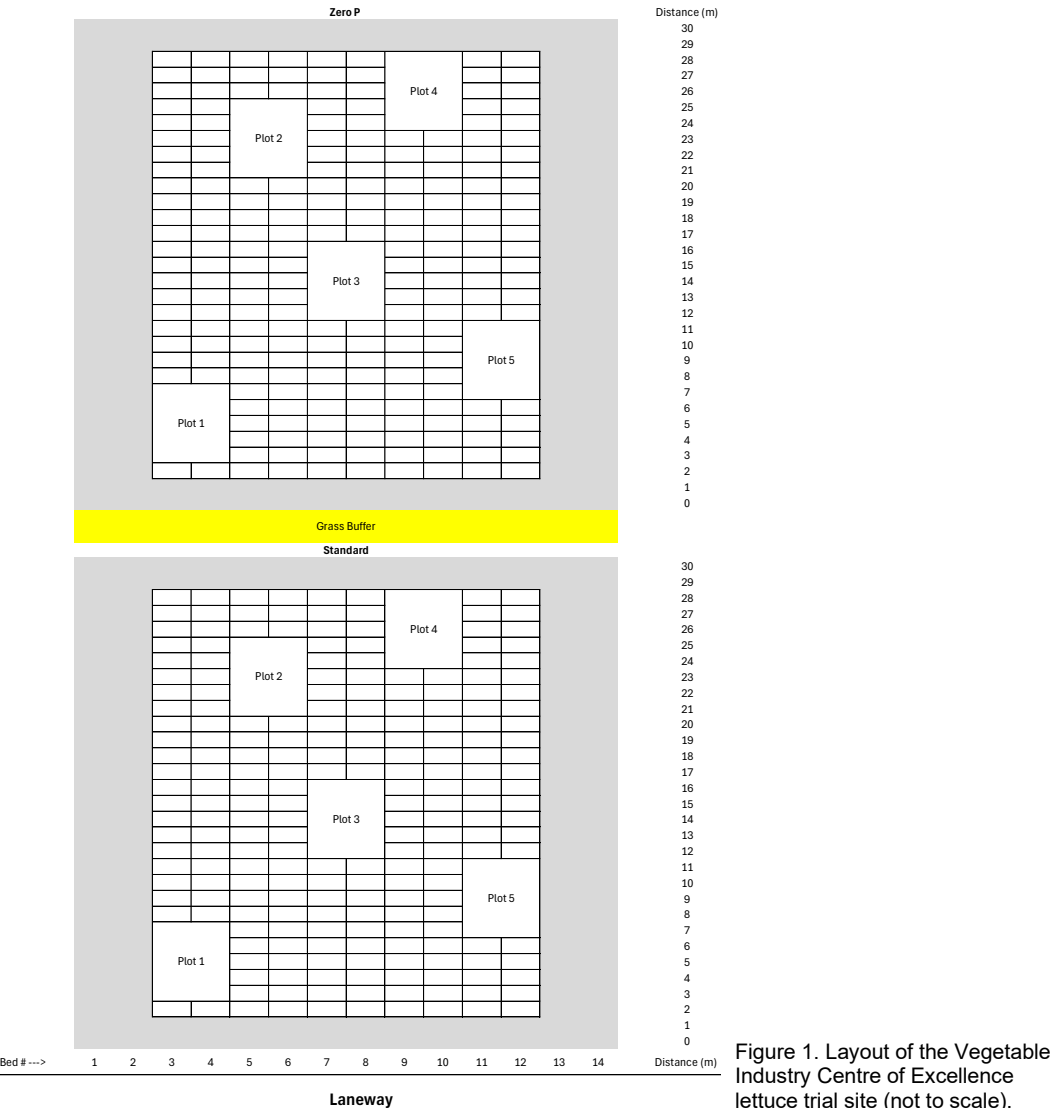


Figure 1. Layout of the Vegetable Industry Centre of Excellence lettuce trial site (not to scale).

2.1.3 Crop management and fertiliser treatments

An iceberg lettuce crop ('Siberinas RZ') was planted on 6 May 2025 at a planting population of ~51,000 plants/ha. The day prior to planting, beds were 'worked' up and fertiliser applied to the bed tops (Table 1). In the Standard zone, base nutrients were applied as YaraMila complex with side dressing N applied as calcium ammonium nitrate. In the Zero P zone nutrients were applied as calcium ammonium nitrate, sulphate of potash and kieserite. No P was applied to this zone. Side dressing N was applied as calcium ammonium nitrate at the same rates as in the Standard zone. Apart from base fertiliser treatments, all other management interventions were consistent across the trial (e.g. sprays) and were managed by VICE according to standard practice. Harvest date was 1 August 2025, 87 days after planting (DAP).

Table 1. Nutrients applied to each treatment at the Te Ahikawariki: Vegetable Industry Centre of Excellence lettuce trial site.

Timing	Nutrient	Standard	Zero P	Variance *
		kg/ha		
Planting (6 May 2025)	N	108 ¹	108 ²	0
	P	45 ¹	0	-45
	K	135 ¹	134 ³	-1
	S	72 ¹	72 ^{3,4}	0
	Mg	14 ¹	20 ⁴	6
	Ca	23 ¹	16 ²	-7
Side dressing (17 June)	N	54 ⁵	54 ⁵	0

¹YaraMila complex. ²Calcium ammonium nitrate (CAN). ³Sulphate of Potash (SOP). ⁴Kieserite. ⁵YaraBela CAN. *Difference in nutrients applied between the Zero P and Standard treatments.

2.1.4 Measurements

Soil fertility

Soil samples for basic fertility, mineral N and potentially mineralisable N (PMN) analysis were collected on 24 April 2025, 11 days before planting. Samples were taken from each monitor plot (Figure 1) and were a composite of six cores for basic fertility and PMN analyses (0-15 cm), and four cores for mineral N analysis (0-15 and 15-30 cm). Basic fertility analyses were conducted at a commercial laboratory and included pH, Olsen phosphorus, P retention, exchangeable calcium, magnesium, potassium and sodium, cation exchange capacity (CEC), base saturation, sulphate-sulphur and organic sulphur. Mineral N and PMN analyses were conducted at New Zealand Institute for Bioeconomy Science (Plant & Food Research group).

At harvest, soil samples were taken for mineral N analysis following the same approach outlined above. At the same time, six sets of bulk density cores (0-15, 15-30 cm) were taken from across the trial area from the mid-point in selected beds.

Crop phenology

To assess transplant shock effects and overall crop development, plant populations were recorded and general observations made on days 1, 6, 9, 13, 16, 20, 34 and 48 days after planting. Canopy cover was recorded using the Canopeo App which is a smart phone enabled tool for recording

fractional green canopy cover (Patrignani & Ochsner 2015). Observations were made from within assigned monitor plots within each management zone.

Biomass sampling

Monitor plots within the trial area were harvested on 30 July 2025, 85 DAP. Plant populations were recorded from a 1 m x 2 bed area (3.7 m²) and head diameters recorded using a pair of callipers. Plots were subsequently harvested at ground level and total fresh weight recorded. A subsample of four whole plants was retained for analysis of dry matter content and concentrations of N, P, K, Ca, Mg, Na, S, B, Mn, Cu and Zn in plant tissue.

Environmental monitoring

Rainfall and air temperature data were obtained from MetWatch station “Pukekohe Res. Stn, Auckland”, located about 200 m from the trial site. Soil moisture and temperature data were recorded using an onsite data logger. Data were recorded hourly using an array of Campbell Scientific CS650 water content reflectometers connected to a CR350 data logger. Probes were installed at 0-15 cm (n=3) and 15-30 cm (n=3) depths within selected beds across both treatments.

2.1.5 Data analysis

Data collation, analysis and graphical presentation were conducted using RStudio Version 12.1 (R Core Team 2021). Treatment effects were assessed using a one-way ANOVA using plot as a blocking factor (see Figure 1). Normality assumptions were verified using Q-Q plots and the Shapiro-Wilk test and the threshold for statistical significance was $p < 0.05$. R's SSlogis function was used to derive a logistic curve for evaluation of the relationship between fresh weight yield and soil P parameters at a plot level.

Nitrogen mass balances for the 0–30 cm depth were calculated for each treatment as the difference between N outputs and N inputs using the following calculation:

$$N \text{ balance (kg N/ha)} = (\text{Mineral N end} + \text{Crop N uptake}) - (\text{Mineral N start} + \text{SONS} + \text{inorganic N applied}) \text{ (Equation 1)}$$

where:

Mineral N Start and *Mineral N End* are the soil mineral N contents at planting and harvest respectively,

calculated as:

$$\text{Mineral (kg N/ha)} = \text{Mineral N (mg/kg)} \times \text{sample depth (cm)} \times \text{soil bulk density (g/cm}^3\text{)} \times 0.1 \times (1\text{-stone content (g/g)}) \text{ (Equation 2)}$$

Crop N uptake is the N uptake in the above-ground biomass component, calculated as:

$$\text{Crop N uptake (kg N/ha)} = \text{Crop yield (t DM/ha)} \times \text{N content in plant tissue (\%w/w)} \times 10 \text{ (Equation 3)}$$

Soil organic N supply (SONS) is the amount of soil organic N mineralised, calculated as:

$$\text{Soil organic N supply (kg N/ha)} = \text{PMN (mg/kg)} \times \text{sample depth (cm)} \times \text{soil bulk density (g/cm}^3\text{)} \times 0.1 \times (1\text{-stone content (g/g)}) / 98 \times n \times \text{Sti} \times \text{Swi} \text{ (Equation 4)}$$

where **PMN** is the potentially mineralisable N test value, **n** is the length of the crop growth period in days and **S_{ti}** and **S_{wi}** are soil temperature and moisture scaling factors calculated from algorithms relating soil temperature and soil water content to N mineralisation, respectively (Qui et al. 2022; Plant & Food Research 2022).

Note mineral N is the pool of N immediately available for crop uptake (present as nitrate and ammonium), while PMN represents the pool of N potentially available for release over the growing season as soil organic matter is mineralised. Input N pools not accounted for include N in rainfall and N from decaying crop residues; while output pools not accounted for include N losses in drainage, gaseous losses (e.g. via denitrification) and N uptake by plant roots. Of these pools, N in rainfall, N from decaying crop residues, gaseous losses and N uptake by plant roots can be assumed to be relatively minor N contributors for the system in question. Consequently, in the N mass balance, positive balances (i.e. Outputs – Inputs) generally indicate additional N supply, probably from mineralisation of organic N, while negative balances indicate a net loss of N from the system, probably through leaching in drainage.

2.2 Results

2.2.1 General weather conditions

Environmental data for the period 8 May – 30 July 2025 are summarised in Figure 2. Overall, conditions were considerably wetter and warmer than the long-term (LT) average (2010 – 2024). Rainfall totalled 628 mm (Figure 2 c), about 70% higher than the LT average for this period (366 mm) while mean air temperature was 12.2°C (LT average = 11.5°C). Soil temperature (0-15 cm) averaged 12.9°C (Figure 2 a). Consistent with frequent rainfall events, soil moisture contents (Figure 2 b) remained elevated for the duration of the monitoring period.

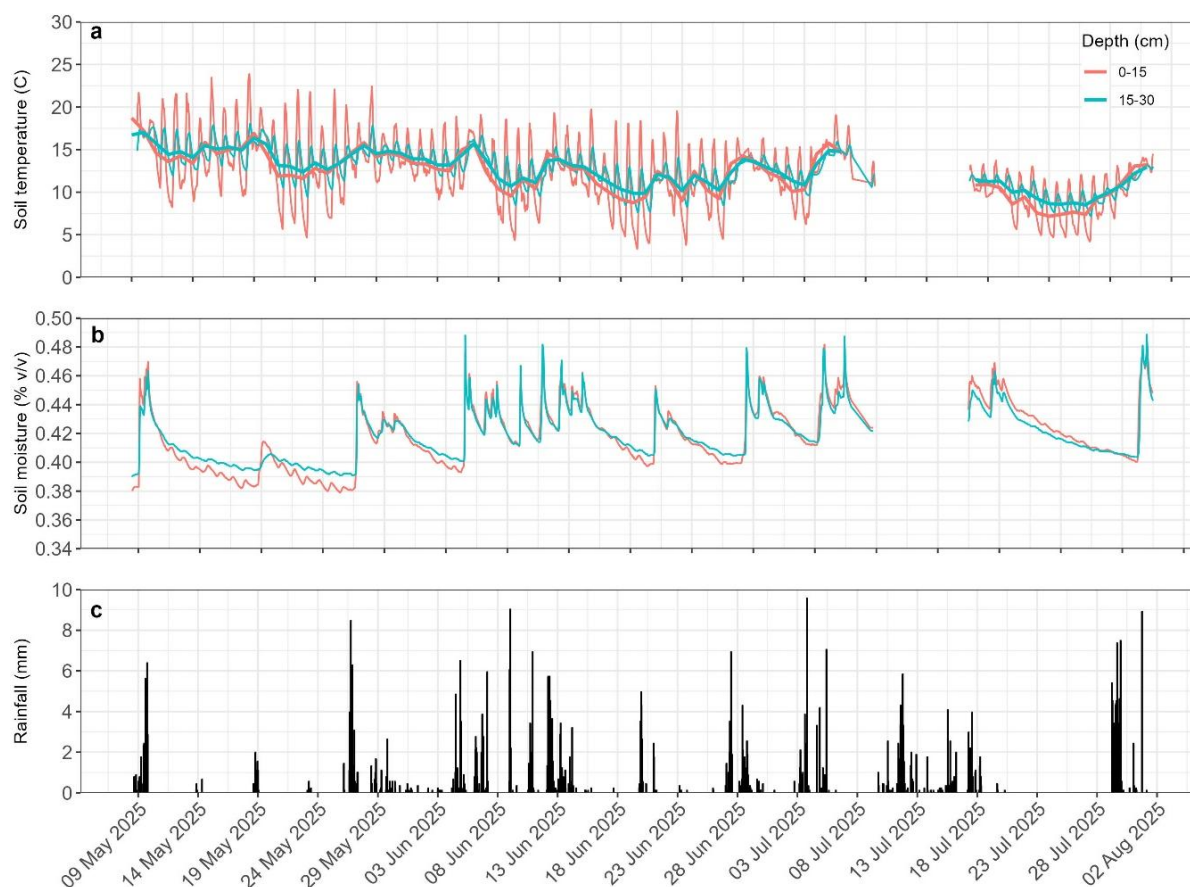


Figure 2. Environmental data (recorded hourly) at the Vegetable Industry Centre of Excellence lettuce trial site for the period (8 May – 24 June 2025) showing (a) soil temperature, (b) soil moisture and (c) rainfall. For (a) soil temperature, mean daily values are included for reference (thick line). Missing soil temperature and moisture data reflect a one-week period where the data logger was offline.

2.2.2 Baseline fertility

Baseline soil fertility data from the trial site are summarised in Table 2. Note mineral N (0-30 cm) and potentially mineralisable N (0-15 cm) data are presented in Table 3 (N balances). Key points are as follows:

- Base fertility measures were all within or above recommended optimum ranges for horticultural production (Hill Labs 2025). Note for P, Reid and Morton (2019) recommend an upper Olsen P and limit of 70 mg/L above which no maintenance P is required.
- Most measures were comparable between treatment zones even where statistically significant ($p < 0.05$) differences were observed (i.e. differences in real terms were small; e.g. CEC, Organic-S). The one exception was for Olsen P (higher in the Zero P treatment by about 17 mg/L) and P retention (lower in the Zero P treatment by about 6%).

Table 2. Summary of baseline soil fertility data (0-15 cm) across Standard and Zero P treatments at the Te Ahikawariki: Vegetable Industry Centre of Excellence (VICE) lettuce trial site, Pukekohe (sampled 24 April 2025, 11 days prior to planting). Values in parentheses are standard deviations (n = 5).

Measure	Depth (cm)	Standard	Zero P	p value ²	Optimum range ³
pH	0-15	6.50 (0.09)	6.52 (0.07)	0.74	5.8-6.5
Olsen P (mg/L)	0-15	68.0 (3.4)	84.6 (7.5)	0.0080 **	30-80
P retention (%)	0-15	59.6 (0.5)	53.4 (2.1)	0.0030 **	
Ca (meq/100g)	0-15	15.2 (1.2)	14.4 (0.5)	0.26	6-12
Mg (meq/100g)	0-15	12.0 (0.7)	11.2 (0.5)	0.12	1-3
K (meq/100g)	0-15	1.61 (0.07)	1.56 (0.03)	0.18	0.5-1
Na (meq/100g)	0-15	1.15 (0.09)	1.33 (0.05)	0.011 *	0.1-0.5
CEC ¹ (meq/100g)	0-15	16.8 (0.8)	16.4 (0.5)	0.0080 **	
Total Base Sat. (%)	0-15	87.7 (0.9)	87.6 (1.1)	0.85	
Sulphate-S (mg/kg)	0-15	17.4 (4.4)	16.2 (7.6)	0.79	10-20
Organic-S (mg/kg)	0-15	7.4 (0.5)	5.8 (0.4)	0.0011 **	12-20

¹Cation exchange capacity. ²P values are given for the comparison of treatment means. Effects are considered significant (*) at $p < 0.05$ and highly significant (**) at $p < 0.01$. ³Optimum ranges are indicative only (source: https://www.hill-labs.co.nz/media/djdbzzhl/3196_technical-note-soil-tests-and-interpretation.pdf).

2.2.3 Crop development

Crop phenology data for the initial growth stage (0 – 48 DAP) are presented in Figure 3. Key points are as follows:

- Plant populations were comparable between treatments for all monitoring dates with minimal dieback observed. Note populations at final harvest were comparable between treatment zones (Appendix 1).
- Similarly, percentage green cover remained comparable between treatments, although there was a slight divergence observed for the final measure (Day48) with slightly more cover observed in the Zero P compared to the Standard treatment (note this difference was not statistically significant).

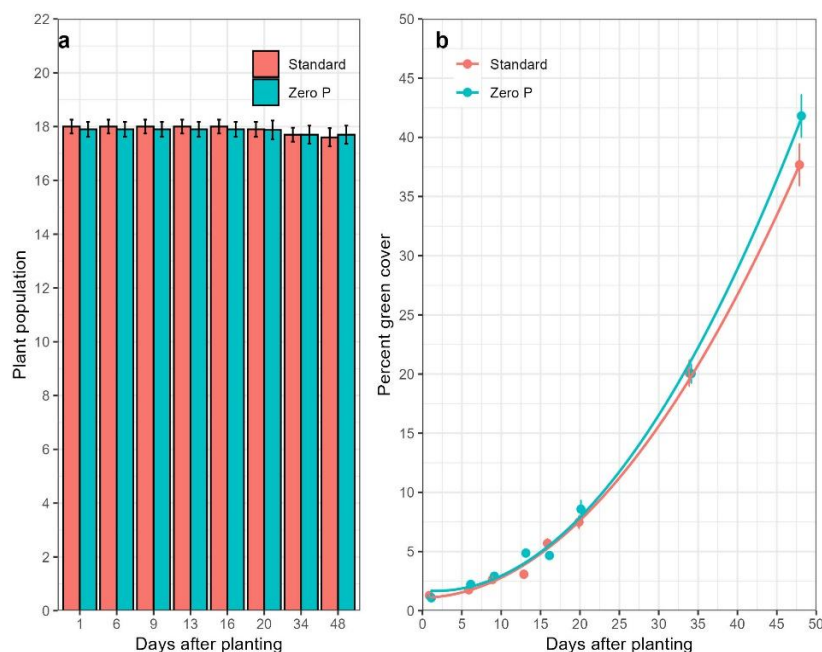


Figure 3. Summary of crop phenology data showing (a) average plant populations and (b) percentage green cover across monitor plots located within Standard and Zero P treatments. Percentage green cover was assessed with the Canopeo App and the fitted line for each treatment is a second order polynomial model ($y = ax^2 + bx + c$; where y = Percent green cover and x = Days after planting). Bars around means are standard errors (n=10).

2.2.1 Biomass production

Biomass production data are summarised in Figure 4 and in Appendix 1. Key points are as follows:

- Total above ground dry matter production was comparable between the Zero P (1.2 t DM/ha) and the Standard P (1.1 t DM/ha) treatments (Figure 4 a).
- There was a significant treatment effect ($p < 0.01$) on total fresh weight yields which were higher in the Zero P (32 t FW/ha) compared to the Standard P (25 t FW/ha) treatment (Figure 4 b).
- There was a significant treatment effect ($p < 0.01$) on head size diameters. On average, these were greater in Zero P (11.3 cm) compared to in the Standard P (10.6 cm) treatment (Figure 4 c).
- General observations through the season and at final harvest suggested that there was more weed pressure in the Standard P compared to Zero P treatment zone (Figure 5). This may have been a contributing factor to lower yields in the Standard P treatment.

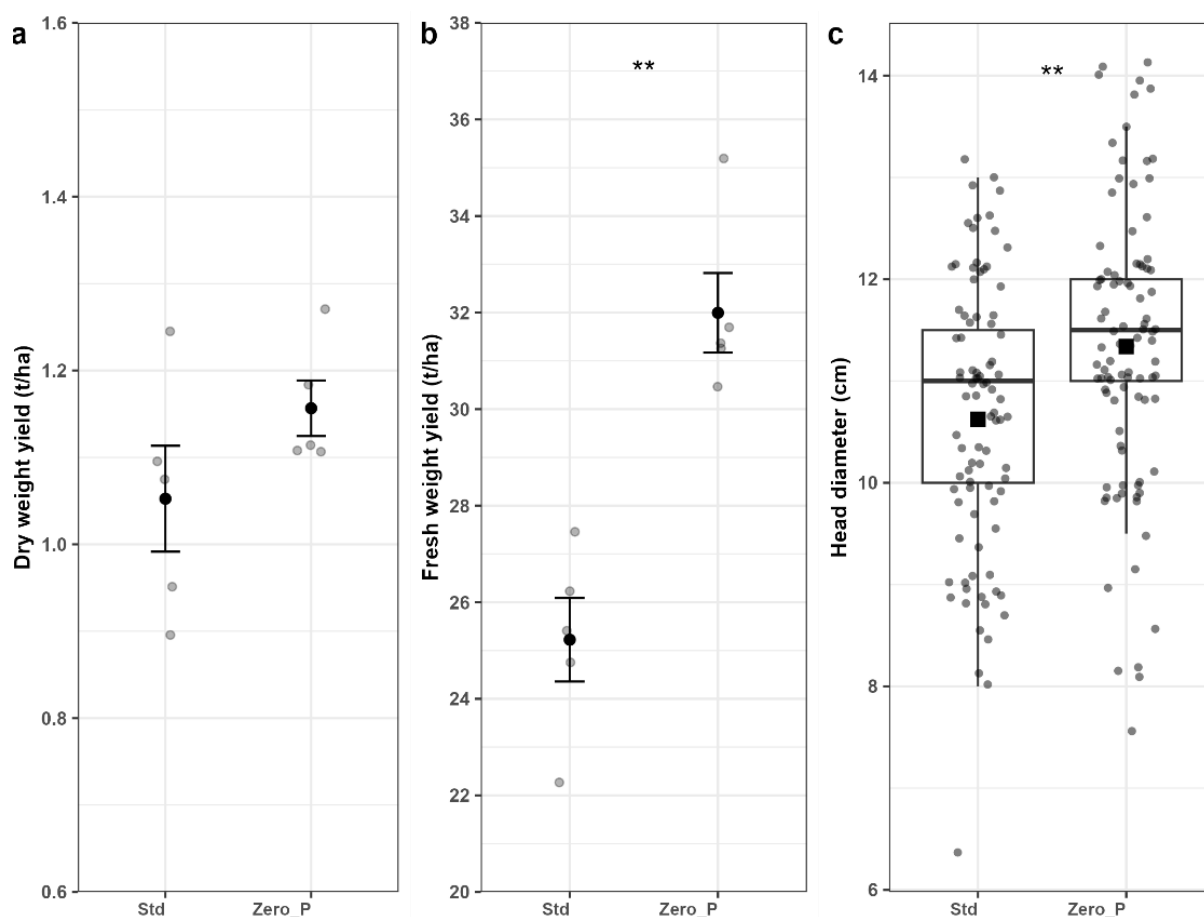


Figure 4. Summary of yield data showing above-ground (a) dry matter production and (b) total fresh weight yields and (c) distribution of head diameter data across Standard and Zero P treatments. For (a) and (b), bars around means are standard errors and for (c) black squares are treatment means. Treatment effects are considered significant (*) at $p < 0.05$ and highly significant (**) at $p < 0.01$.



Figure 5. Pictures of harvest plots across Standard and Zero P treatments showing residual weed biomass which was observed to be greater in the Standard compared to Zero P treatment zones.

2.2.2 Nutrient concentrations and uptake in biomass

Macronutrient concentration and uptake data are summarised in Figure 4 and in Appendix 2. Key points are as follows:

- For macronutrient concentrations in plant tissue, significant treatment effects ($p < 0.01$) were observed for P and K (both higher in the Zero P treatment). Concentrations of N, Ca, Mg and S (Figure 6 a) and trace elements B, Cu, Mn and Zn (Appendix 2) were comparable between treatments.
- Considering above-ground macronutrient uptake, significant treatment effects were observed for P ($p < 0.01$) and K and S ($p < 0.05$) (all higher in the Zero P treatment). For all other macronutrients (Figure 6 b) and trace elements (Appendix 2), uptakes were comparable between treatments.

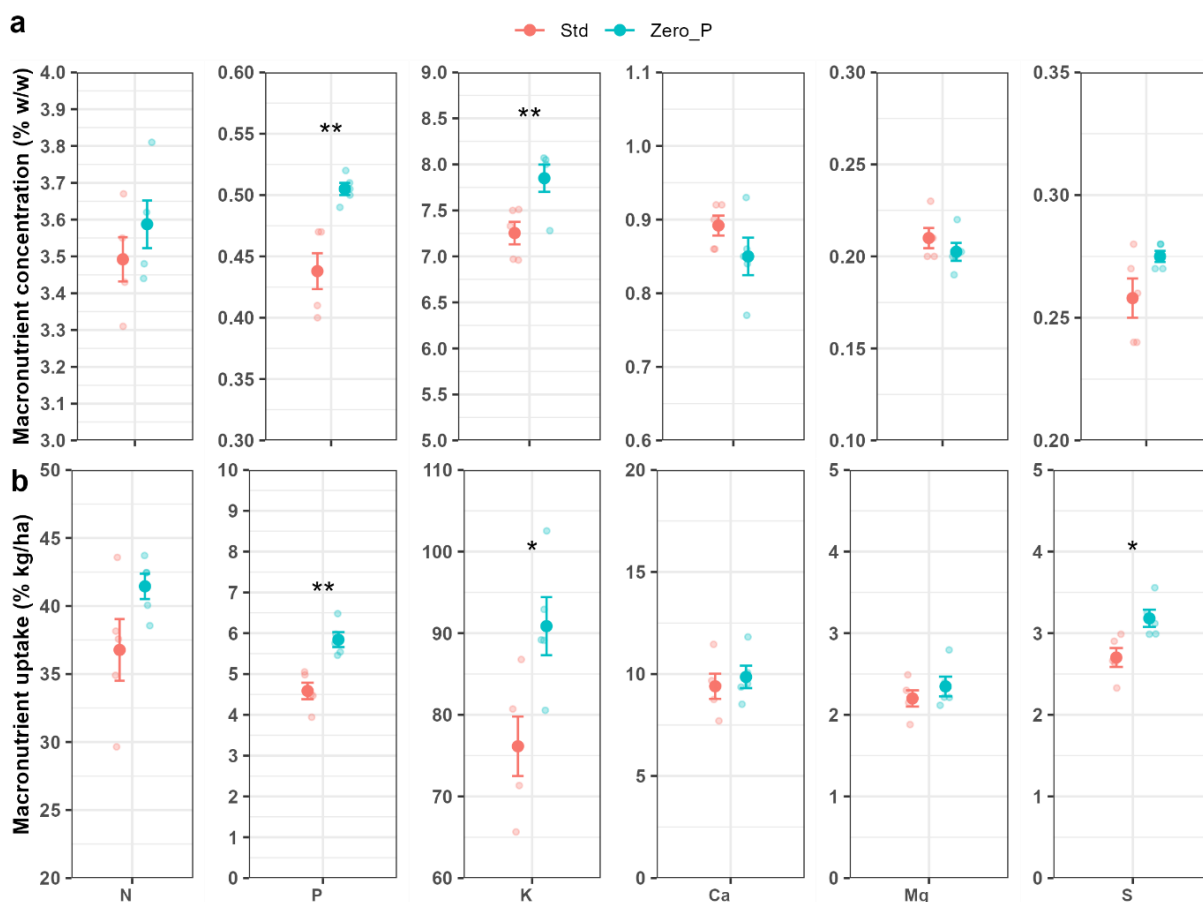


Figure 6. Summary of (a) macronutrient concentrations and (b) uptakes in above-ground biomass across Standard and Zero P treatments at the VICE lettuce trial site. Bars around means are standard errors and small points are individual replicate values ($n = 5$). Treatment effects are considered significant (*) at $p < 0.05$ and highly significant (**) at $p < 0.01$.

2.2.1 Nitrogen mass balances

Nitrogen mass balance data are presented in Table 3. Key points are as follows:

- Soil mineral N at planting averaged 20 kg/ha (0-30 cm) across the trial site, while soil organic N supply (SONS) was estimated at ~15 kg/ha (0-15 cm).
- Despite a near significant treatment effect ($p = 0.054$), N inputs (mineral N start + SONS + fertiliser inputs) were comparable between treatments (219 – 226 kg/ha) (i.e. differences in real terms were small). Applied fertiliser accounted for about 85% of total N inputs across the trial.
- There were no treatment effects on residual mineral N (13 – 16 kg/ha; 0-30 cm), or on above-ground crop N uptake (37 – 40 kg/ha), and total N outputs (mineral N end + crop N uptake) were comparable between treatments (52 – 53 kg/ha).
- There was no treatment effect on the overall N balance (Output – Input) which averaged -167 kg N/ha in Standard treatment and -172 kg N/ha in the Zero P treatment. This is N 'unaccounted' for and likely lost from the root zone (assumed to be 30 cm) predominantly through leaching.
- Overall N use efficiency was low with above-ground crop N uptakes accounting for about 21% of N applied in fertiliser or 17% of total N inputs (mineral N start + SONS + fertiliser inputs).

Table 3. Nitrogen mass balance data for the VICE lettuce trial, May – August 2025.

Treatment	Min N Start (0–30 cm)	SONS 1 (0–15 cm)	Inorganic N applied 2	TOTAL Input 3	Min N End (0–30 cm)	Crop N uptake 4	TOTAL Output 5	N BALANCE 6
	kg N/ha							
Standard	17	14	189	219	16	37	52	-167
Zero P	22	15	189	226	13	40	53	-172
<i>p-value</i> 7	0.10	0.055	-	0.054	0.11	0.22	0.74	0.23

¹ Soil Organic N Supply is an estimate of N supply from mineralisation of soil organic matter. ³ Calculated as the sum of Min N Start, PMN and Inorganic N applied. ⁴ Above-ground N uptake ⁵ Calculated as the sum of Min N End and Crop N uptake. ⁶ Total OUTPUT – Total INPUT. ⁷ Effects are considered significant at $p < 0.05$.

2.3 General discussion and conclusions

The aim of this trial was to test the hypothesis that withholding P fertiliser from a high Olsen P (70 – 80 mg/L), granular soil type would not negatively affect lettuce crop yields. This hypothesis was supported, that is, production metrics including crop development, biomass yields, and nutrient uptakes were comparable, or in some cases increased, in the Zero P treatment compared to the Standard P treatment. Yields in the Zero P treatment (~ 32 t FW/ha whole plant yield) were also comparable to what would typically be expected for winter iceberg lettuce sown at 51,000 plants/ha in the Pukekohe area (30 t FW/ha whole plant yield ≈ 15 t FW/ha head removal; Joseph Balle pers. comm).

Direct comparison between the two treatments was somewhat confounded by differences in starting Olsen P concentrations between the two management zones (Standard = 68 mg/L; Zero P zone = 85 mg/L), and more weed pressure in the Standard treatment. Lower yields in the Standard treatment may have be the result of 1) lower soil P supply, 2) increased competition from weeds or 3) a combination of these factors. Given that starter fertiliser was banded on the surface (Figure 7), it is likely that P applied at planting did not affect Olsen P within the root zone resulting in lower P uptake. The lower P concentrations observed in plant tissue from this zone seem to corroborate this (Figure 6 a).



Figure 7. Picture of the Standard treatment area taken on 7 May 2025 (1 day after planting) showing surface banding of the starter fertiliser.

Using individual plot data, there was also a good correlation between FW yields and starting Olsen P (Figure 8) which suggests reduced P supply as the predominant mechanism for lower yields in the Standard treatment. The optimal Olsen P for this scenario appeared to be around 75 mg/L, that is, FW yields were not substantially increased above this concentration. While this observation should be interpreted with caution due to limited data points ($n = 10$), it is, nevertheless, broadly consistent with recommendations provided by Reid and Morton (2019) who suggest that for lettuce, maintenance P is not required above an Olsen P of 70 mg/L.

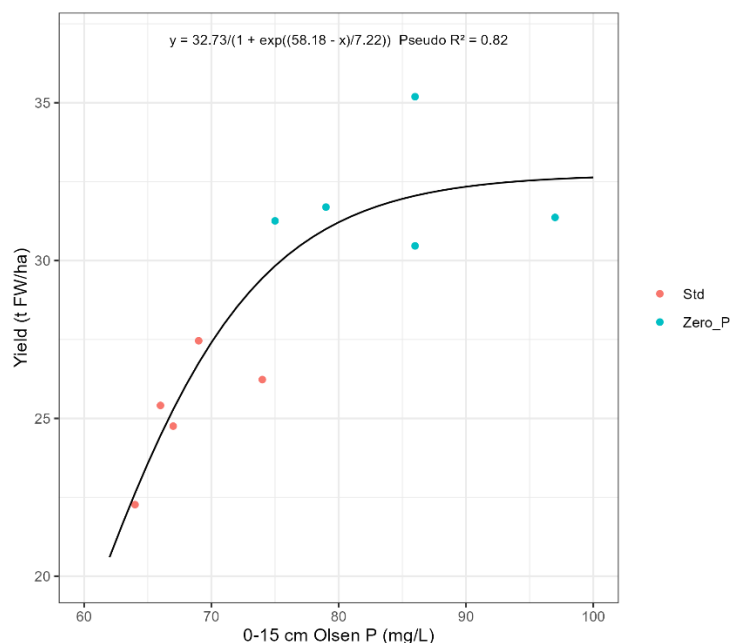


Figure 8. Relationship between lettuce fresh weight yield (t/ha) and 0-15 cm Olsen P (mg/L). A logistic curve has been fitted to the data.

Regarding N balances, withholding P fertiliser had no effect on N use efficiency which was low across the trial. Crop N uptakes averaged 39 kg/ha across the trial accounting for about 21% of N applied in fertiliser or 17% of total N inputs (mineral N start + soil organic N supply + fertiliser inputs). Low N use efficiency was consistent with a very wet growing period (rainfall was 70% above the LT average) and cool temperatures (i.e. winter growing conditions) combined with the shallow root system of the crop in question.

Regarding P balances, above-ground P uptake averaged 5 kg/ha across the trial (note that while there was a significant treatment effect, differences in P uptake between the treatments were small in real terms at ~ 1 kg/ha). Assuming a 70% market cut, P exported from the site would be about 3.5 kg/ha or about 8% of fertiliser applied in the Standard treatment. For comparison, in a summer production scenario with a head removal of 30 t/ha, P export would be about 9 kg/ha (Reid & Morton 2019). Overall, these data highlight the basic mechanism behind soil P enrichment which occurs when P inputs in fertiliser exceed P export in product. Without precise application strategies guided by soil test results, this enrichment can persist, leading to unnecessary application of P fertiliser and heightened environmental risks. This problem appears particularly acute for winter production, where lower product P export coincides with a perception that more P is needed for crop establishment, especially on high P retention soils. However, data from this trial suggest that this is not necessarily the case, provided that Olsen P concentrations are maintained within an optimal range. Furthermore, these trial data highlight the importance of incorporating fertiliser prior to planting. Surface-applied product not only has a limited effect on Olsen P for the immediate crop, but also carries a considerable risk of loss through runoff events.

3 Component 2: Regional STP scoping study

3.1 Methods

3.1.1 Sampling sites

A total of 30 sampling sites were identified across the wider Pukekohe and Pukekawa region ('Northern' sites; Table 4; Figure 9) and around Matamata ('Eastern' sites; Table 4; Figure 10). The sites were located on commercial cropping blocks with a history of long-term mixed cropping or intensive vegetable production (> 5 years). Sites were located on high P-retention soils with dominant soil orders listed as either 'Granular' (n = 17) or 'Allophanic' (n= 13) (Manaaki Whenua 2025).

3.1.2 Sampling approach

Three sampling transects were established at each site, 100 m long and spaced 25 m apart and oriented perpendicular to bed or mound rows where these were in place. Ten samples were taken from each transect (approximately every 10 m) and composited into a bulk sample to give three analysis samples per site. Samples were taken from the 0-15 cm depth using a step on corer from the centre point of beds or mounds, or from the mid row and plant line where established crops were in place. Where crops had been recently established (i.e. < 1 month), samples were taken from within the bed or mound but away from fertiliser bands.

3.1.3 Measurements

Samples were submitted to a commercial soil testing laboratory for analysis of Olsen phosphorus (Olsen P), phosphate retention (P retention) and Water Extractable Phosphate (WEP) according to the following methodologies: Olsen P determined via discrete analysis following extraction of air dry soil in 0.5 M NaHCO₃ (1:20 soil/solution ratio) at pH 8.50 for 30 min (Olsen et al. 1954) and reported as mg/L of soil; P retention determined as the percentage of P retained by an air-dried sample following reaction with a 1000 mg/L phosphate solution (1:5 soil/solution ratio; pH 4.6) for 16 h (Blakemore et al. 1987); WEP determined colorimetrically following extraction in distilled water (1:300 soil/solution ratio) (McDowell & Condron, 2004).

Table 4. Summary of key information for the 30 cropping blocks sampled as part of the regional soil test phosphorus (STP) scoping study.

Site	Region	Dominant soil order	Previous crop	Crop at sampling
1	Northern	Granular	Broccoli	Grass (> 6 months)
2	Northern	Granular	Lettuce	Grass (< 2 months)
3	Northern	Allophanic	Broccoli	Broccoli (recently planted)
4	Northern	Allophanic	Broccoli	Broccoli (recently planted)
5	Northern	Allophanic	Lettuce	Fallow (raised beds)
6	Northern	Granular	Broccoli	Fallow (raised beds)
7	Northern	Granular	Spinach	Grass (< 6 months)
8	Northern	Granular	Grass/clover with lambs	Fallow (raised beds)
9	Northern	Granular	Grass/clover with lambs	Grass (< 6 months)
10	Northern	Granular	Potatoes	Broccolini (harvested)
11	Northern	Granular	Potatoes	Grass (< 6 months)
12	Northern	Granular	Onions	Potatoes (recently planted)
13	Northern	Granular	Onions	Grass (< 6 months)
14	Northern	Granular	Potato	Fallow (potato mounds)
15	Northern	Granular	Brassica	Fallow (raised beds)
16	Northern	Granular	Potato	Fallow (raised beds)
17	Northern	Granular	Onion	Fallow (raised beds)
18	Northern	Granular	Lettuce	Fallow
19	Northern	Granular	Onion	Fallow (potato mounds)
20	Northern	Granular	Carrot	Fallow (raised beds)
21	Eastern	Allophanic	Carrot	Grass
22	Eastern	Allophanic	Maize	Grass
23	Eastern	Allophanic	Onion	Grass
24	Eastern	Allophanic	Maize	Grass
25	Eastern	Allophanic	Potato	Fallow
26	Eastern	Allophanic	Maize	Fallow
27	Eastern	Allophanic	Maize	Onion (recently planted)
28	Eastern	Allophanic	Maize	Fallow
29	Eastern	Allophanic	Maize	Fallow
30	Eastern	Allophanic	Onion	Clover



Figure 9. Location of sites (white circles) within the 'Northern' sampling region (n = 20). Image sourced from Google Earth.

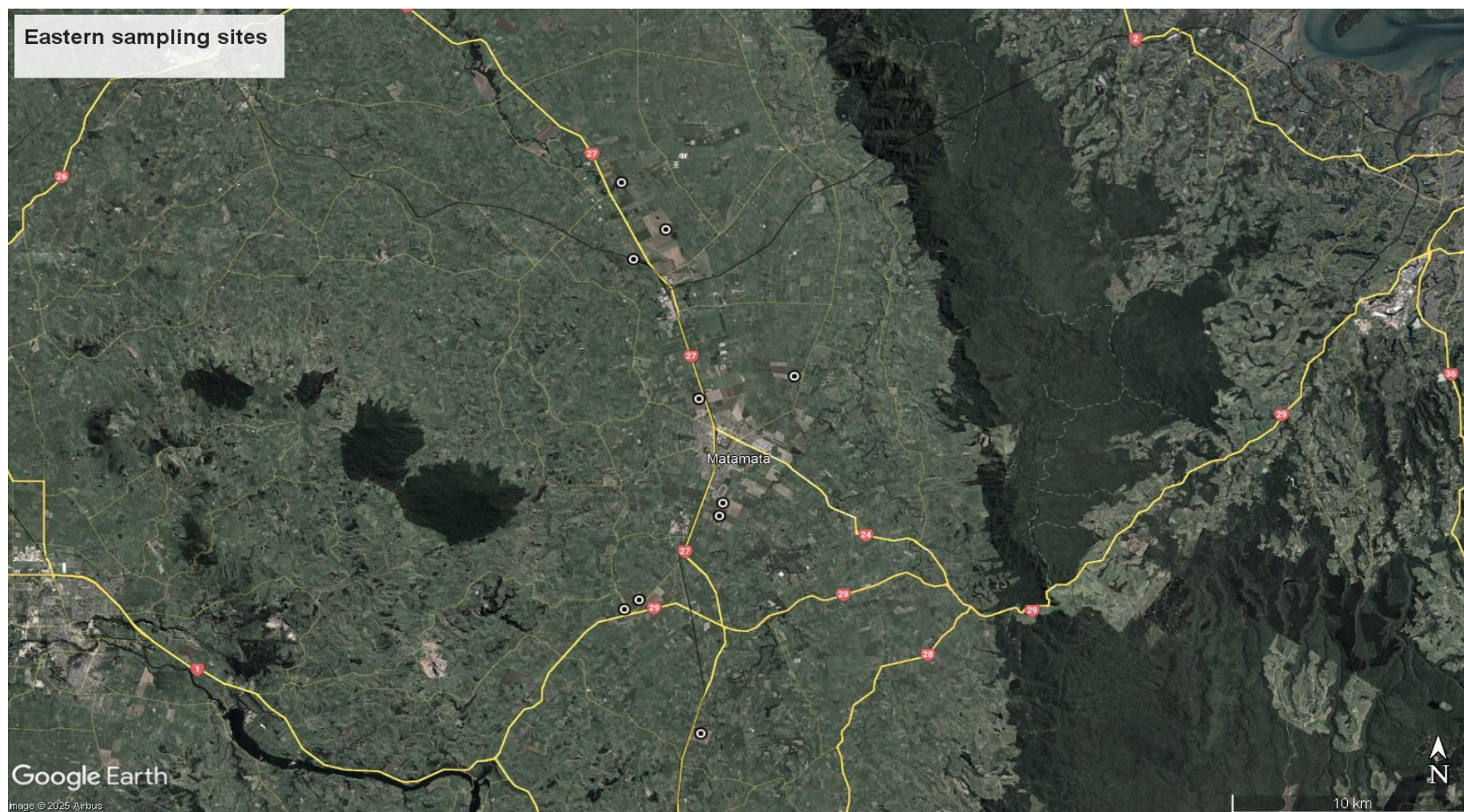


Figure 10. Location of sites (white circles) within the ‘Eastern’ sampling region (n = 10). Image sourced from Google Earth.

3.2 Results

Soil test data from the 30 sampling sites are summarised in Table 5 with individual site data for Olsen P and P retention presented in Figure 11. Key points are as follows:

- Median Olsen P (0-15 cm) across all sites was 81 mg/L with median concentrations for the granular soils (112 mg/L) observed to be about double those observed in the allophanics (62 – 66 mg/L) (Table 5). Note data at the regional scale are best interpreted using median values due to the presence of some substantial outliers (e.g. ~410 mg/L for Site 15; Figure 11). In terms of variability, concentrations within sites were reasonably consistent with coefficient of variation (CEV) values generally less than 20%. Considering target ranges for crop production, 10% of sites (n = 3) were below an 'optimal' range for most vegetable crops (35 – 70 mg/L), 30% of sites (n = 9) were within the target range and 60% of sites (n = 18) were above it (Figure 11). About 37% of sites (n = 11) had Olsen P concentrations considered to be excessive or in a very high range (> 100 mg/L).
- Median P retention (0-15 cm) across all sites was 62% (Table 5). The Eastern allophanic sites had notably higher P retention (88%) compared to the Northern allophanic (62%) and granular (52%) sites. P retention was generally consistent within a site with CEV values on average less than 10%. Higher variability at some sites (e.g. Site 3 and 4; Figure 11) was probably due to a change in soil order across the sampling area.
- Median water extractable P (WEP) across all sites was 0.15 mg/L (Table 5). This measure provides an estimate of dissolved reactive P (DRP) concentration in overland flow, and is influenced by soil P loading (i.e. Olsen P) and P retention (see Section 3.3). Median WEP increased in the order Eastern allophanic > Northern allophanic > Northern granular.

Table 5. Summary of Olsen P, soil P retention and water extractable P (WEP) test results (0-15 cm) from across 30 mixed cropping blocks located across the northern and eastern sampling regions.

Measure	Region	Soil Order	Across ¹				Within ²	
			Mean	Median	SD	n_Total	Mean CEV	n_Site
Olsen P (mg/L)	Northern	Allophanic	61	62	9	9	15	3
	Northern	Granular	134	112	84	51	12	17
	Eastern	Allophanic	61	66	28	30	11	10
	All	All	102	81	74	90	12	30
P retention (%)	Northern	Allophanic	69	62	19	9	23	3
	Northern	Granular	55	52	7	51	5	17
	Eastern	Allophanic	86	88	11	30	8	10
	All	All	67	62	18	90	8	30
WEP (mg/L)	Northern	Allophanic	0.12	0.13	0.04	9	20	3
	Northern	Granular	0.29	0.28	0.20	51	15	17
	Eastern	Allophanic	0.08	0.08	0.06	30	26	10
	All	All	0.21	0.15	0.19	90	19	30

¹ Means and standard deviations (SD) for all samples (n_Total) within the presented sampling strata. Mean coefficient of variation (CEV) across sampling sites (n_Site). This gives an indication of average within site variability for the presented sampling strata. CEV = standard deviation/mean x 100.

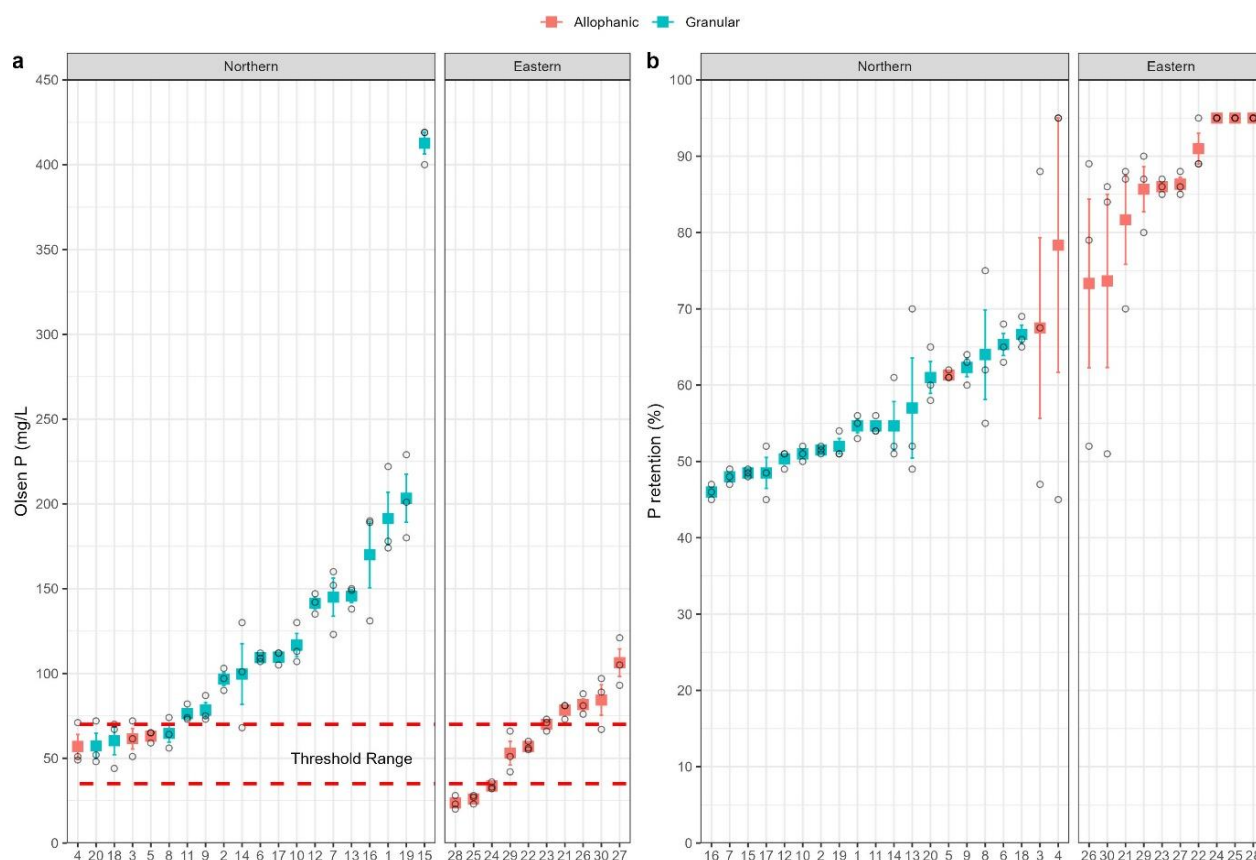


Figure 11. Soil test data from 30 mixed cropping sites across the northern and eastern sampling regions showing (a) Olsen P concentrations and (b) P retention in 0–15 cm topsoil samples classified as either Granular or Allophanic. Data have been arranged numerically in ascending order and bars around means (•) are standard errors. Transparent circles (○) are individual replicate values (n=3). The 'Threshold Range' (a) reflects recommendations provided by Reid and Morton (2019) where crop response is unlikely above the Olsen P limit supplied (upper limit is for lettuce at 70 mg/L and lower limit is for spinach at 35 mg/L).

3.3 General discussion and conclusions

Research within New Zealand and globally has demonstrated that the risk of P loss in subsurface and overland flow from soils increases with soil test P concentration (Heckrath et al. 1995; McDowell & Sharpley 2001; McDowell et al. 2003). Data from this study clearly corroborate this with strong correlations observed between water extractable P (WEP) and Olsen P across and within both soil order data sets (Figure 12 a). Water extractable P is considered a good surrogate measure for dissolved reactive P in surface runoff, and has been shown to be well correlated with the quotient of Olsen P and P retention in grassland soils (McDowell & Condron, 2004). Similarly, very good correlations were obtained between WEP and Olsen P/P Retention in this data set (Figure 12 b; $R > 0.88$), highlighting the utility of this measure for assessing P loss risk from cropping soils. Note that the Olsen P/P Retention measure (sometimes termed 'the degree of P saturation') is seen as a more useful predictor of P release into solution during drainage or runoff events (i.e. compared to agronomic soil P tests) because it accounts for both the soil's P concentration and its P sorption capacity (Blombäck et al. 2021; van Doorn et al. 2024). Importantly, there was a considerable divergence between the regression observed in our data set and the McDowell and Condron (2004) equation; that is, WEP concentrations from our soils were a lot higher than those predicted by McDowell and Condron (2004). On closer inspection, however, it was evident that there was distinct 'change point' at which WEP began to increase rapidly per unit change in Olsen P; this appeared to occur between an

Olsen P of 40 – 50 mg/L (Figure 13 a). For Olsen P/P Retention, this change point appeared to occur around 0.40 (Figure 13 b). Below this value, there was close alignment between our data and WEP predicted by McDowell and Condron (2004). Note there were far fewer samples with Olsen P < 40 mg/L ($n = 9$), and these were restricted to the allophanic soils. Consequently, more data are required to determine a more precise concentration threshold for this change point and whether this is different for allophanic compared to granular soils.

Overall, these data represent a useful first step in identifying where in the STP continuum the risk of P loss to the wider environment is increased. The observed Olsen P changed point of 40 – 50 mg/L suggests that above this concentration, P sorption sites in these allophanic and granular cropping soils are largely saturated, and any additional P is more likely to remain in soil solution or be weakly bound, making it more susceptible to leaching or runoff. It is important to highlight that observed 'change points' are a function of the P test used, soil type and desorption scenario (Maguire et al. 2005). For example, in a study on acid soils, Horta et al. 2007 found Olsen P change points at 20 mg/kg for high soil:solution ratios (e.g., drainage scenarios) and 61 mg/kg and 57 mg/kg for lower ratios (e.g., runoff scenarios). In New Zealand, a value of 50 mg/kg is often used as a general environmental threshold for Olsen P (Taylor et al. 2016) while for DPS, a value of 0.25 is often taken to be the critical value above which the risk of P loss in drainage increases significantly (Elbasiouny et al. 2020).

Using a conservative change point threshold of 50 mg/L Olsen P, we can conclude that topsoil P saturation (0-15 cm depth) was likely exceeded at 27 or 90% of the sites sampled (Figure 11). Furthermore, with two thirds of the sites sampled having Olsen P values above agronomic thresholds (~70 mg/L), and one third in an excessive range (> 100 mg/L), there appears to be a considerable (and urgent) need to reduce soil P loading across the north and eastern Waikato and south Auckland regions mixed cropping blocks to within more environmentally sustainable ranges.

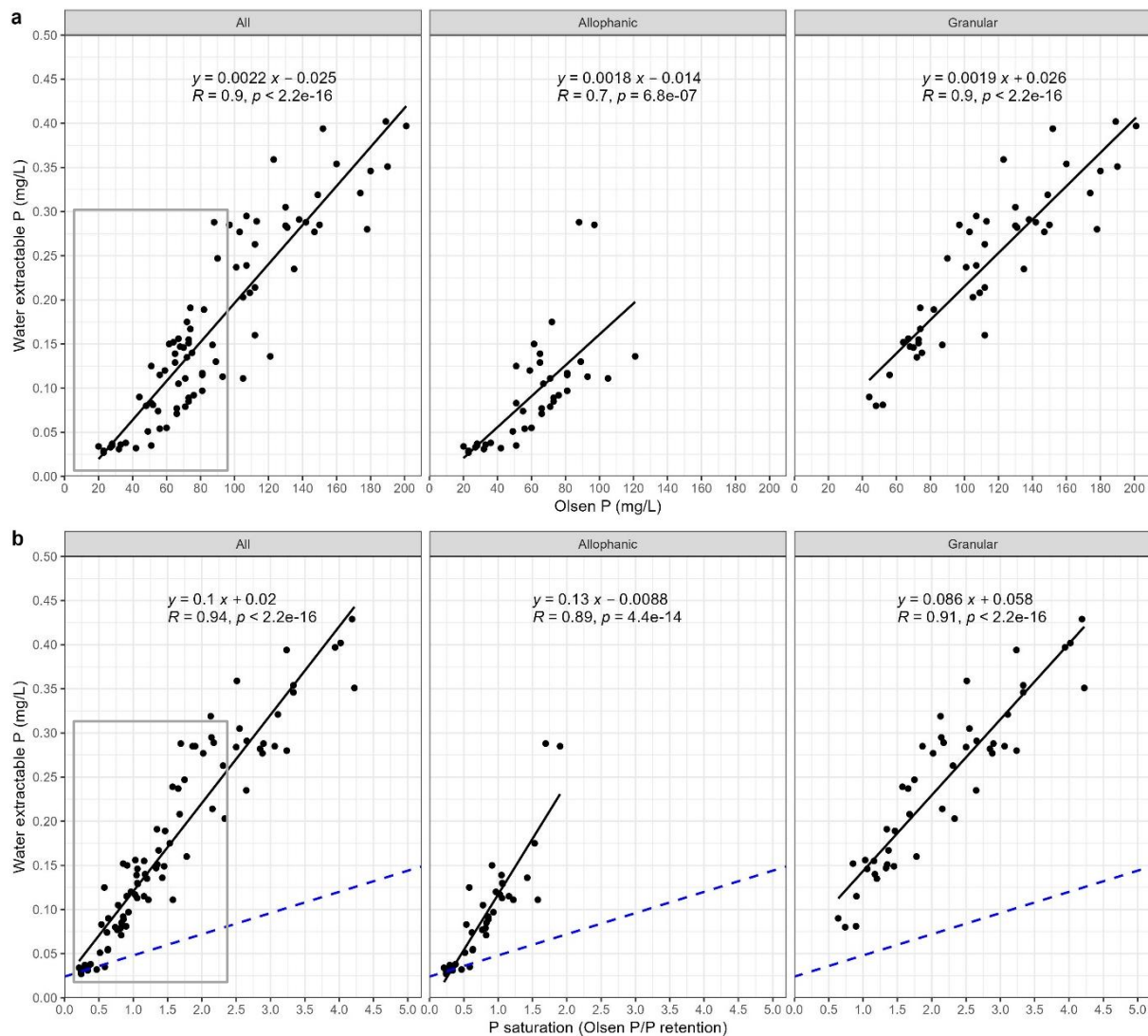


Figure 12. Relationship between water extractable P (WEP) and (a) Olsen P and (b) P saturation for samples taken from 29 mixed cropping sites across the northern and eastern sampling regions (note data from site 15 has been excluded from this analysis). Linear regressions have been applied to the entire data set ('All', $n = 90$) or separately to the allophanic ($n = 39$) or granular ($n = 51$) soil data sets. The blue line in Figure b is the relationship between WEP and P saturation from McDowell and Condron (2004) [DRP concentration (overland flow) = 0.024 (Olsen P/P retention) + 0.024]. Data within the grey boxes are presented in Figure 13.

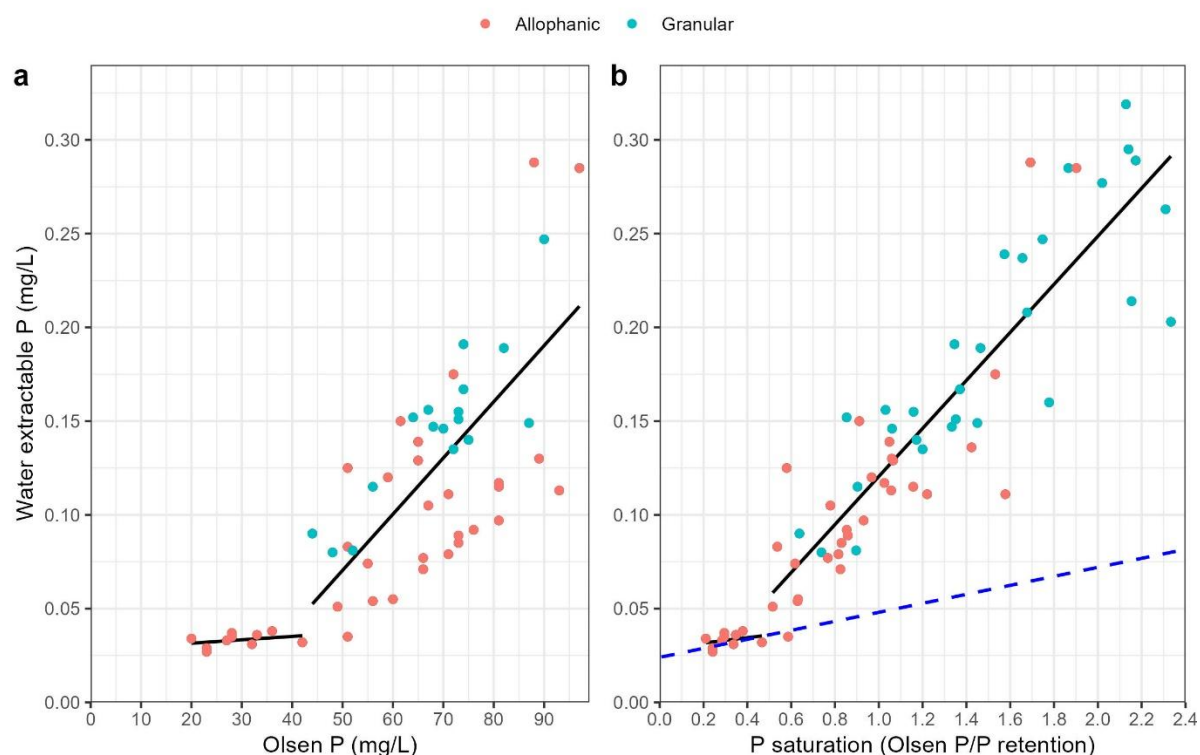


Figure 13. Relationship between water extractable P (WEP) and (a) Olsen P and (b) P saturation for samples with Olsen P < 100 mg/L. Separate linear regressions have been applied at Olsen P < 43 mg/L and Olsen P > 43 mg/L to highlight what appears to be a soil Olsen P 'change point' (~43 mg/L) above which the concentration of WEP increases more rapidly. The blue line in Figure b is the relationship between WEP and P saturation from McDowell and Condron (2004) [DRP concentration (overland flow) = 0.024 (Olsen P/P retention) + 0.024].

4 Evidence-based guidance for optimising P management in high P retention soils

Optimising P management on intensively cropped soils requires finding an appropriate balance between maintaining soil P supply at agronomic optimums while minimising environmental risks associated with excess application of P fertiliser. This balance can be difficult to achieve, at least from an environmental perspective where target limits for dissolved reactive P concentrations in receiving water bodies are as low as 0.02 mg/L (Australian and New Zealand Governments 2018). Consequently, pursuing low water extractable P (WEP) concentrations in soils (i.e. as an environmental marker) may result in Olsen P concentrations lower than the agronomic targets, potentially impairing production (McDowell et al. 2020). An important starting point in optimising P management is, therefore, to understand at what point in the STP continuum concentrations are either 1) in excess of crop requirements or 2) where they breach specific risk criteria in relation to environmental impact.

In relation to 1), current evidence-based recommendations are that an Olsen P of 40 – 70 mg/L is sufficient for most vegetable crops (Reid & Morton, 2019). Furthermore, work by Reid et al. (2020, 2024) has demonstrated that target STP values to achieve maximum production are independent of soil P retention, that is *there is no evidence that high soil P retention increases the optimum or target Olsen P for vegetables*. High P-retention soils, will however, require more P to achieve a particular STP target. Findings from the field trial (Section 2), broadly corroborate these recommendations with maximum yields achieved around an Olsen P of ~ 75 mg/L for a winter lettuce crop. It should be noted that this study was not designed to determine yield response to Olsen P *per se*, but rather whether yields could be maintained in the absence of P fertiliser inputs on a soil with high Olsen P and moderate to high P retention (this hypothesis was proven true). Another example of yield response to Olsen P on a high P retention soil (76%) is provided in Reid and Morton (2019), in this case for onions where an agronomic optimum of 45 mg/L is proposed. In these guidelines, Olsen P thresholds for withholding P fertiliser in high yield potential scenarios are 60 mg/L for process beans, 60 mg/L for buttercup squash, 45 mg/L for cabbage, broccoli and cauliflower, 40 mg/L for carrots, 70 mg/L for lettuce, 55 mg/L for onions, 50 mg/L for potatoes, 35 mg/L for spinach, silverbeet and beetroot, 35 mg/L for sweetcorn, and 50 mg/L for process tomatoes.

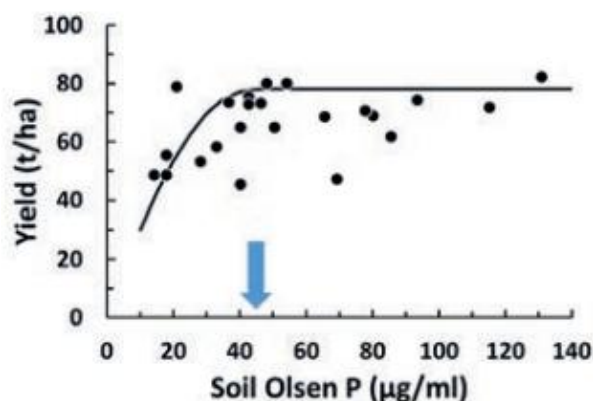


Figure 14. Onion yield response to Olsen P as measured by Prasad et al. (1988). The blue arrow represents the agronomic optimum and the solid black line is predicted yield response (Figure extracted from Reid & Morton, 2019).

Based on these recommendations and findings from the field study, we can conclude that there appears to be no reasonable basis for applying additional P to high P retention cropping soils when Olsen P > 75 mg/L.

In relation to 2), data from the regional P sampling study demonstrated a distinct Olsen P ‘change point’ at which WEP began to increase rapidly per unit change in Olsen P. For Olsen P this appeared to occur between 40 – 50 mg/L and for the Olsen P/P Retention measure around 0.40. It is important to note that our data set contained few samples with Olsen P < 40 mg/L (n = 9) and these were

restricted to the allophanic soil order. Consequently, more data are required to determine a precise concentration threshold for this change point and whether this is different for allophanic compared to granular soils. Data from this study are, nevertheless, a good starting point for identifying what might be termed a 'sweet spot' for optimising production while minimising environmental impact. An Olsen P threshold of 50 mg/L appears to be a good initial estimate for achieving this balance, although lower thresholds may be preferable in sensitive catchments or where crop nutrient requirements are lower. It is also important to note that P retention has a significant effect in determining an 'optimum' Olsen P threshold for a specific production context. For example, an eastern allophanic soil with an Olsen P of 70 mg/L and a P retention of 88% (WEP ~ 0.10 mg/L) will have a similar environmental risk profile when compared to a northern granular soil with an Olsen P of 40 mg/L and a P retention of 52% (WEP ~ 0.10 mg/L) (Figure 15). So, while both soil orders would be categorised by moderate to high P retention, there are important differences with respect to how these soils need to be managed to achieve balanced agronomic and environmental outcomes. It is interesting to note that the sites sampled in this study with the lowest P retention (i.e. the northern granulars; median P retention = 52%) were also the sites with the highest Olsen P concentrations (median P Olsen P = 112 mg/L). From an environmental perspective, these are 'high risk' sites and should be targeted first for the implementation of management strategies to reduce STP loading.

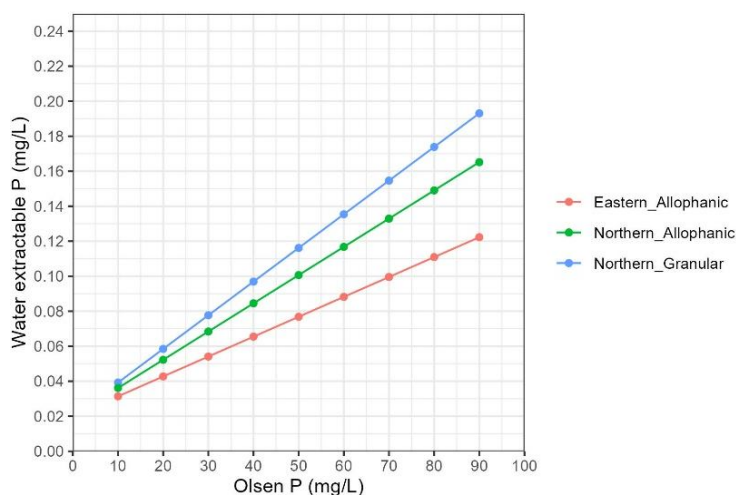


Figure 15. Modelled relationship between water extractable P and Olsen P (0-15 cm) for samples with P retention of 88% (Eastern Allophanic), 62% (Northern Allophanic) and 52% (Northern Granular). Relationships were derived using the linear regression in Figure 12 b for all soils ($y = 0.1 \times \text{Olsen P} / \text{P Retention} + 0.02$).

Recommendations:

- An Olsen P of around 50 mg/L appears to be suitable for maintaining soil P supply for most vegetable crops (based on current evidence-based recommendations), and up to 75 mg/L for high demanding crops. This represents a good balance between maintaining soil P supply and minimising environmental risks associated with P loss in surface runoff from moderate to high P retention cropping soils. There is no reasonable basis for applying additional P when Olsen P > 75 mg/L, even on high P retention soils.
- For crops with higher P demand or higher Olsen P thresholds (e.g. lettuce), management strategies should be employed to improve P uptake efficiency, for example, banding starter fertiliser close to the plant root zone. Broadcasting or banding of P fertiliser on the surface should be avoided as this has a very limited effect on available P for the immediate crop, and also carries a considerable risk of loss through runoff events.
- For sites with high Olsen P > 80 mg/L, focused attention should be given to reducing soil P reserves to within target agronomic ranges. Continued P application to high Olsen P soils is likely a waste of economic resource and an unacceptable environmental risk.

5 Summary and next steps

Based on the findings from this study, we believe that there is a significant opportunity to better utilise existing P stocks in the highly fertile – high P-retention cropping soils of northern and eastern Waikato and south Auckland regions. While there is an economic incentive to drawdown legacy P stocks (i.e. less fertiliser P needs to be applied), a key rationale is to reduce environmental impacts associated with diffuse P transfer into receiving waterways. In the moderate to high P-retention soils (> 50%) studied here, reducing Olsen P from 100 mg/L to 50 mg/L (i.e. midpoint target range for vegetable crops) could reduce DRP (dissolved reactive P) concentrations in overland flow by up to 55%. This impact could be even greater at sites with higher STP levels or where lower target STP ranges are required.

To support long-term improvements in phosphorus management for vegetable and mixed crop production, we recommend initiating a research programme spanning five or more years, with the following objectives:

1. Quantify the impact of phosphorus drawdown on crop yield, specifically, to determine the threshold below which yield penalties occur, and how this varies across different vegetable crops. It should be noted that yield - Olsen P response curves are already established for many crops, and the conventional approach has been to apply fertiliser to reach these target soil test values. A key project objective, therefore, would be to demonstrate to growers that *reducing* soil phosphorus levels to the established targets does not compromise yield.
2. Reassess agronomic phosphorus optimums for vegetable crops grown in high phosphorus-retention soils, and evaluate how these optimums align with environmental risk thresholds.
3. Evaluate and refine management practices to enhance phosphorus use efficiency in intensive cropping systems. Potential strategies include targeted fertiliser placement, cover cropping, soil health improvements, and the use of phosphorus-solubilising amendments to mobilise recalcitrant phosphorus reserves.
4. Investigate whether starter P fertiliser is required for vegetable production in cold soil conditions, even if soil test P values are adequate.

Findings from this research would be used to inform best management practices for phosphorus use, aiming to enhance the long-term sustainability of vegetable production in Aotearoa New Zealand. Grower involvement and field days will be important, so that this research leads to knowledge transfer and practice change.

6 Acknowledgements

Thank you to Te Ahikawariki: The Vegetable Industry Centre of Excellence (VICE) for hosting the legacy P field trial and to Howe Young for management of the crop.

Thank you to LeaderBrand (Nikita Leighton), Balle Brothers (Kelvin Doidge and Roger Tomlin) and AS Wilcox & Sons (Bryan Hart, Ewan Cragg and James Blair) for the provision of and assistance in identifying sampling sites for the regional STP scoping study.

Thank you to Stephen Trollove and Duncan Hedderley for statistical review and comments on the final report.

7 References

Australian and New Zealand Governments, (2018). Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Canberra, ACT: Australian and New Zealand Governments and Australian state and territory governments.

Blakemore LC, Searle PL, Daly BK. 1987. Methods for chemical analysis of soils. New Zealand Soil Bureau Scientific Report 80. Lower Hutt, N.Z. p 44.

Blombäck K, Bolster CH, Lindsjö A, Hesse K, Linefur H, Parvage MM. 2021. Comparing measures for determination of phosphorus saturation as a method to estimate dissolved P in soil solution. *Geoderma*. 383:114708.

Elbasiouny H, Elbehiry F, El-Ramady H, Brevik EC. 2020. Phosphorus Availability and Potential Environmental Risk Assessment in Alkaline Soils. *Agriculture* 10(5):172.

Heckrath G, Brookes PC, Poulton PR, Goulding KWT. 1995. Phosphorus Leaching from Soils Containing Different Phosphorus Concentrations in the Broadbalk Experiment. *Journal of Environmental Quality* 24(5): 904-910.

Hill Labs. 2025. Soil tests and interpretation. Technical Note. KB Item: 3196, version 7. https://www.hill-labs.co.nz/media/djdbzzhl/3196_technical-note-soil-tests-and-interpretation.pdf [Accessed August 2025].

Horta MdC, Torrent J. 2007. The Olsen P method as an agronomic and environmental test for predicting phosphate release from acid soils. *Nutr Cycl Agroecosyst* 77: 283–292.

Manaaki Whenua 2025. S-Map Online version 5.1.146. <https://smap.landcareresearch.co.nz/> [Accessed June 2025].

Maguire RO, Chardon WJ, Simard RR. 2005. Assessing potential environmental impacts of soil phosphorus by soil testing. In: Sims JT, Sharpley AN (eds), *Phosphorus: Agriculture and the Environment*. ASA CSSA SSSA, Madison WI, pp 145–180.

McDowell RW, Sharpley AN. 2001. Approximating Phosphorus Release from Soils to Surface Runoff and Subsurface Drainage. *Journal of Environment Quality* 30(2): 508-520.

McDowell RW, Monaghan RM, Morton J. 2003. Soil phosphorus concentrations to minimise potential P loss to surface waters in Southland. *New Zealand Journal of Agricultural Research* 46(3): 239-253.

McDowell RW, Condron LM. 2004. Estimating phosphorus loss from New Zealand grassland soils. *NZ J Agri Res.* 47(2):137–145

McDowell R, Dodd R, Pletnyakov P, Noble A. 2020. The Ability to Reduce Soil Legacy Phosphorus at a Country Scale. *Front. Environ. Sci.* 8:6.

Nair VD. 2014. Soil phosphorus saturation ratio for risk assessment in land use systems. *Frontiers in Environmental Science*. Volume 2 – 2014.

Olsen SR, Cole CV, Watanabe FS, Dean LA. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. Washington, DC: U. S. Department of Agriculture Circular; p. 939.

Patrignani A, Ochsner TE. 2015. Canopeo: A powerful new tool for measuring fractional green canopy cover. *Agronomy Journal*. 107(6): 2312-2320.

Prasad M, Spiers TM, Ravenwood IC. 1988. Target phosphorus soil test values for vegetables. *New Zealand Journal of Experimental Agriculture* 16: 83-90.

Qiu W, Curtin D, Hu W, Beare MH. 2022. Sensitivity of organic matter mineralisation to water availability: role of solute diffusivity and the “Birch effect”. *Soil Res* 61(1): 9-19.

R Core Team. 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL <https://www.R-project.org/>.

Reid JB, Morton JD. 2019. Nutrient management for vegetable crops in New Zealand (1.0). <https://www.hortnz.co.nz/assets/Compliance/Nutrient-Management-for-Vegetable-Crops-in-NZ-Manual-Feb-2020.pdf> [Accessed June 2025].

Reid JB, Trolove SN, Tan Y, Curtin D. 2020. Does soil anion storage capacity affect plant response to Olsen P status? *New Zealand Journal of Crop and Horticultural Science*, 48:3, 133-142.

Reid JB, Searle BP, Tan Y. 2024. Supply of phosphorus and nitrogen affects both growth and development rates in onion, *New Zealand Journal of Crop and Horticultural Science* 1–19.

Taylor MD, Drewry JJ, Curran-Cournane F, Pearson L, McDowell RW, Lynch B. 2016. Soil quality targets for Olsen P for the protection of environmental values. In: *Integrated nutrient and water management for sustainable farming*. (Eds L.D. Currie and R. Singh). <http://flrc.massey.ac.nz/publications.html>. Occasional Report No. 29. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 12 pages.

The New Zealand Institute for Plant and Food Research Limited. 2022. Guidelines for Soil Nitrogen Testing and Predicting Soil Nitrogen Supply. Version 1.1. September 2022. <https://www.plantandfood.com/en-nz/article/soil-nitrogen-testing-and-predicting-nitrogen-supply> [Accessed February 2025].

van Doorn M, van Rotterdam D, Ros G, Koopmans GF, Smolders E, de Vries W. 2024. The phosphorus saturation degree as a universal agronomic and environmental soil P test. *Crit Rev Environ Sci Technol*. 54(5):385–404.

Appendix 1. Lettuce production data for Standard and Zero P treatments. Values in parentheses are standard errors of the mean

Measure	Standard	Zero P	<i>p value</i> *
DM%	4.16 (0.27)	3.62 (0.11)	0.0048
Yield (t DM/ha)	1.05 (0.14)	1.16 (0.07)	0.20
Yield (t FW/ha)	25.2 (1.9)	32.0 (1.8)	0.0011
Population (plants/plot)	18.6 (1.3)	18.8 (0.84)	0.79
Head size diameter (cm)	10.6 (1.3)	11.3 (1.4)	< 0.001

* Treatment effects are considered significant (*) at $p < 0.05$ and highly significant (**) at $p < 0.01$.

Appendix 2. Lettuce nutrient concentration and uptake data across Standard and Zero P treatments. Values in parentheses are standard errors

Element	Concentration			Uptake (kg/ha)			
	Unit	Standard	Zero P	<i>p value</i> *	Standard	Zero P	<i>p value</i> *
N	%w/w	3.49 (0.13)	3.59 (0.15)	0.34	36.8 (5.1)	41.4 (2.1)	0.12
P	%w/w	0.44 (0.03)	0.51 (0.01)	0.004	4.59 (0.45)	5.84 (0.41)	0.003
K	%w/w	7.25 (0.273)	7.85 (0.33)	0.007	76.1 (8.2)	90.9 (8.0)	0.030
S	%w/w	0.26 (0.02)	0.28 (0.01)	0.087	2.70 (0.26)	3.18 (0.24)	0.024
Ca	%w/w	0.89 (0.03)	0.85 (0.06)	0.21	9.40 (1.38)	9.86 (1.23)	0.62
Mg	%w/w	0.21 (0.01)	0.20 (0.01)	0.37	2.20 (0.22)	2.35 (0.27)	0.41
B	mg/kg	24.8 (1.3)	25.6 (2.3)	0.47	2.60 (0.25)	2.96 (0.36)	0.12
Cu	mg/kg	13.2 (0.8)	12.0 (1.2)	0.13	1.38 (0.14)	1.39 (0.17)	0.96
Mn	mg/kg	143 (18)	137 (26)	0.73	15.0 (2.4)	16.0 (3.89)	0.65
Zn	mg/kg	31.6 (2.4)	33.8 (4.0)	0.36	3.30 (0.24)	3.92 (0.67)	0.11

* Treatment effects are considered significant (*) at $p < 0.05$ and highly significant (**) at $p < 0.01$.

A smart
green
future.
Together.