SUSTAINABLE VEGETABLE SYSTEMS

Final Report | July 2024

PART 1

Disclaimer

The Sustainable Vegetable Systems (SVS) web application provided on website www.svstool.co.nz (the SVS Tool) has been developed by a partnership comprising the Ministry of Primary Industries (MPI), The New Zealand Institute for Plant and Food Research Limited (PFR), Potatoes New Zealand Incorporated (PNZ), Horticulture New Zealand Incorporated (HortNZ), and the Vegetable Research and Innovation Board (representing Onions New Zealand Incorporated, Vegetables New Zealand Incorporated, Process Vegetables NZ and the New Zealand Buttercup Squash Council) (together the SVS Partners).

The SVS Tool has been designed to provide users with insight about nitrogen flows through a nitrogen budget, and guidance on nitrogen fertiliser application.

Use of the SVS Tool is voluntary and the user should exercise their own discretion before deciding to use it.

Use of the SVS Tool is at the sole risk of the user and none of the SVS Partners provide any 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 the SVS Tool.

To the maximum extent permitted at law, the SVS Partners shall not 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 the SVS Tool.

Report reference:

Barber A, Stenning H, Searle B, Brown H (2024, July). Sustainable Vegetable Systems Final Report. Prepared by Agrilink NZ and PFR for the Sustainable Vegetable Systems partners.

Contents

1 Overview

1.1 Project outcome

Making the invisible visible and helping growers improve their nitrogen use efficiency.

In New Zealand, the vegetable sector is actively transitioning towards more sustainable production practices. Amongst a raft of practices in an extremely complex and ever-changing vegetable growing system, nitrogen (N) stands out as a key economic and environmental consideration.

The Sustainable Vegetable Systems (SVS) Project has developed a new tool that makes the invisible visible.

Measured numbers beat modelled numbers

Planning requires a model to project into the future, but it's the SVS Tool's ability to adjust modelled numbers with measured in-season soil tests that has created a powerful decision support tool that reflects the current season's actual conditions.

Environmental sustainability

Achieving environmentally sustainable vegetable production involves managing inputs to meet economic crop production needs, while reducing environmental impact.

Given the variability within fields, from field to field, and year to year, a sophisticated approach to crop management is necessary to reduce environmental impact and optimise production. The SVS project delivered controlled experiments that informed the development of more accurate N flow models. This allows growers to better match N applications with crop demand, therefore helping to reduce N loss to the environment. Alongside this, four years of ground truthing using monitoring sites right around New Zealand built grower engagement and trust.

A tool to support decisions

We anticipate that the user base of the SVS Tool will be both growers and their trusted advisors, including independent agronomists, fertiliser representatives, and researchers. Using the SVS Tool will give users increased confidence and awareness of soil N testing and soil-crop N flows, optimising management decisions such as fertiliser application (quantity and timing) and rotation planning (increasing the utilisation of crop residues).

Ultimately, the SVS project has improved understanding of N management, enabling growers to improve nutrient use efficiency built upon years of experience and sound scientific knowledge. The SVS Tool supports growers' Farm Environment Plans by providing the evidence of their Good Management Practices.

The SVS project was funded by the Ministry for Primary Industries, Potatoes New Zealand, the Vegetable Research & Innovation board, and Horticulture New Zealand.

FOR MORE INFORMATION

The first generation SVS Tool can be accessed at www.svstool.co.nz and by contacting the SVS Partners or the Project Manager Andrew Barber andrew@agrilink.co.nz.

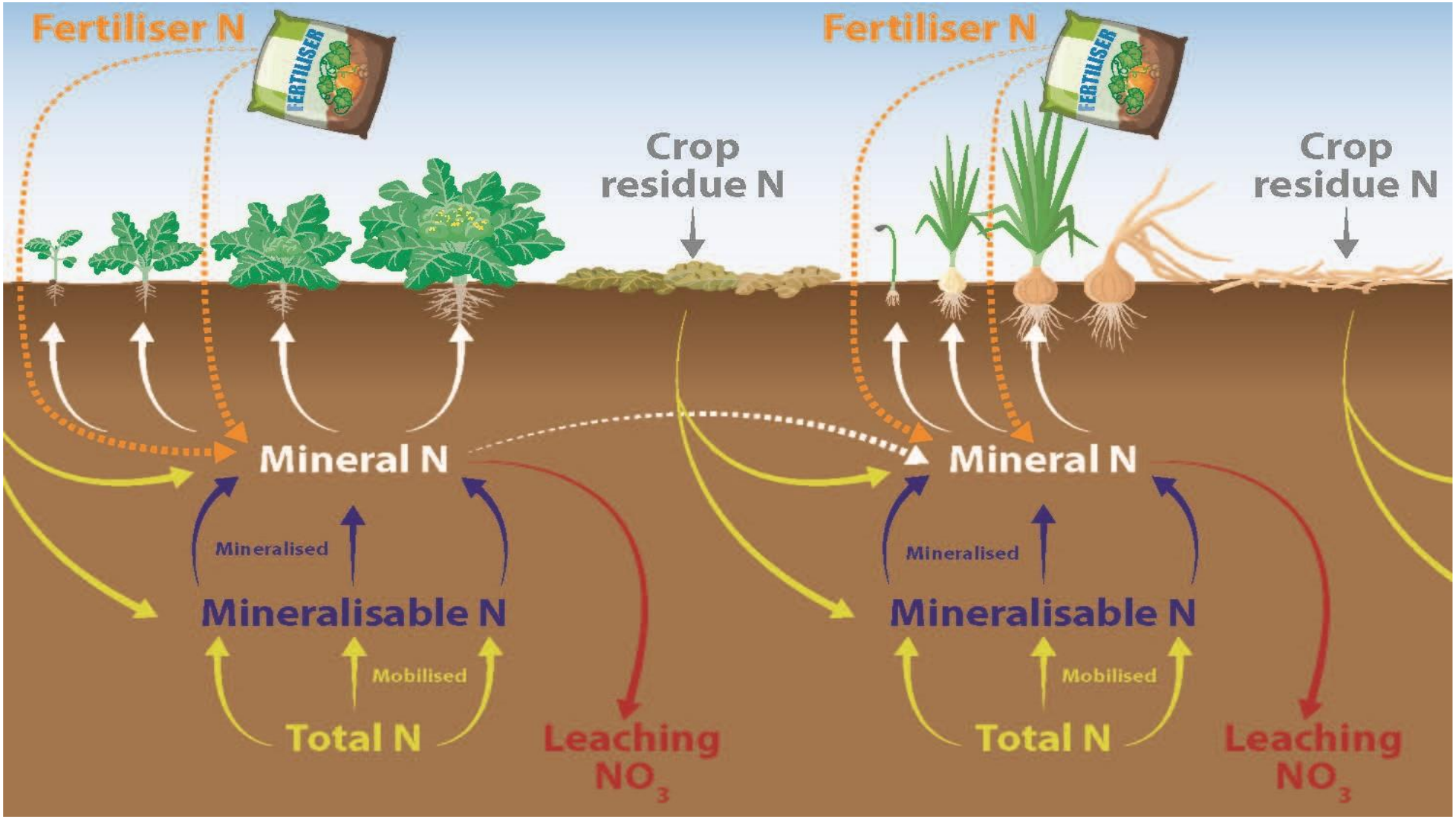


Figure 1. The nitrogen flows through a vegetable system. The SVS tool estimates soil mineral N and matches fertiliser rate and timing to better meet crop demand, helping reduce fertiliser needs and improving environmental outcomes.

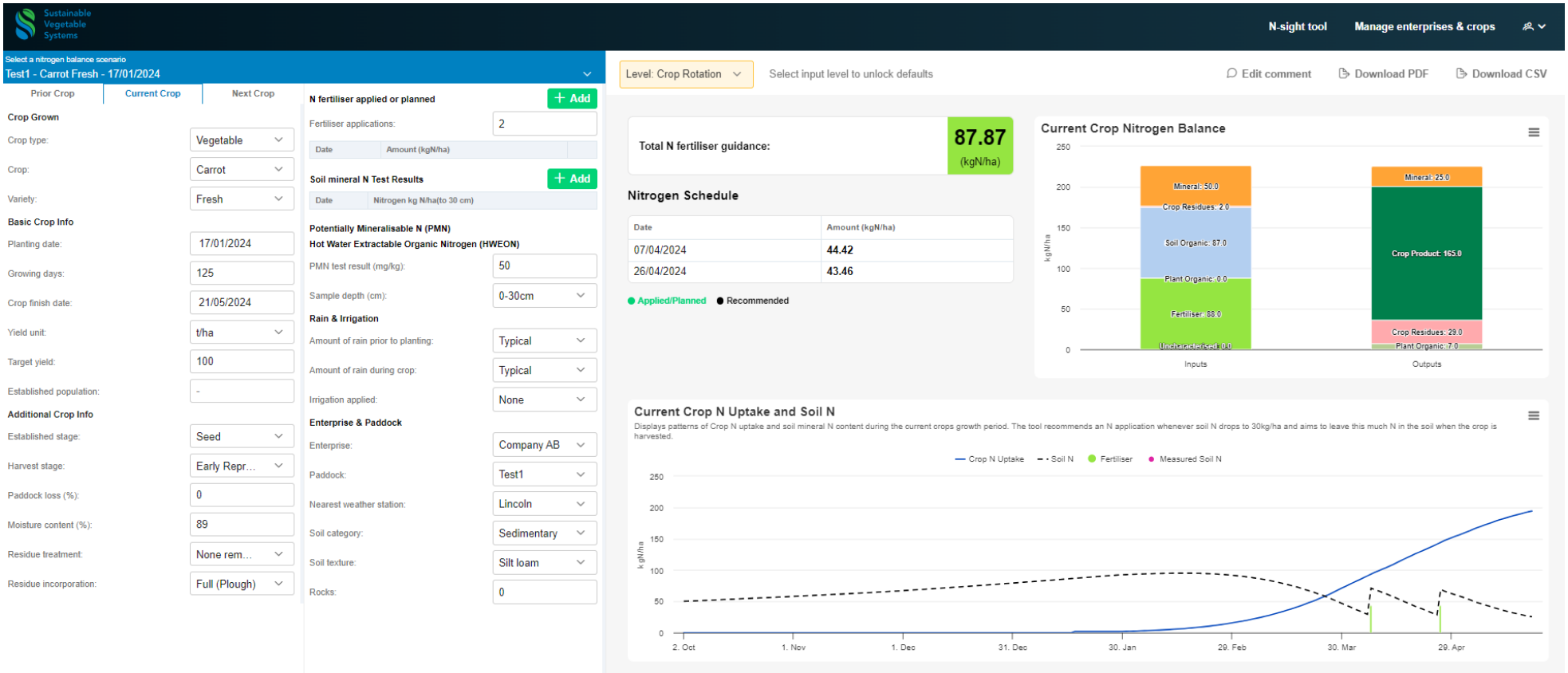


Figure 2. Screenshot of the Sustainable Vegetable Systems (SVS) Tool accessible from www.svstool.co.nz.

"But that doesn't apply to me ..."

Measured numbers beat modelled numbers every time.

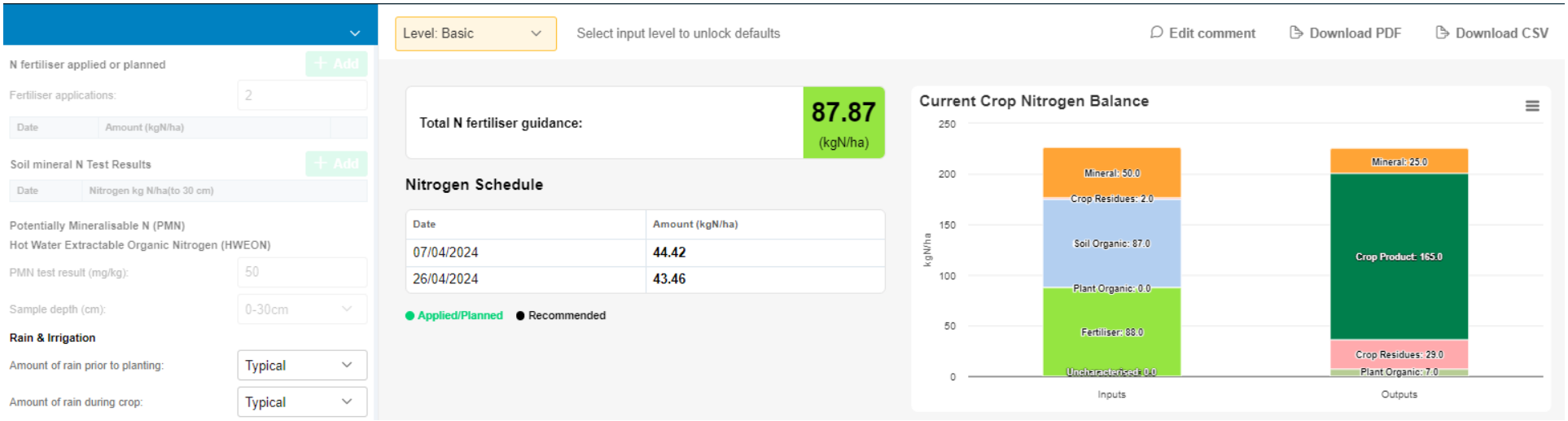


Figure 3. Basic Level nitrogen budget with defaults.

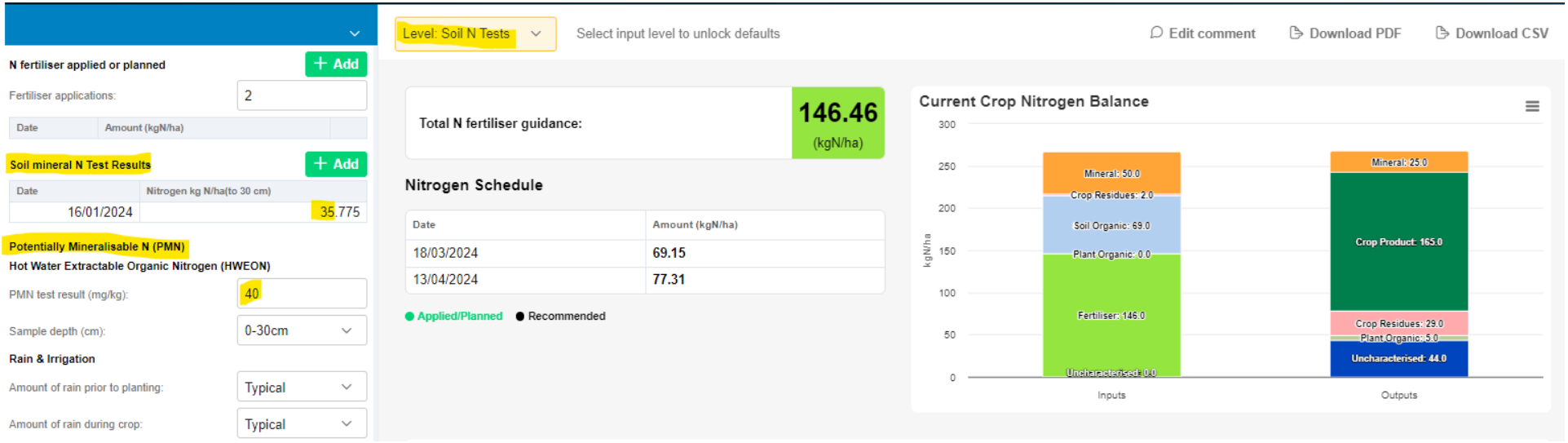


Figure 4. Soil testing tunes the guidance and budget.

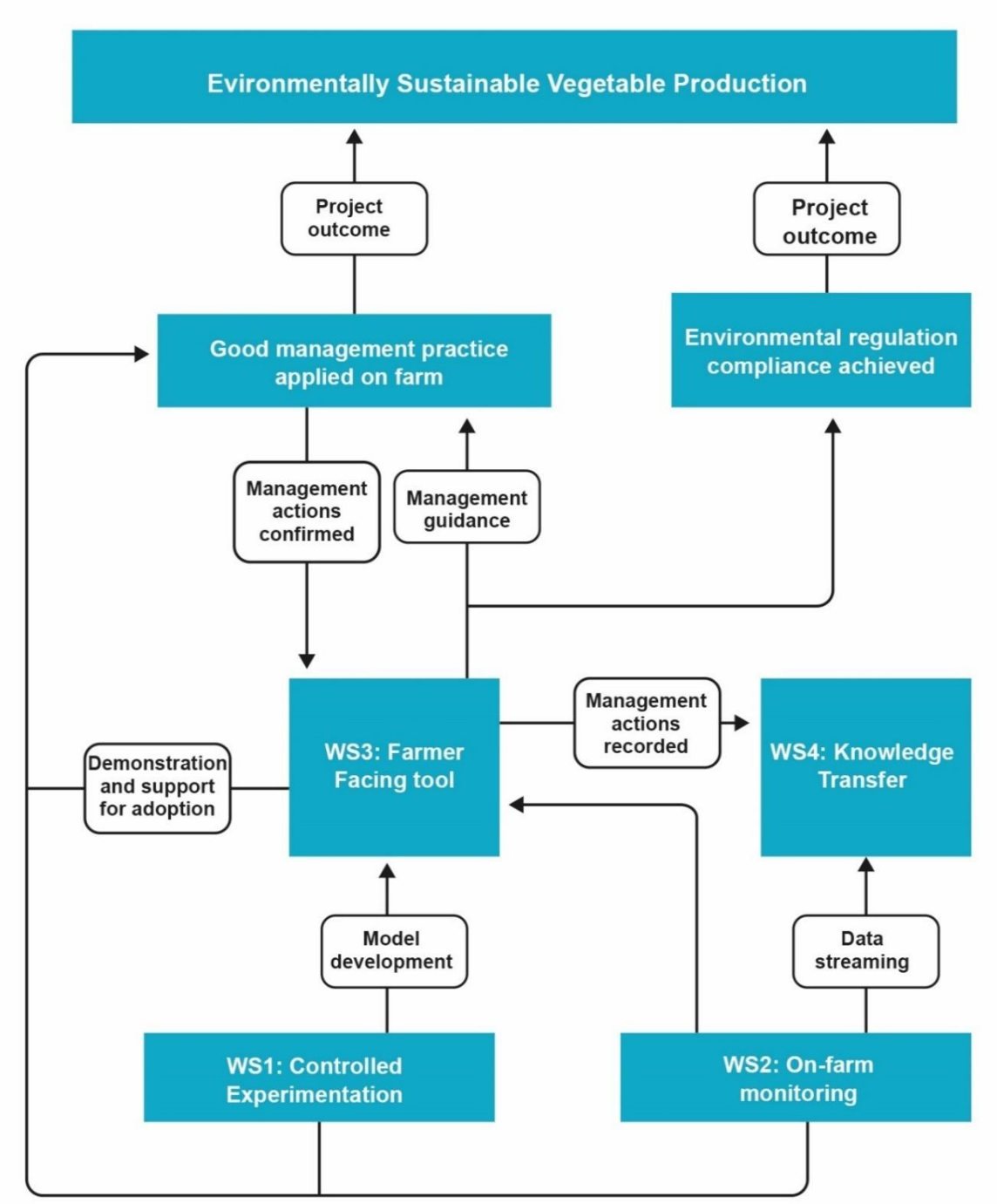


Figure 5. The Sustainable Vegetable Systems (SVS) project structure, with interdependent workstreams with data flows between each, ultimately empowering growers to make sustainable management decisions.

The SVS Project provided a decision support tool for applied good nitrogen management practices that achieves environmentally sustainable vegetable production. The project achieved this outcome through controlled experiments (Workstream 1), on-farm monitoring (Workstream 2), a farmer facing decision support tool (Workstream 3), and dissemination (Workstream 4).

1.2 SVS key documents

The Vegetable Research & Innovation website currently houses a selection of key resources developed as part of the SVS Project, in addition to a link directing users to the tool. See Table 1.

Table 1. Related SVS documents housed on VR&I.

Document	Description
SVS Final Report	This report, covering the key project workstreams and outcomes.
SVS User Guide	User guide for the First Generation SVS Tool.
Sustainable Vegetable Systems Summary May 2024	High level project summary.
Nitrogen Soil Testing Factsheet V6	Information sheet to aid understanding about different nitrogen testing options.
Sustainable Vegetable Systems – annual report 2024	This report summarises the data, modelling and outreach of the SVS project

1.3 Funding

The SVS Project was funded by the Ministry for Primary Industries (MPI), Potatoes New Zealand (Potatoes NZ), Vegetable Research & Innovation board (VR&I), and Horticulture New Zealand (HortNZ), through a combination of cash and in-kind support. Other project in-kind contributors included growers, councils, service industry providers and Plant & Food Research.

Investment period	Co-investor contribution	MPI contribution	Total investment
Whole project 1/7/2020 – 30/06/2024	$2.850 m	$4.715 m	$7.565 m

Table 2 on the next page provides more details about the project's funding.

Table 2. Breakdown of project funding by year and workstream.

	Year 1	Year 2	Year 3	Year 4	Total Project			
	Actual	Actual	Actual	Actual	Original Budget	Actual	Variance	Comments
Workstream 1 - Trials	$1,282,216	$1,153,001	$745,233	$6,393	$3,186,843	$3,186,843	$-	
Workstream 2 - Monitoring	$191,825	$252,447	$251,505	$134,933	$848,259	$830,710	-$17,549	
Workstream 3 -Modelling	$104,542	$220,694	$320,165	$250,738	$725,000	$896,138	$171,138	Additional model and tool development costs
Workstream 4 - Dissemination	$92,326	$109,969	$164,561	$246,864	$684,898	$613,720	-$71,178	
Gov. & mgmt.	$165,026	$146,235	$151,721	$156,829	$680,000	$619,811	-$60,189	Savings in time and travel, redeployed to WS3
Total	**$1,835,934**	**$1,882,346**	**$1,633,184**	**$795,757**	**$6,125,000**	**$6,147,221**	**$22,221**	Additional modelling costs contributed by the industry
MPI	$1,485,576	$1,556,217	$1,251,899	$412,848	$4,715,000	$4,715,000*	$0	* incl. MPI's final contribution of $8,461
Co-investor cash	$352,500	$352,500	$352,500	$377,500	$1,410,000	$1,435,000	$25,000	Additional industry funding
Co-investor in-kind	$318,022	$238,636	$263,494	$595,212	$1,386,757	$1,415,364	$28,607	
Total investment	**$2,156,097**	**$2,147,353**	**$1,867,893**	**$1,385,560**	**$7,511,757**	**$7,565,364***	**$45,147**	Additional industry cash and in-kind funding.

1.4 Outcome Logic Model

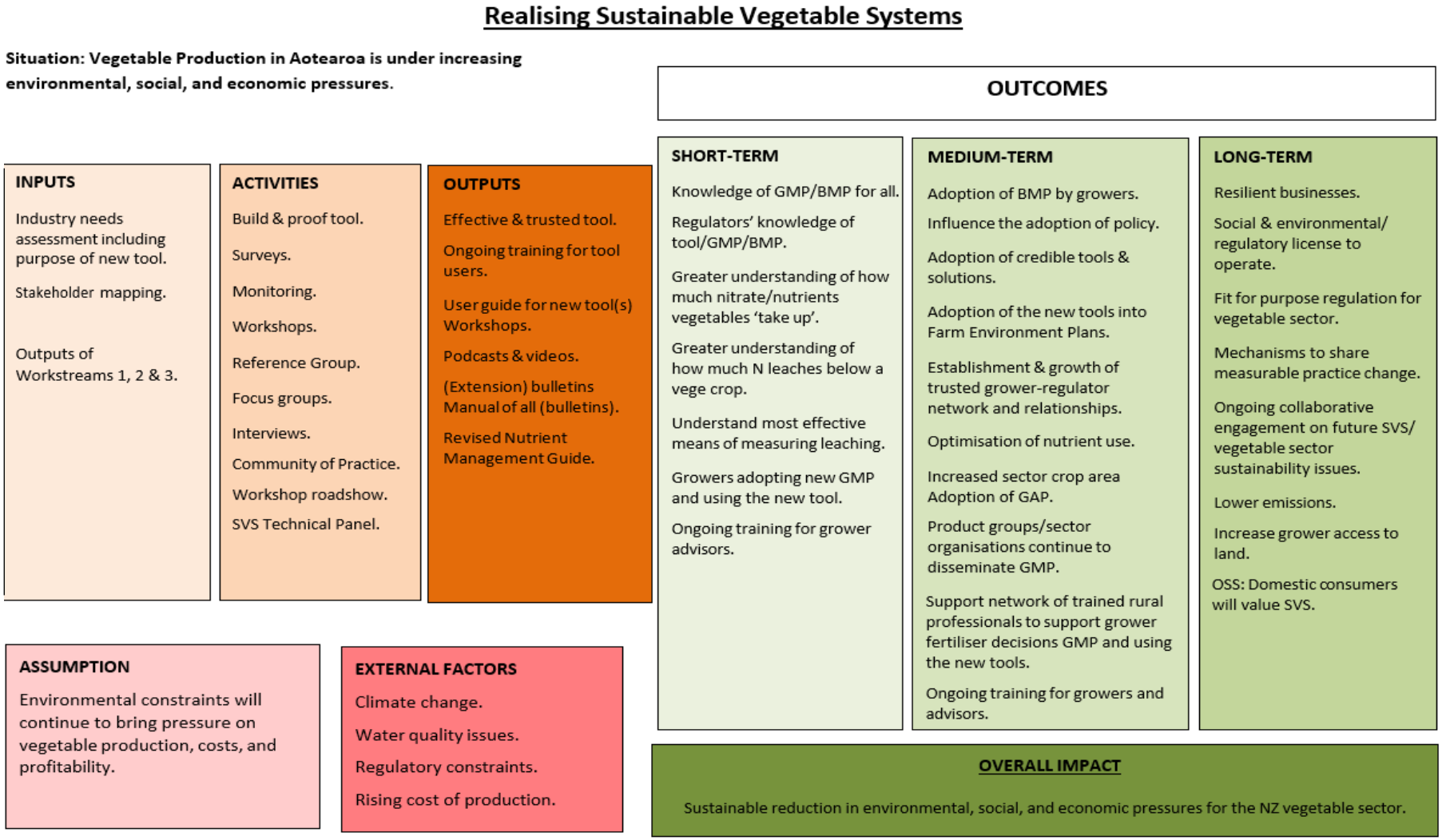


Figure 6. Outcome logic model for SVS project.

The true extent of SVS's overall impact will only become apparent over the next 5-10 years. However, without question, the SVS Project has delivered a scientifically robust, fertiliser decision maker centric, industry supported decision support tool.

Five of the seven short term outcomes in the outcome logic model refer to knowledge or greater understanding. At its very heart the SVS Tool is a knowledge tool. It provides nitrogen fertiliser guidance, it integrates an array of soil nitrogen tests, and it presents a nitrogen budget, all essential elements that the SVS project needed to deliver. Ultimately, the SVS Tool provides the foundation for meaningful discussions and leads inquiring minds to explore further how nitrogen flows through extremely complex vegetable production systems. It is through this knowledge and confidence that practice change occurs. It is only practice change that leads to improved environmental, social, and economic outcomes.

The challenge facing the industry now is having developed their nitrogen decision support tool, that the SVS Tool does not end up like some before it, in a tool graveyard in the sky.

The pathway to ensure this does not happen is currently being mapped out. The industry has backed the SVS Tool with ongoing user interface, model, and fertiliser decision maker support. It is the decision maker support that is the foundation of industry discussions about future steps in nutrient management. Through SVS Workstream 4, extension, user engagement, confidence building and implementation have been successfully piloted. The SVS Tool is being used in the MfE and industry funded Pukekohe Catchment project. The approach being implemented takes away two key learnings from the SVS dissemination programme. Firstly, that the tool is extended out through the service industry, which is built upon their familiarity and confidence in the SVS Tool. Secondly, it is only by working one on one with growers through their trusted service industry providers that time and space is created to implement practice change.

Through the HortNZ Growing Change programme, advisers are being trained in the use of the SVS Tool and nitrogen risk assessment tools, to support of growers' Farm Environment Plans. These activities feed into the medium-term outcomes identified in the Outcome Logic Model.

2 Workstream One: Intensive field trials

2.1 Overview

The Workstream 1 sections bring together research undertaken by The New Zealand Institute for Plant and Food Research Limited (PFR), particularly the 2023 Summary Report (Searle et al. 2023) and 2024 Summary Report (Searle et al. 2024) – the full reports are available upon request.

The Sustainable Vegetable Systems (SVS) project aims to provide a tool that will help fertiliser decision makers determine the best rate of nitrogen (N) fertiliser for their crop that maximises yield returns but minimises N losses from the crop system. A particular focus is on minimising N losses via leaching, an important part of ensuring cleaner waterways in New Zealand.

The SVS Tool was developed based on a N balance approach – all the N inputs and N outputs of a crop system. A benefit of the N balance approach is that it integrates the complex dynamics of N in the crop-soil system and captures the beneficial effects of N additions for achieving crop yield, as well as the potential for losses. An N balance approach has been used to quantify best management for cereals and estimate losses (Tei et al. 2020; Bohman et al. 2021; Tamagno et al. 2022) but this hadn't been applied to a similar extent in vegetables. The SVS programme filled this gap.

In Workstream 1 (Figure 1) PFR measured the different components of a crop system in replicated experiments to quantify a varied N fertiliser rate effect on the N balance. The Workstream 1 trials were set up as rotations – because the N history of a crop can affect the subsequent crop.

There were two main objectives from the data acquired through Workstream 1:

1. Determine the N balance and its response to applied N fertiliser rates. This is necessary to understand how the overall system is functioning, and what the balance – and potential losses – can be given N management decisions.

2. Quantify the growth and N uptake curves of different crops. These are integrators of N movement within the system, given interactions of climate. This data helped our understanding of how the N balance functions given different management conditions and how management options might improve outcomes.

The data obtained in Workstream 1 provided a retrospective view of factors affecting the N balance. However, decisions on fertiliser rate and timing need to be made before the crop goes in the ground and therefore a prospective – forward looking – N balance is needed. The only way to achieve this was by modelling the soil-crop N system, this being the focus of Workstream 3 (Figure 5). Models of N uptake for different vegetable crops were developed in this workstream and the model of nitrate leaching losses developed in Workstream 3 was refined based on Workstream 1 data, with these feeding into the SVS Tool developed in Workstream 3.

2.2 Methodology

Four different rotations were established in Workstream 1, consisting of different crops chosen together with growers and agronomists (the SVS Technical Panel) to represent key crops where information was most needed. These rotations were grown at the research farms of PFR in Canterbury (Lincoln) and Hawke's Bay (Havelock North); details of crops and sowing dates are shown in Table 3 and in Figure 7.

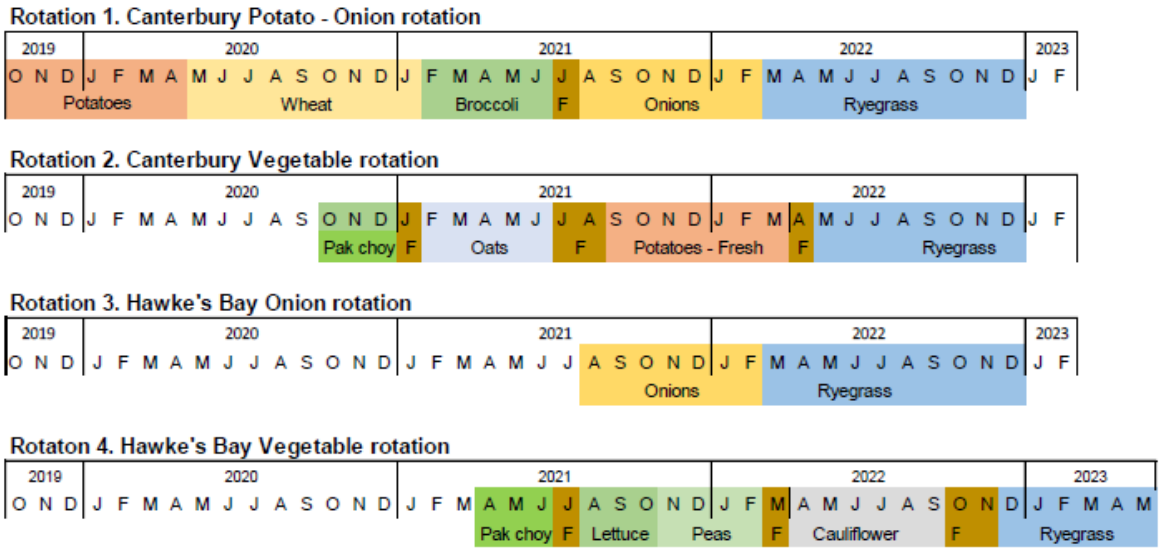


Figure 7. Rotations and crops grown in Workstream 1.

Each rotation consisted of four rates of N fertiliser and two rates of irrigation, replicated four times. This resulted in a total of 32 plots in each rotation (128 plots in total across all four rotations). Each experiment was set with a split-plot design, with irrigation rate as the main plot and N rate as the sub-plot. The aim of the irrigation treatments was to provide an irrigation rate at which yield was not compromised. For this, irrigation was applied to ensure that soil moisture deficit would not trigger yield reduction, and this depends on crop type. The irrigation 1 treatment aimed to ensure that there was little to no drainage, and so irrigation was applied to replace lost water to a deficit of 15–20 mm below field capacity. This also accommodated for potential rainfall events during the season. The irrigation 2 treatment ensured that additional irrigation was applied, so that the deficit sat close to field capacity and thus increased the likelihood of drainage.

The N fertiliser rates varied from crop to crop (Table 3) and depended on the supply from soil mineral N and mineralisable N, which were measured at planting. One aim was to ensure that the N3 treatment reflected what was considered to be a good management rate. This rate was determined with input from the SVS Technical Panel, and by consulting literature and tools (e.g., Potato Calculator, Nutrient Management Handbook for Vegetables) that provided good N management fertiliser rates. The number and timing of side-dressings was also confirmed with the Technical Panel. In some cases, where soil N supply was sufficient that very low rates of additional fertiliser were needed, the aim of the N treatments was to have enough spread of N to provide useful data on N uptake and losses from the system for modelling purposes. Each N treatment plot remained consistent across the duration of the rotation – hence a N3 plot (Good Management Practice) consistently received the N3 treatment rate for all crops.

Table 3. Crop general information for Workstream 1 rotations. Data shown include variety, sowing date, and amount of nitrogen (N) fertiliser (kg/ha) applied. Multiple side-dressing applications of the N fertiliser are indicated by "/".

Crop	Variety	Sow date	Nitrogen treatment			
			N1	N2	N3	N4
Rotation 1 (Lincoln)						
Potatoes (processed)	'Russet burbank'	22/10/19	21 (21)	121 (21/25/25/25/25)	221 (21/50/50/50/50)	421 (21/100/100/100/100)
Wheat	'Catherine'	19/05/20	150 (75/75)	150 (75/75)	150 (75/75)	150 (75/75)
Broccoli	'Nobel'	03/03/21	0	30 (15/15)	60 (30/30)	120 (60/60)
Onion	'Tilbury'	07/09/21	0	60 (30/30)	120 (60/60)	140 (120/120)
Perennial ryegrass (seed)	'Nui'	06/05/22	29 (29)	74 (29/20/15/10)	119 (29/40/30/20)	209 (29/80/60/40)
Rotation 2 (Lincoln)						
Pak choy	'Shanghai'	07/12/20	0	30 (15/15)	60 (30/30)	140 (60/80)
Oats	'Milton'	02/03/21	0	0	0	0
Potatoes (fresh)	'Agria'	22/10/21	0	103 (31/31/41)	206 (62/62/82)	412 (124/124/164)
Perennial ryegrass (seed)	'Nui'	06/05/22	0	60 (15/20/15/10)	120 (30/40/30/20)	240 (60/80/60/40)
Rotation 3 (Hawke's Bay)						
Onion	'Tilbury'	07/12/20	0	30 (15/15)	60 (30/30)	140 (60/80)
Ryegrass	50:50 mix of 'Asset' and 'Tama'	02/03/21	0	0	0	0
Rotation 4 (Hawke's Bay)						
Pak choy	'Shanghai'	07/12/20	0	30 (15/15)	60 (30/30)	140 (60/80)
Lettuce	'Contessa'	02/03/21	0	0	0	0
Peas	'Ashton'	22/10/21	0	103 (31/31/41)	206 (62/62/82)	412 (124/124/164)
Cauliflower	'Casper'	06/05/22	0	60 (15/20/15/10)	120 (30/40/30/20)	240 (60/80/60/40)

Crop biomass was sampled monthly following the date of crop sowing. Sample area was adjusted depending on crop type; for instance, for the wheat crop a 0.5 m^2 quadrat defined the sample area, while for the broccoli crop a 1 m length of bed was sampled. For the final harvest, the sample area was doubled in size; biomass collected at this stage was partitioned into above ground canopy, marketable and residue components. After recording fresh and dry weights, samples were sent to the laboratory for analysis of N content. Preliminary yield data are summarised in Table 3.

From these data, the total amount of N taken up by the crop, and the amount in marketable yield and crop residue was calculated. These are all important parts of the N flow within a crop system.

Soil mineral N samples were collected from six depths at the start and end of each crop. These were: 0–15, 15–30, 30–60, 60–90, 90–120 and 120–150 cm. During crop growth, samples were collected monthly to a depth of 120 cm to coincide with biomass samples. At each sample time, two cores per depth were collected in each plot.

Additional samples were collected prior to planting from the 0–15 cm depth for basic nutrient analysis to help determine the need for additional nutrients such as phosphorus (P) and potassium (K). Prior to planting, soil samples from 0–15 and 15–30 cm depths were also collected and analysed for soil mineralisable N (using the PMN test), and the results were used to calculate the amount of N that could potentially become available during the season.

Soil bulk density was measured at intervals to a depth of 15 cm at the start of each rotation and was measured once during crop growth to a depth of 0–15 and 15–30 cm. These values are used to convert mineral N concentrations to kg N/ha in the soil.

Soil water content was measured weekly to fortnightly in each plot. In the top 20 cm, this was done using two Time Domain Reflectometer guide rods (TDRs) per plot – one measurement within the planting row and one between rows. Soil water content at further depths (20–40, 40–60, 60–80, 80–100, 100–120, 120–140, and 140–160 cm) was measured with a neutron probe.

2.3 Results

The data collected through Workstream 1 allowed PFR to calculate the N balance for each crop under each treatment. The N balance is the difference between all the inputs and outputs of N within the crop-soil system.

Inputs to the N balance

Soil mineral-N at start of growth. This is an indication of N that is immediately available to the crop for growth once sown and is important in helping determine N requirements for a crop (McLellan et al. 2018; Tei et al. 2020; Tamagno et al. 2022). PFR collected soil N at depths of 0–15, 15–30, 30–60, 60–90, 90–120 and 120–150 cm. Most balances use a depth of 30 cm as deeper samples are not easily or routinely collected from fields. A question is to what depth the soil N should be measured upon which the balance is based.

Soil mineralisable N. This is a measure of the N that will be released from the soil via mineralisation. PFR used the PMN test to calculate how much N is made available during the life of the crop via soil organic matter mineralisation. Samples have been gathered to a depth of 30 cm as there is little mineralisation below these depths.

Previous crop residues. For the first crop of each rotation, PFR estimated this from knowledge of the crop and previous recorded values of residue concentrations. Otherwise, PFR used measured values of N content and biomass to estimate total N uptake of residue component of the crop.

Fertiliser N applied. For each crop, a good management practice rate (N3 treatment) was determined based on information from the Vegetable Nutrient Management handbook (Reid & Morton 2019) and input from agronomists (SVS Technical Panel).

Outputs from the N balance

Exported N. This is the amount of N that leaves the field as sold yield.

Residue N. This is the amount of N that remains in the field after harvest; it is crop material that is non-marketable and returned to the soil before the subsequent crop is sown.

Estimating exported and residue N requires measurement of the biomass dry weight of each component of the crop and the N% of that biomass. These are not routinely measured in commercial practice, and so any tool that predicts the N balance needs to predict these components. This requires understanding the biomass growth curve, the proportions of crop partitioned to each component, and parameters describing dry matter percentage and N%.

Soil mineral-N at harvest. An indication of how much N is left behind after the crop. It is unclear as to what a target level for soil N at harvest might be; high values increase the risk of loss during any fallow period/early development of subsequent crop (Verhagen & Bouma 1998), while very low values may compromise soil function and growth of the following crop.

Uncharacterised N. This is the amount of N that could be lost during the crop growth period, and it assumes that there is a mass balance of N in the system. This portion of N is made up of nitrogen that may have moved in water flow to below the 30 cm soil layer, or nitrogen that may be gaseous emission from the soil surface. Here we are interested in estimating what the unaccounted-for N may be, given different N rates and crops, and what factors may affect it. The value is estimated as:

Uncharacterised N = Total N inputs − Total N outputs

The framework used for estimating the N balance (the value of Uncharacterised N) is shown in Figure 8. The estimated outputs are separated into N exported from the field as sold yield, and N remaining in-field. The in-field N is further separated into N remaining in the soil after harvest, N in residue, or potentially lost N (uncharacterised).

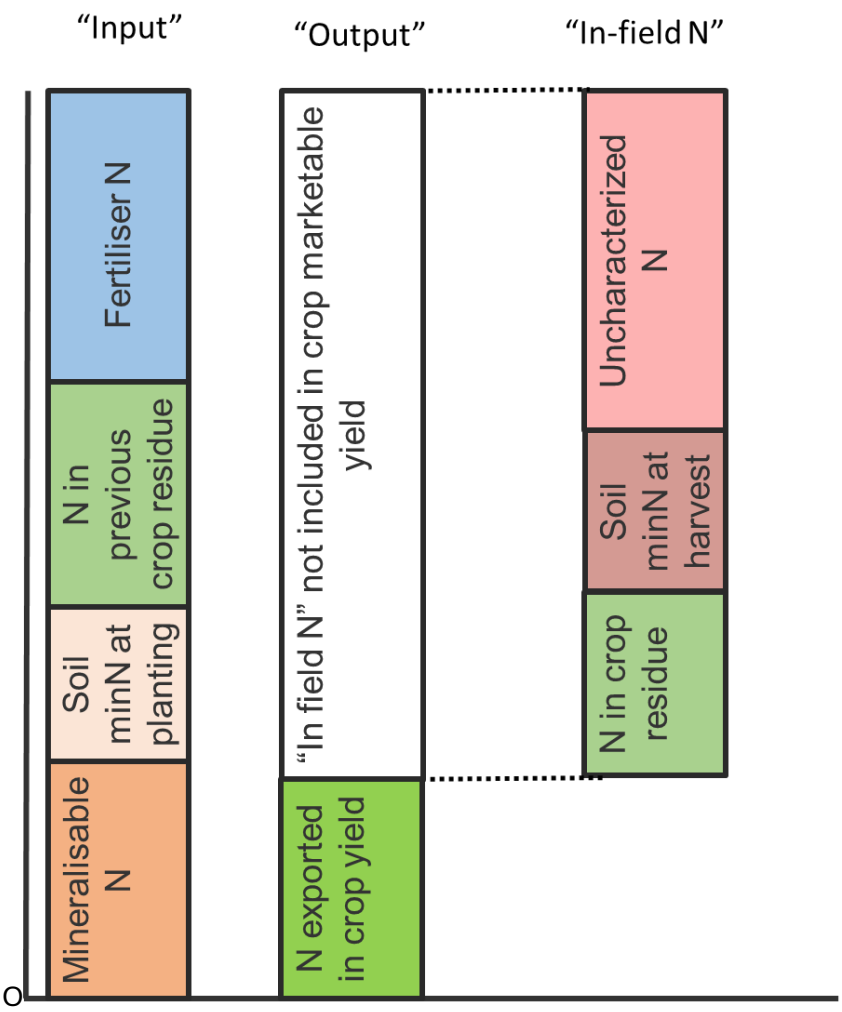


Figure 8. Framework for nitrogen (N) balance calculation.

2.3.1 Rotation 1

Mineral N change and Potential Environmental N Loss (Uncharacterised N)

To interpret the N balance, it is useful to understand soil mineral-N movement during the rotation. To graphically display this, we envisioned nitrate movement along depth and distance of time – this creates a 'spatial map' in depth and time of soil nitrate concentrations across the rotation. PFR used a standard inverse distance weighting algorithm in R (Singh & Soman 2020) to determine points in the depth and time axes. The resulting plots of soil nitrate-N in the top 90 cm for the different N rates of Rotation 1 are shown in Figures 9–12.

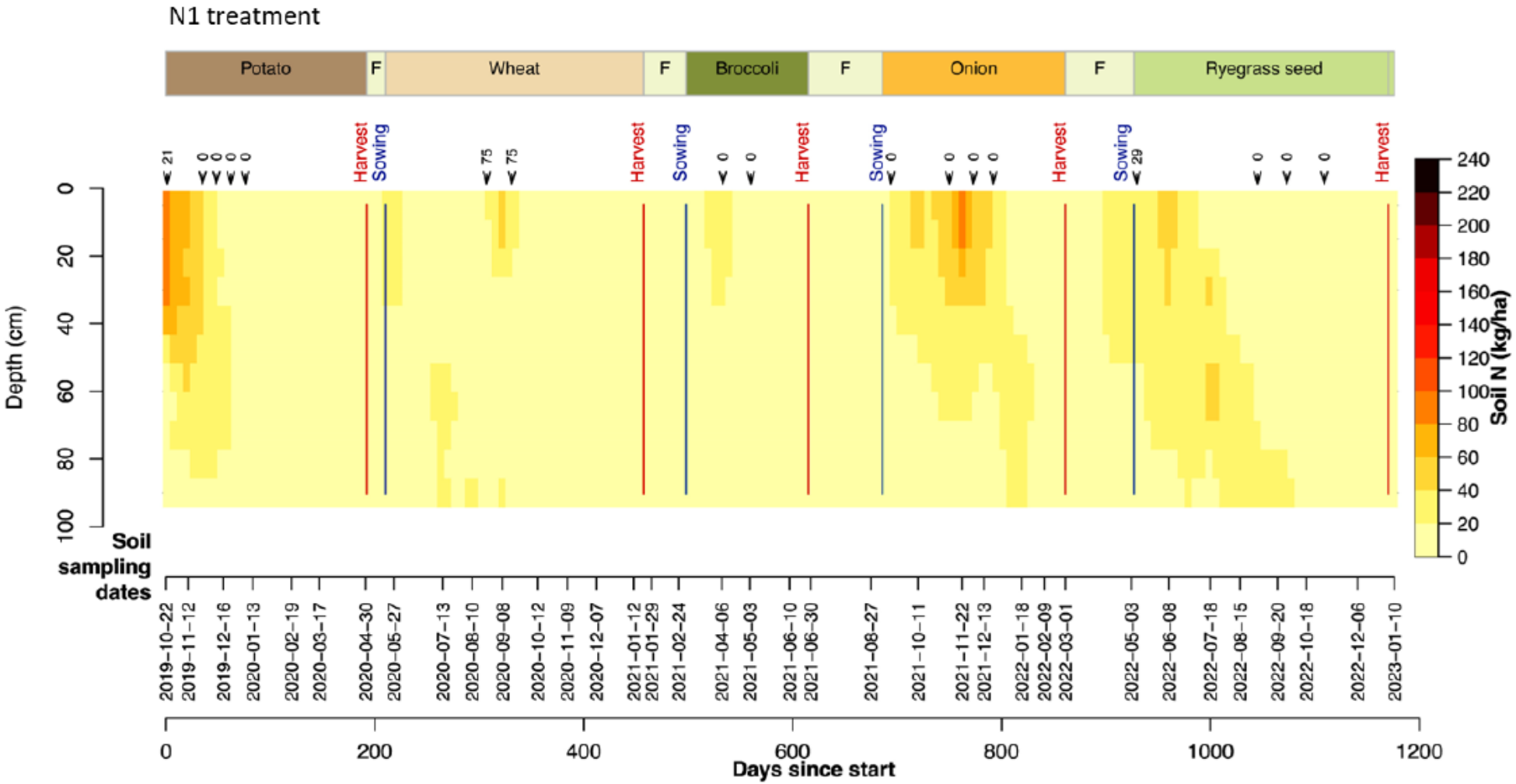


Figure 9. N1 treatment soil nitrate-nitrogen (N) interpolation plot to a soil depth of 90 cm across Rotation 1 sown at The New Zealand Institute for Plant and Food Research Limited (PFR), Lincoln, Canterbury. Upper arrows represent N fertiliser application dates and amounts for the different crops in the rotation. The period between harvest and sowing of the subsequent crop is fallow period (F).

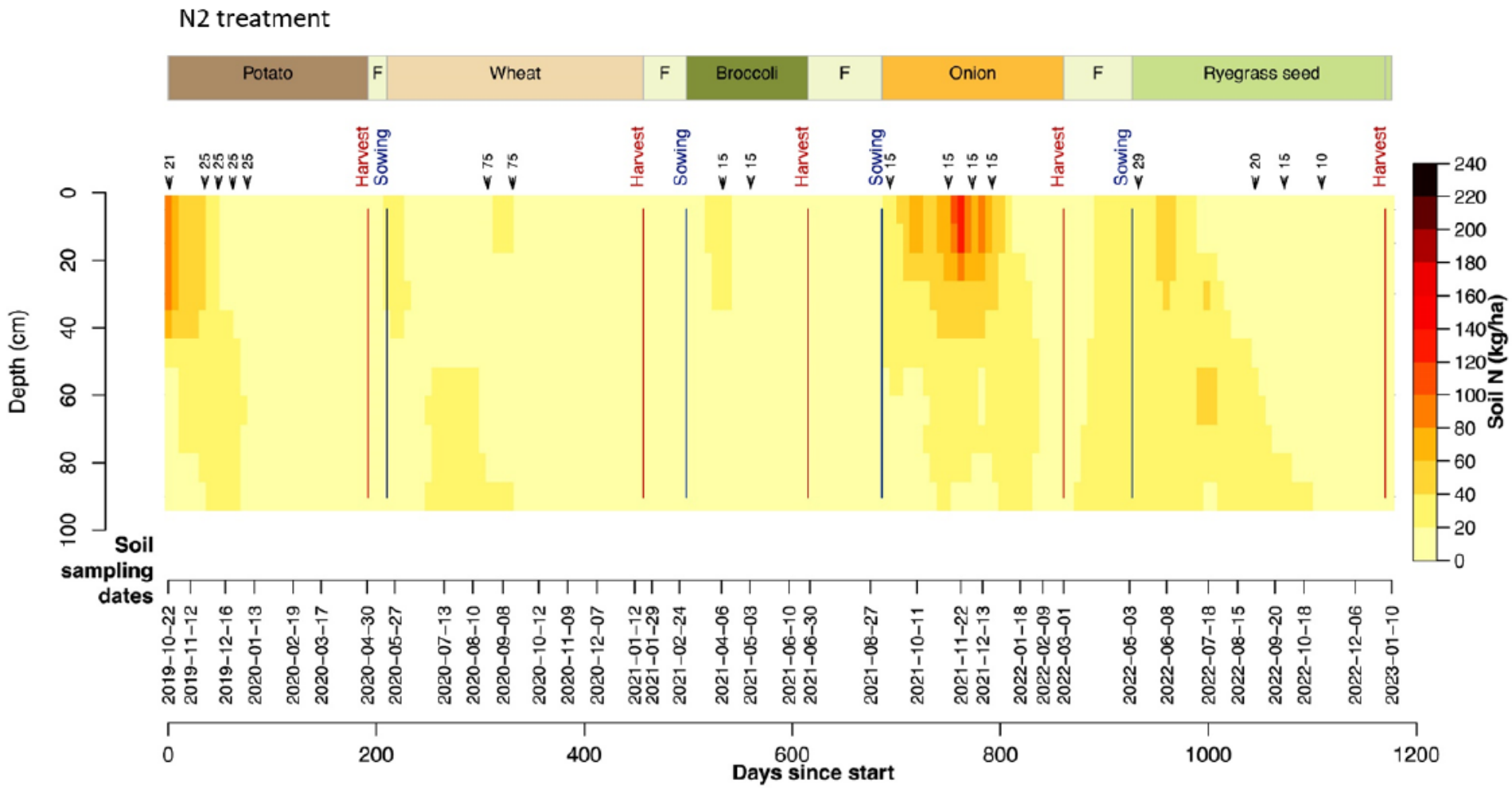


Figure 10. N2 treatment soil nitrate-nitrogen (N) interpolation plot to a soil depth of 90 cm across Rotation 1 sown at The New Zealand Institute for Plant and Food Research Limited (PFR), Lincoln, Canterbury. Upper arrows represent N fertiliser application dates and amounts for the different crops in the rotation. The period between harvest and sowing of the subsequent crop is fallow period (F).

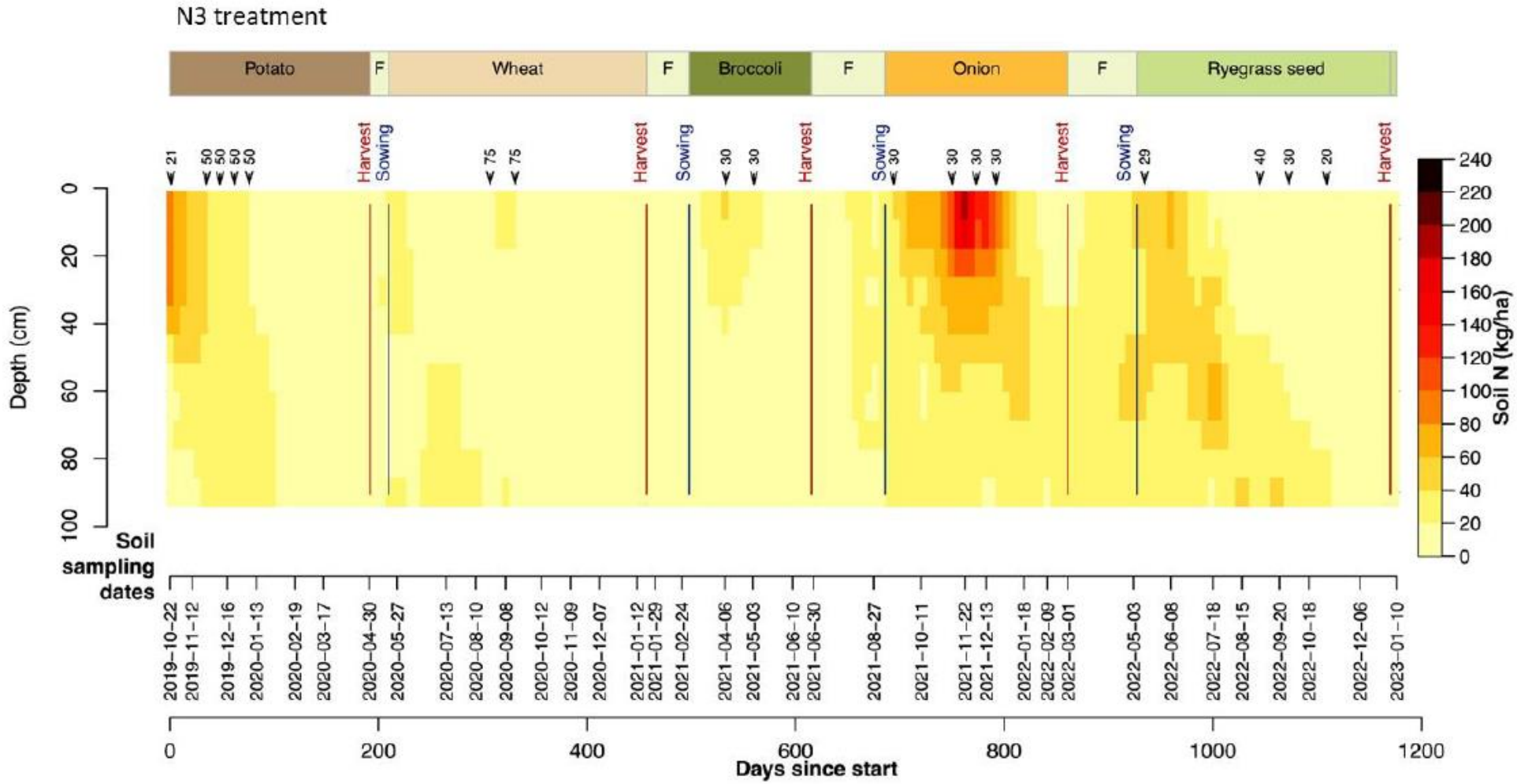


Figure 11. N3 treatment soil nitrate-nitrogen (N) interpolation plot to a soil depth of 90 cm across Rotation 1 sown at The New Zealand Institute for Plant and Food Research Limited (PFR), Lincoln, Canterbury. Upper arrows represent N fertiliser application dates and amounts for the different crops in the rotation. The period between harvest and sowing of the subsequent crop is fallow period (F).

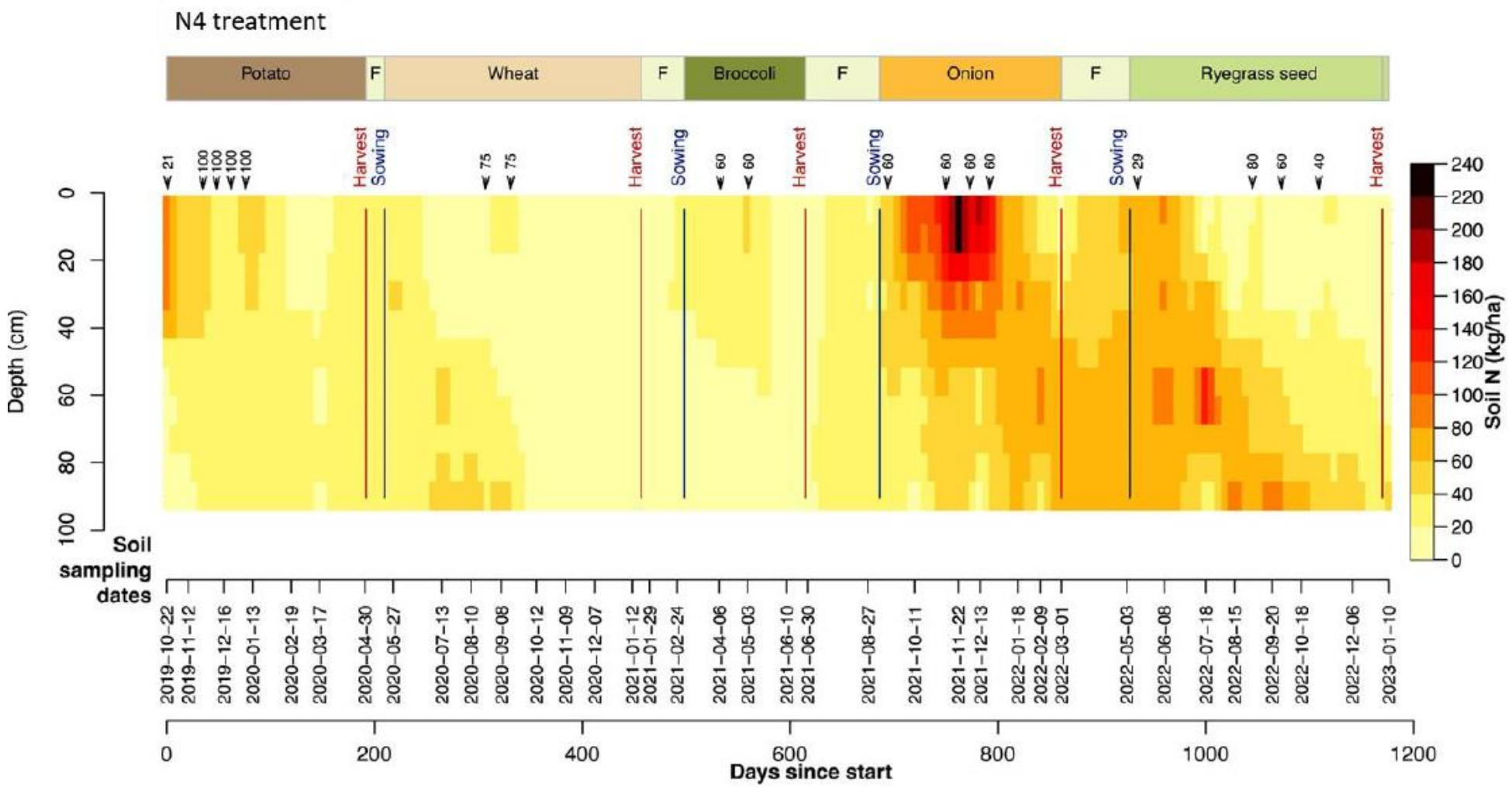


Figure 12. N4 treatment soil nitrate-nitrogen (N) interpolation plot to a soil depth of 90 cm across Rotation 1 sown at The New Zealand Institute for Plant and Food Research Limited (PFR), Lincoln, Canterbury. Upper arrows represent N fertiliser application dates and amounts for the different crops in the rotation. The period between harvest and sowing of the subsequent crop is fallow period (F).

These plots (Figures 9–12) clearly show the changes in soil mineral-N across the rotation as affected by different crops and N rate. Some general observations are:

- Soil mineral-N at depths below 30 cm increases with N rate and this is particularly noticeable in the potato, wheat, onion and ryegrass crops.
- There is an increase in soil mineral-N in the fallow period between crops. This is due to mineralisation happening within the fallow period. The SVS Tool was modified to capture this important period by extending the time series graph to include the fallow period prior to the current crop.
- The reason for leaching recorded in the wheat crop, prior to fertiliser application (Searle et al. 2022), can be seen in the plots with an increase in mineral-N below 60 cm.
- There is a large spike in soil mineral-N in the onion crop, and the intensity increases with N rate. When selecting the fertiliser rate for onion, it was decided not to include the broccoli residue being returned, as there was uncertainty of when, and how much, would be available. The spikes in mineral-N correspond with the amount of N in the broccoli residue if N from both soil organic matter mineralisation and fertiliser application is accounted for (Searle et al. 2021).
- The rate of decomposition of broccoli residue in the onion crop appears to vary with N rate – occurring later in the N1 treatment (Figure 9) compared with the N4 treatment (Figure 12). This illustrates the importance of residue of previous crops for N management.
- The mineral-N values of the soil reflect the input-output parts of the N balance, with accumulation of soil N at depths greater than 60 cm indicating an oversupply of N for the crop.
- Soil mineral-N is high at 60 cm in both the potato and onion and particularly at the N4 treatment. This suggests that the mineral-N content at depths of 30 or 60 cm may give different N balances for these crops.

PFR estimated the N balance for soil mineral-N input and output from 0–30 and 0–60 cm depths and plotted Uncharacterised N in response to N treatment. An analysis of variance (ANOVA via Genstat, VSN International Ltd [2022]) was also conducted to see if calculating the N balance using N from different soil depths resulted in different Uncharacterised N outcomes (Table 4). This analysis indicated that irrigation had no effect on the N balance in these crops, and so the data reported focus on N responses.

The results from Table 4 indicate that:

- Uncharacterised N increases significantly ($p<0.001$) with N rate in potato, broccoli, and onion, and this is regardless of soil depth used for estimating the contribution of soil mineral-N to inputs and outputs.
- In contrast, Uncharacterised N decreased significantly ($p<0.01$) with N rate in wheat, from a maximum average Uncharacterised N of 64 kg N/ha with the N2 treatment to 22 kg N/ha with the N4 treatment when calculated using soil mineral-N in the top 30 cm of soil. The trend was similar when using the top 60 cm of soil but not significant.
- The depth of soil mineral-N contribution to the N balance calculation had no effect in broccoli regardless of N treatment. In wheat, there was a greater Uncharacterised N at the N4 treatment when calculated with soil mineral-N to a depth of 60 cm compared with 30 cm depth. In potato, Uncharacterised N was greater at all N treatments when calculated

based on soil mineral-N to a depth of 60 cm. Root depth could be an important contributor to this, but it also seems there is a complex interaction between crop uptake and variations in soil N supply.

Given that most of the mineral-N is in the top 30 cm (55–88%, depending on stage in Rotation 1), and that most of the roots involved in uptake are in the top 30 cm of soil (Kristensen & Thorup-Kristensen 2007), and that the Uncharacterised N response to N rate has the same pattern regardless of depth, it is possible to calculate the N balance with soil N depths to 30 cm. This also has an added advantage of a sampling depth more easily fitted into routine commercial practice. There is significant variation in the Uncharacterised N at each N rate regardless of crop; for example, the value of Uncharacterised N values at N3 for potato are 98 kg N/ha. There was no significant correlation between variation in Uncharacterised N and variation in initial mineral-N in the soil (Pearsons r = 0.03, p=0.213).

Table 4. Statistical significance of nitrogen (N) rate at 30 and 60 cm on mean Uncharacterised N for potato, wheat, broccoli and onion crops of Rotation 1, and significance of difference between depths at each N rate. The LSD (p=0.05) is a measure of a significant difference between means at the 5% level.

Crop	Potato		Wheat		Broccoli		Onion	
Soil depth of mineral-N supply (cm)								
N rate	30	60	30	60	30	60	30	60
1	8.4	94.1	52.3	62.7	2.5	4.0	2.9	2.2
2	45.8	117.8	63.8	77.0	15.3	15.8	49.6	42.3
3	91.7	166.0	35.8	45.6	18.9	17.4	121.8	90.1
4	182.1	220.7	21.6	55.9	76.0	69.8	231.2	183.8
N sig. (p)	<0.001	<0.001	<0.001	NS	<0.001	<0.001	<0.001	<0.001
N LSD (p=0.05)	32.9	37.9	25.8	35.7	21.8	23.5	32.3	40.7
Depth sig. (p) at each N rate								
1	<0.001		NS		NS		NS	
2	<0.001		NS		NS		NS	
3	<0.001		NS		NS		NS	
4	0.026		0.024		NS		0.009	
Depth LSD (p=0.05)	33.8		29.7		21.3		34.9	

The Uncharacterised N level at the different N rates varies with crop. For instance, in the N3 treatment, Uncharacterised N of potato is 92 and onion 122 kg N/ha. These are higher than the Uncharacterised N of 36 and 19 kg/ha for wheat and broccoli. These Uncharacterised N levels are not just a function of applied N fertiliser rate – for instance the N3 fertiliser rate for wheat was 150 kg N/ha and that of onions 120 kg N/ha – but despite a 30 kg N/ha difference in N rate, there was an 86 kg N/ha difference in Uncharacterised N. Clearly, there is a crop effect on Uncharacterised N that may be associated with root depth activity and growth characteristics, or differences in previous crop residue decomposition.

Nitrogen balances

The calculated N balance for each crop is shown in Figures 14–18.

The N remaining in-field is the difference between the total N inputs and that exported in sold product. This in-field N is split into the portion that remains in the soil as mineral-N at harvest, the residue component of the crop, and the remainder which is the Uncharacterised N.

The N uptake characteristics of the crop are an important driver of the Uncharacterised N. General observations of the crops are:

- Exported N of the potato crop (Figure 14) accounted for 57% of the total N input on average for treatments N1 to N3. At the N4 treatment, exported N accounted for 48% of the total N input. The amount of N found in residue accounted for 59% of the in-field N at the N1 treatment and dropped to 18% at the N4 treatment, while the residual soil N only reduced from 34% to 23% of in-field N. The Uncharacterised N increased from 7% of the in-field N at the N1 treatment to 59% at the N4 treatment.
- In contrast, the exported N in wheat (Figure 15) was relatively constant and averaged 59% of total N input. Of the in-field component, the residual soil N was also relatively constant and was less than 11%. The residue N increased from 46% at the N1 treatment to 72% with the N4 treatment, while Uncharacterised N portion decreased from 45% to 16% of the in-field N.
- The exported N component of broccoli (Figure 16) was much lower than potato or wheat, starting at 22% of total N at the N1 treatment, and reducing to 11% at the N4 treatment. The residue component also decreased from 85% of the in-field N at the N1 treatment to 58% at the N4 treatment, while the Uncharacterised N increased from 3 to 25%. The large residue component reflects the different crop characteristics of a large canopy with a small, harvested component.
- In the onion crop (Figure 17) the exported N component was 62% of all N in the system at the N1 treatment, and this reduced to 28% in the N4 treatment, a much larger decrease than observed in the potato crop (Figure 14). Uncharacterised N was 57% of in-field N at the N1 treatment, starting higher than the broccoli or potato crop and similar to the wheat. At the N4 treatment Uncharacterised N increased to 80% of the in-field N of the system.

These results indicate that the N balance is a crop-specific result and depends on the way the crop takes up and uses N. The Uncharacterised N component of the in-field N for onion at the N1 treatment (no fertiliser added) was much higher than that for the broccoli and potato crop.

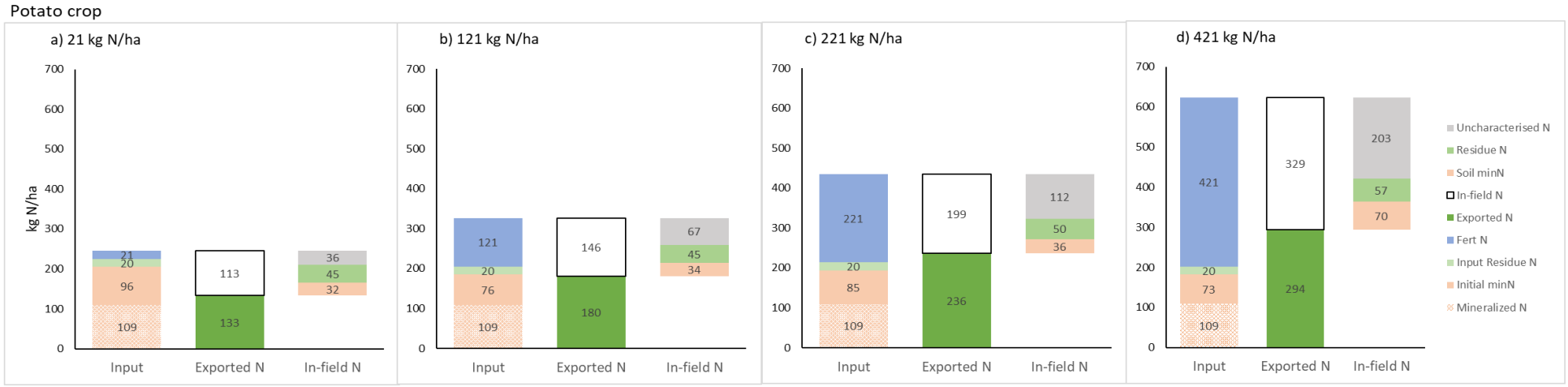


Figure 14. Nitrogen (N) balance of potato crop from Rotation 1 at different N rates. Potato crop was the variety 'Russet Burbank' sown on 22 October 2019 at The New Zealand Institute for Plant and Food Research Limited(PFR), Lincoln, Canterbury.

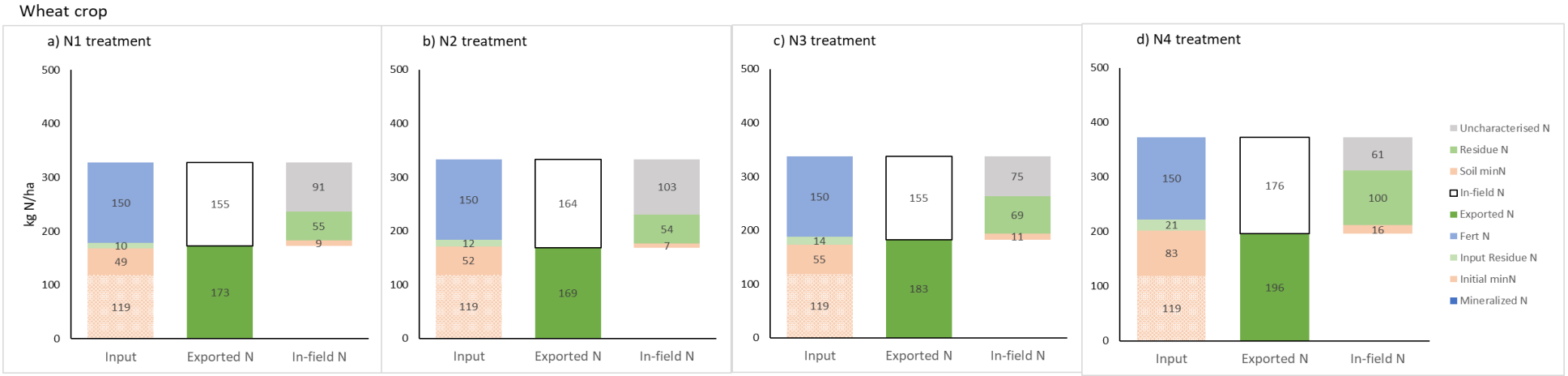


Figure 15. Nitrogen (N) balance of wheat crop from Rotation 1 at different N rates. Wheat crop was the variety 'Catherine' sown on 19 May 2020 at The New Zealand Institute for Plant and Food Research Limited (PFR), Lincoln, Canterbury.

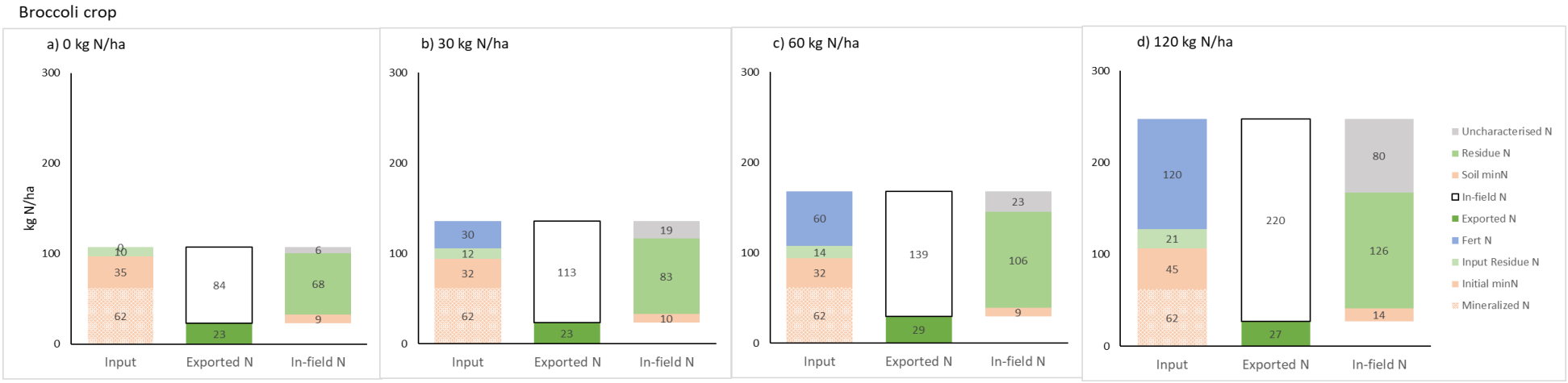


Figure 16. Nitrogen (N) balance of broccoli crop from Rotation1 at different N rates. Broccoli crop was the variety 'Nobel' transplanted on 3 March 2021 at The New Zealand Institute for Plant and Food Research Limited (PFR), Lincoln, Canterbury.

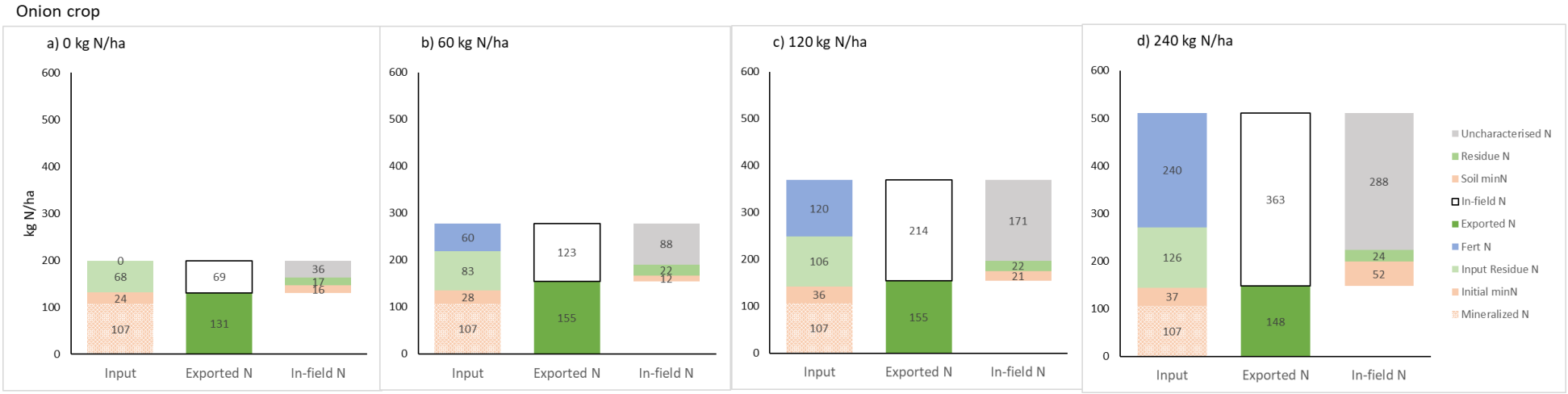


Figure 17. Nitrogen (N) balance of onion crop from Rotation 1 at different N rates crop. Onion crop was the variety 'Tilbury' sown on 7 September 2021 at The New Zealand Institute for Plant and Food Research Limited (PFR), Lincoln, Canterbury.

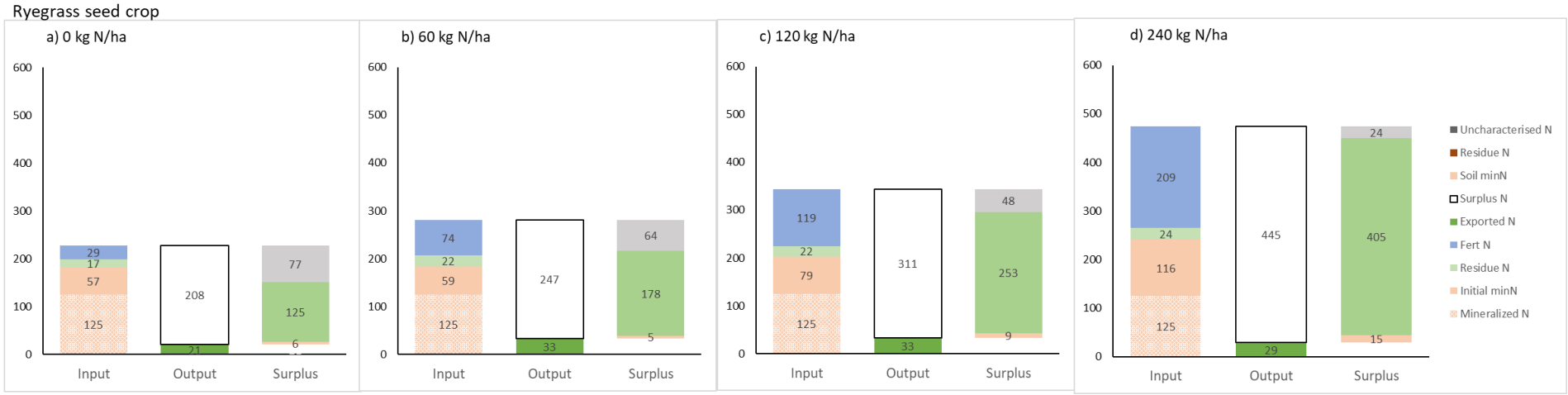


Figure 18. Nitrogen (N) balance of onion crop from Rotation 1 at different N rates crop. Ryegrass crop was the variety 'Nui sown on 6 May 2022 at The New Zealand Institute for Plant and Food Research Limited (PFR), Lincoln, Canterbury.

2.3.2 Rotation 2

Mineral N change and Uncharacterised N

The plots of interpolated soil mineral-N to depths of 90 cm for Rotation 2 are shown in Figures 19-22. Results show:

- There were relatively high concentrations of soil mineral-N in the top 40 cm for the pak choy crop. Adding N fertiliser increased the concentration of N and seemed to move it to lower depths, particularly towards the end of the pak choy crop in the N4 treatment.
- There was an increase in soil mineral-N during the fallow period and before the oats were sown after the pak choy. This is most likely due to soil N mineralisation. In the N4 treatment, there was a marked spike in soil mineral-N before sowing of the oats due to a combination of high residual N at pak choy harvest and the soil N mineralisation occurring during the fallow period. The increase in mineral-N was also observed in the other fallow periods.
- The oats crop was sown into high mineral-N soil, but it used the N even to depths of 90 cm, as evidenced by the changes observed in the N4 treatment (Figure 22).
- For treatments N1 to N3 of the potato crop, the crop used the mineral-N available in the top 30 cm. In N3, considered best management practice treatment, soil N supply is well maintained throughout most of the life of the crop. The N rate for the N3 treatment of the potato crop was decided on using the prototype model developed in Workstream 3. Then, in the field, nitrate test strips were used to determine actual soil nitrate-N content, and these were used to make final decisions on fertiliser N rate. Consequently, an additional 20 kg N/ha was applied at the last side-dressing. This approach seemed to match supply with crop demand reasonably well compared with the potato crop in Rotation 1 (Figure 14) where soil mineral N was below 20 kg N/ha at each depth for a large portion of crop growth.
- There was an increase in mineral-N in the fallow period before the ryegrass seed crop, and this continues after the crop is sown, even in the N1 treatment, where no fertiliser was applied. This increase could be due to ongoing mineralisation, but the increasing intensity at the N4 treatments suggests it might be residues from the fresh potato crop, where the canopy was terminated prior to full senescence.

Uncharacterised N was estimated using N from the top 30 and 60 cm of soil (Table 5). There were no significant differences in Uncharacterised N with N rate when estimated using N from the top 60 cm of soil (Table 5). These results corroborate results from Rotation 1, suggesting that the calculation of N balance using the top 30 cm of soil can provide a useful indicator of the N balance of a crop.

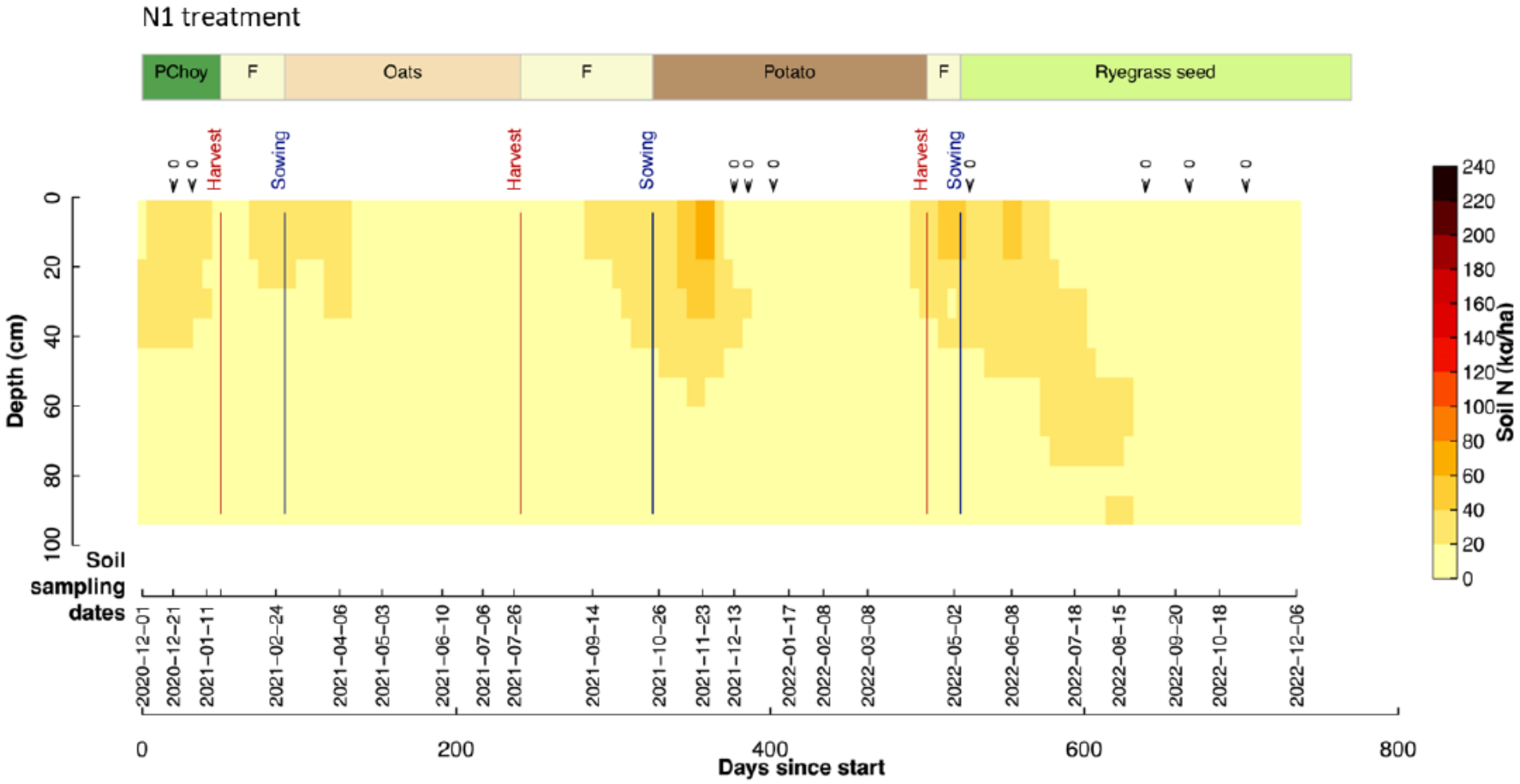


Figure 19. N1 treatment soil nitrate-nitrogen (N) interpolation plot to a soil depth of 90 cm across Rotation 2. Upper arrows represent N fertiliser application dates and amounts for the different crops in the rotation. The period between harvest and sowing of the subsequent crop is fallow period (F).

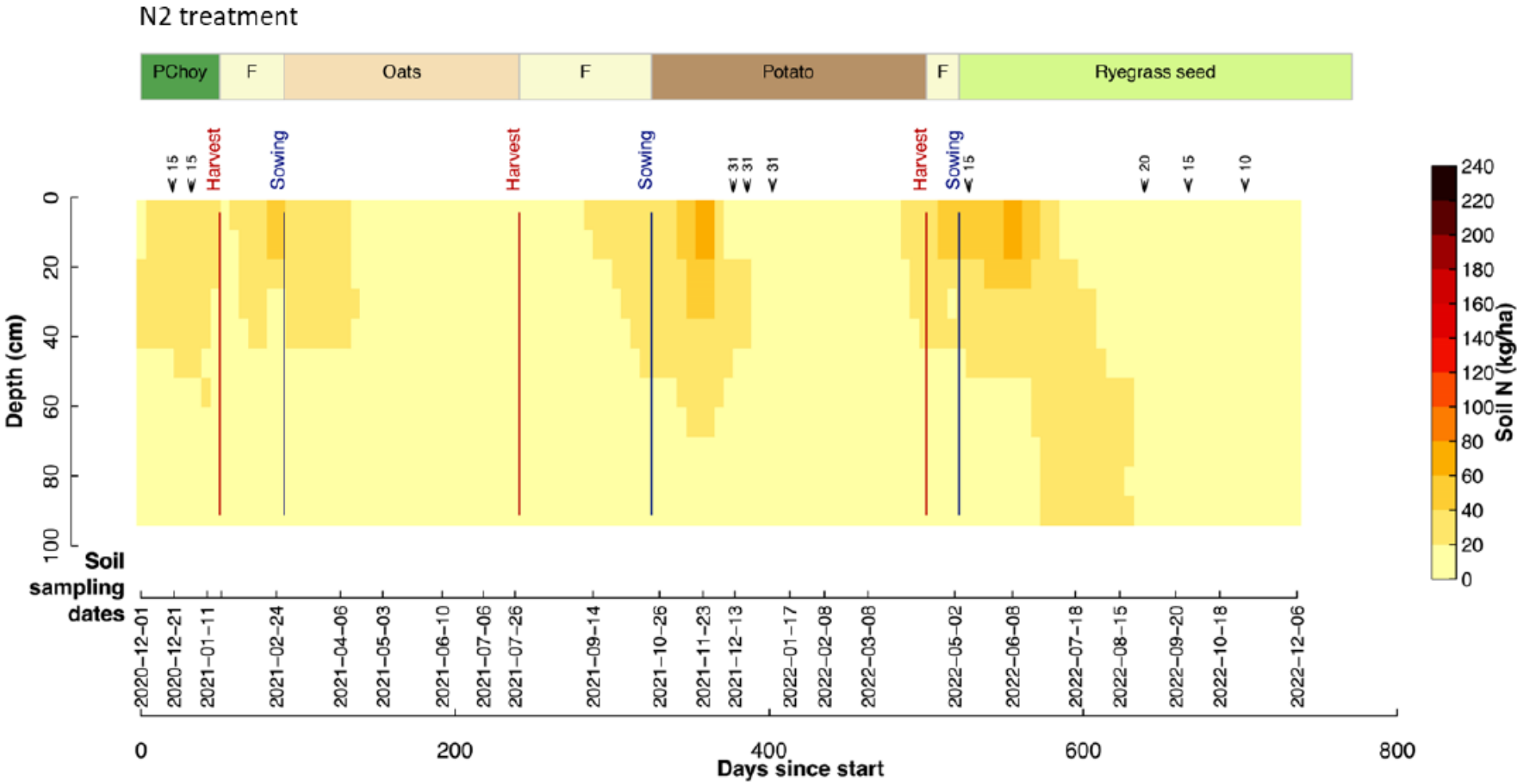


Figure 20. N2 treatment soil nitrate-nitrogen (N) interpolation plot to a soil depth of 90 cm across Rotation 2. Upper arrows represent N fertiliser application dates and amounts for the different crops in the rotation. The period between harvest and sowing of the subsequent crop is fallow period (F).

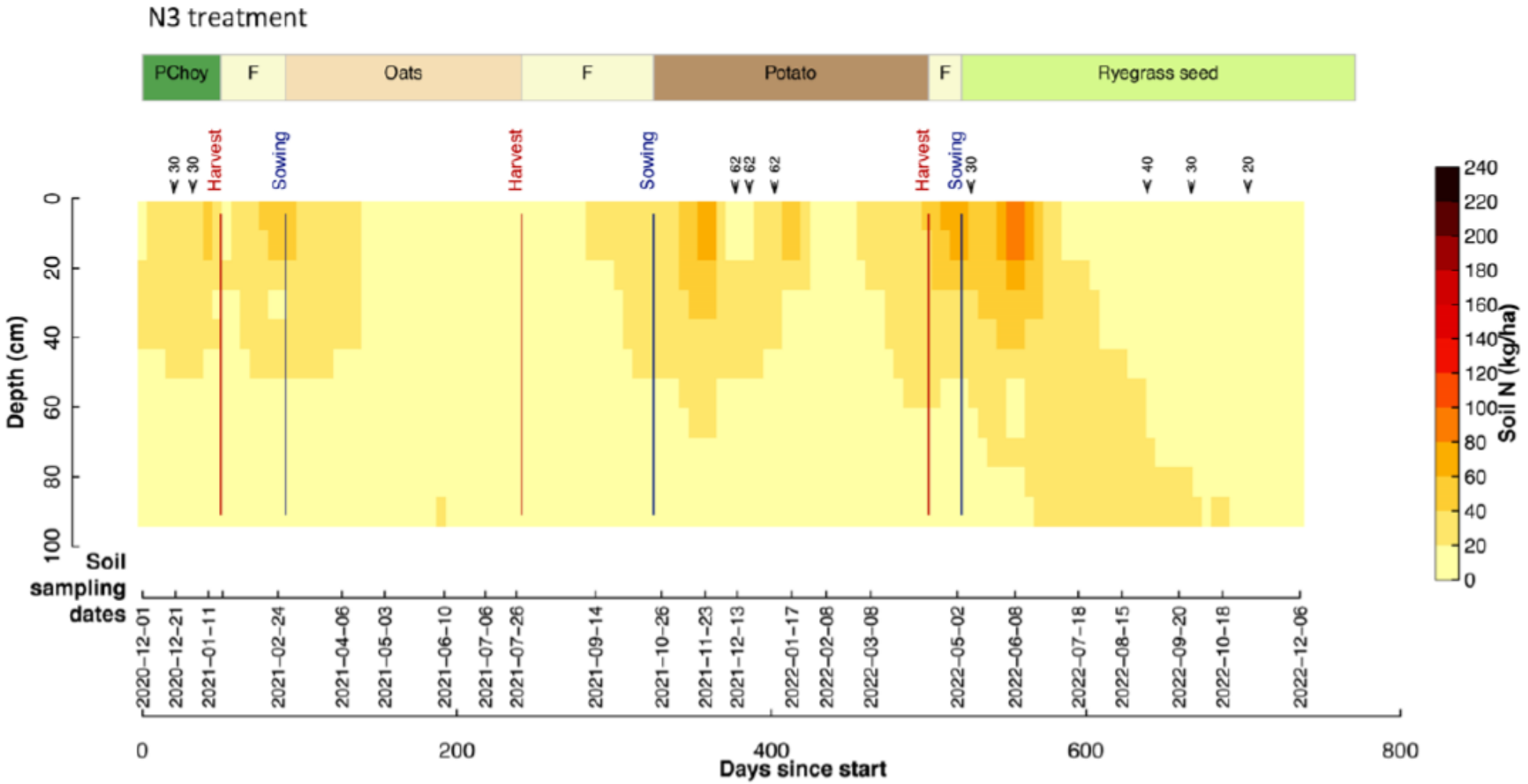


Figure 21. N3 treatment soil nitrate-nitrogen (N) interpolation plot to a soil depth of 90 cm across Rotation 2. Upper arrows represent N fertiliser application dates and amounts for the different crops in the rotation. The period between harvest and sowing of the subsequent crop is fallow period (F).

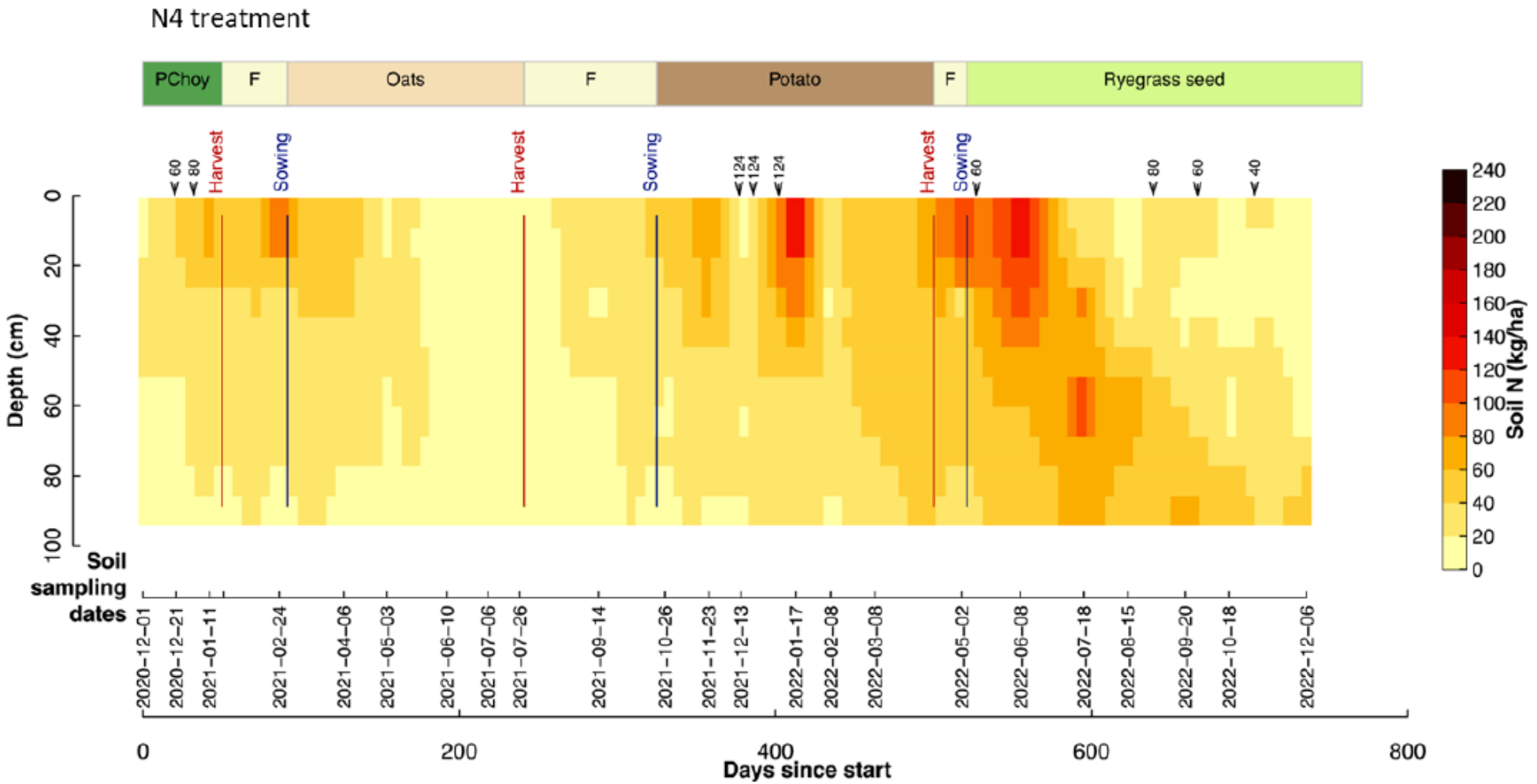


Figure 22. N4 treatment soil nitrate-nitrogen (N) interpolation plot to a soil depth of 90 cm across Rotation 2. Upper arrows represent N fertiliser application dates and amounts for the different crops in the rotation. The period between harvest and sowing of the subsequent crop is fallow period (F).

Table 5. Statistical significance of nitrogen (N) rate at 30 and 60 cm on mean Uncharacterised N (Potential Environmental Nitrogen Loss during crop growth) for pak choy, oats and fresh market potato crops of Rotation 2, and significance of difference between depths at each N rate. The LSD, least significant difference, (p=0.05) is a measure of a significant difference between means at the 5% level.

Crop	Pak Choy		Oats		Potato	
Soil depth of mineral-N supply (cm.)						
N rate	30	60	30	60	30	60
1	4.3	113.4	20.0	30.7	5.3	56.2
2	11.0	100.1	33.7	33.8	19.2	81.8
3	21.9	127.2	39.5	29.9	21.4	84.6
4	26.5	92.1	52.4	53.2	61.2	95.9
N sig. (p)	NS	NS	0.05	NS	0.03	NS
N LSD (p=0.05)	19.1	35.7	22.7	34.9	42.4	50.2
Depth sig. (p) at each N rate						
1	<0.001		NS		0.007	
2	<0.001		NS		0.006	
3	<0.001		NS		0.006	
4	<0.001		NS		NS	
Depth LSD (p=0.05)	27.8		28.4		21.3	

Nitrogen balances

The calculated N balances for pak choy, oats and fresh market potatoes are shown in Figures 23–26. Some general observations from the N balances are:

- Export N accounted for 25% of the total N input in the N1 treatment for pak choy, increased to a maximum of 52% at the N3 treatment and decreased to 42% in the N4 treatment. Up to 80% of the in-field N of pak choy was in the residue component at the N1 treatment but only 26% in the N4 treatment. At the same time the residual soil N component of the in-field N increased from 14% to 55%. The Uncharacterised N increased from 5% to 19% as N treatment increased from N1 to N4, though at N3 Uncharacterised N accounted for 30% of in-field N.
- In contrast, in oats, the export N component of the whole system decreased with N rate from 71% of all N in the system at the N1 treatment to 61% at the N4 treatment. The Uncharacterised N started much higher than in the pak choy crop, with 56% of the in-field N as Uncharacterised N at the N1 treatment compared with 5% for pak choy.
- For the potato crop in Rotation 2, export N was 66% of all N in the system at the N1 treatment and decreased slightly to 60% at the N4 treatment. The Uncharacterised N increased from 16% of in-field N to 26% with treatments increasing from N1 to N4.

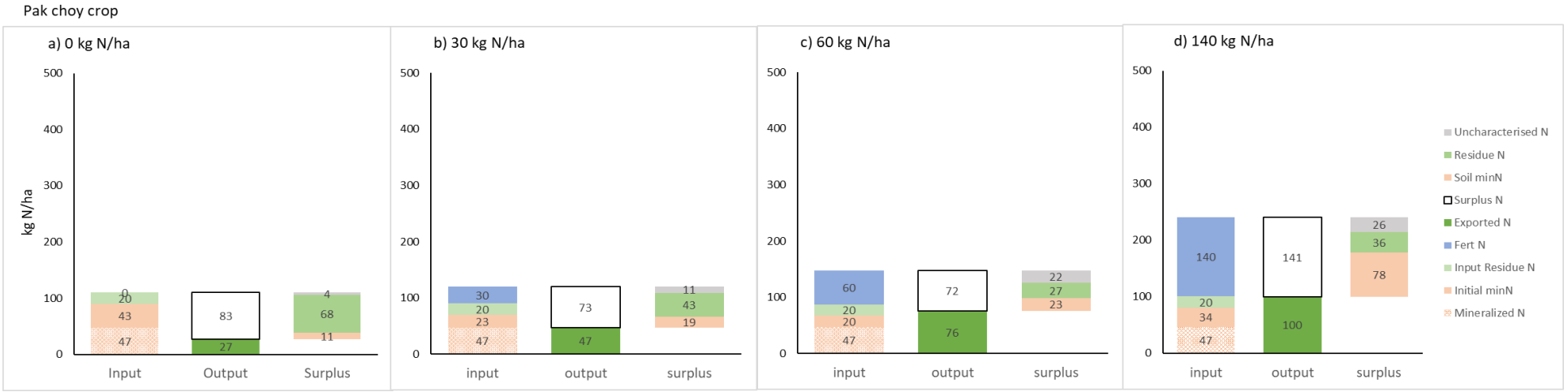


Figure 23. Nitrogen (N) balance of pak choy crop from Rotation 2 at different N rates. Pak choy crop was the variety 'Shanghai' sown on 7 December 2020 at The New Zealand Institute for Plant and Food Research Limited (PFR), Lincoln, Canterbury.

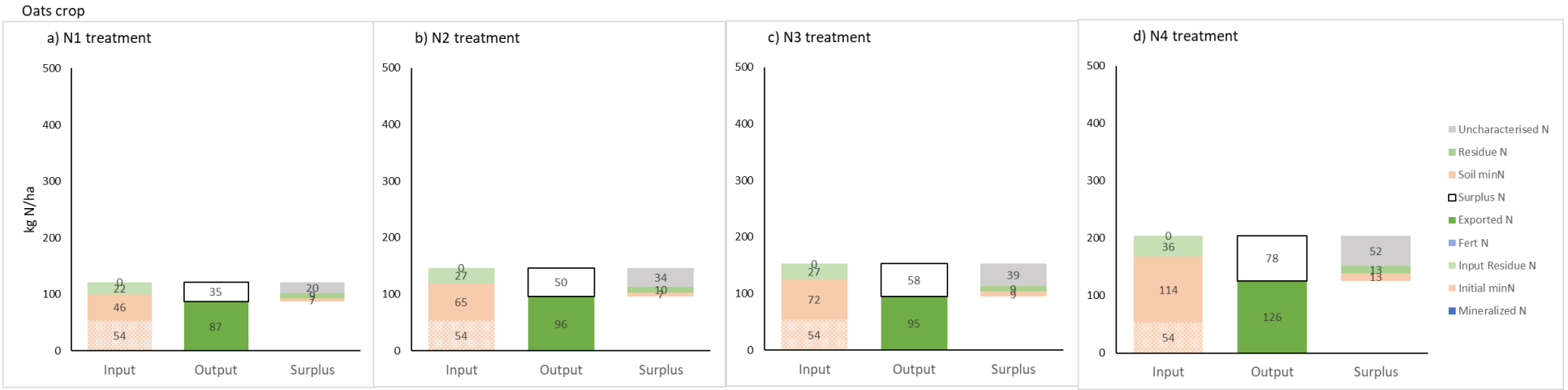


Figure 24. Nitrogen (N) balance of oat crop from Rotation 2 at different N rates. Oat crop was the variety Milton sown on 19 May 2020 at The New Zealand Institute for Plant and Food Research Limited (PFR), Lincoln, Canterbury as a catch crop.

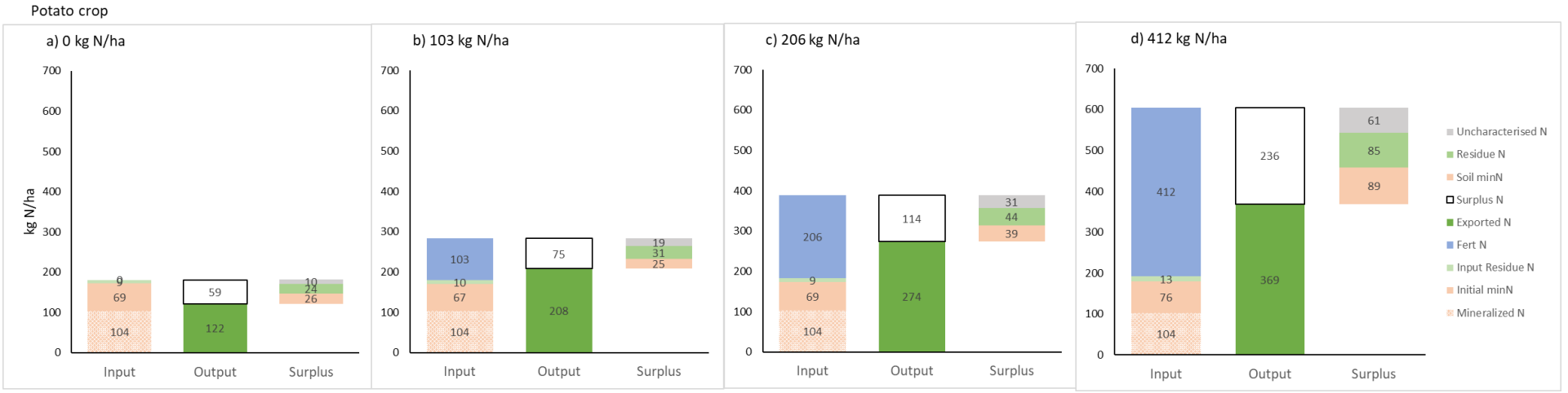


Figure 25. Nitrogen (N) balance of potato crop from Rotation 2 at different N rates. Pak choy crop was the variety 'Agria' sown on 22 October 2021 at The New Zealand Institute for Plant and Food Research Limited (PFR), Lincoln, Canterbury.

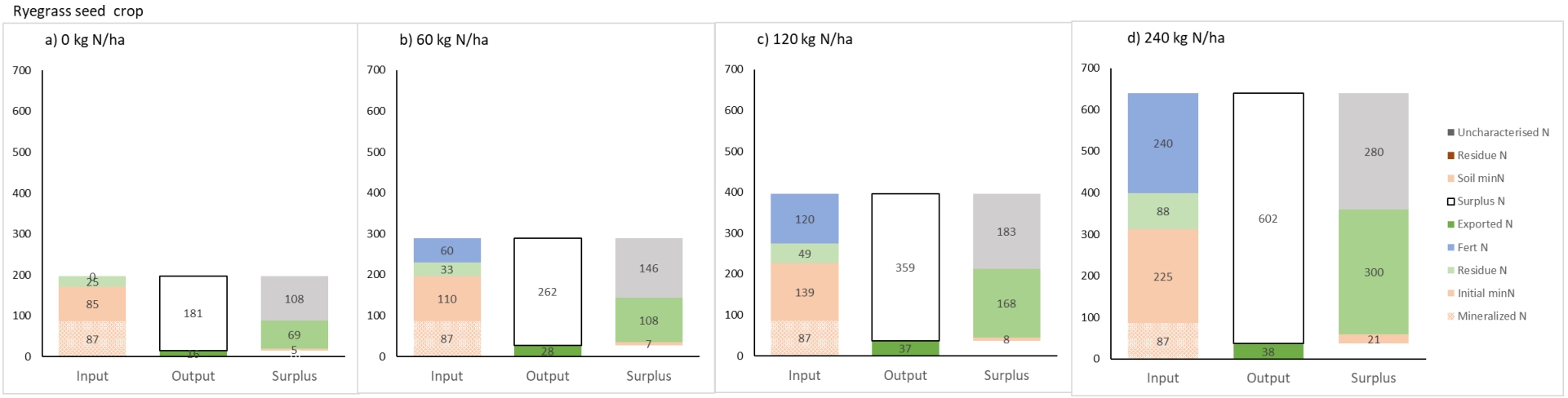


Figure 26. Nitrogen (N) balance of ryegrass seed crop from Rotation 2 at different N rates. Ryegrass crop was the variety 'Nui sown on 6 May 2022 at The New Zealand Institute for Plant and Food Research Limited (PFR), Lincoln, Canterbury.

2.3.3 Rotation 3.

Mineral N change and Uncharacterised N

The plots of interpolated soil mineral-N to depths of 90 cm for Rotation 3 are shown in Figures 27–30. Results show:

- There were relatively high concentrations of soil mineral-N in the top 90 cm for all crops but this lowered especially towards the end of the forage ryegrass crop.
- There were significantly higher concentrations below 30 cm in the soil and this was relatively constant over the bulk of the season, and possibly associated with a high water table at this site. Some consideration to high water tables should be given in the management of N fertiliser in vegetable production systems.
- There was an initial increase in soil mineral N at the start of the fallow period, but then this decreased towards the end (associated with increased rain). In the N1 and N2 treatment there is also a decrease below the 30 cm layer which is commensurate with some movement of soil mineral N below these points, and also further depth. However, the concentrations of mineral N below 30 cm in the N3 and N4 treatment increased.
- The forage ryegrass crop received no fertiliser. There was a decrease in the concentrations of mineral N in the soil towards the end of the forage crop; this is partly due to too much rain, especially in the late January/early February period, but also due to uptake by the forage crop. It can be seen that the forage crop obtained mineral N from below the 30 cm layer of soil.

Nitrogen balances

The calculated N balances for onion and forage ryegrass are in Figures 31 and 32. Some general observations from the N balances are:

- Export N accounted for 25% of the total N output in the N1 treatment for onions and this decreased to 15% at the N4 treatment. The planting population was lower than the onion crop in Rotation 1, as was the yield, and this accounts for the lower percentage of Export N in this crop. Less than 3% of the total N output was in onion residue.
- The Uncharacterised N increased from 72% at the N1 treatment to 79% in the N4 treatment. In the N3 treatment the Uncharacterised N accounted for 77% of the in-field N. In comparison, Uncharacterised N of the onion crop in Rotation 1 was 62% in the N4 treatment.
- The forage ryegrass had a negative Uncharacterised N indicating it used mineral N from below the 30 cm layer of soil used to estimate the N balance. This can also be seen in Figures 27–30 where soil mineral N under the ryegrass crop decreased over time, including below the 30 cm layer.

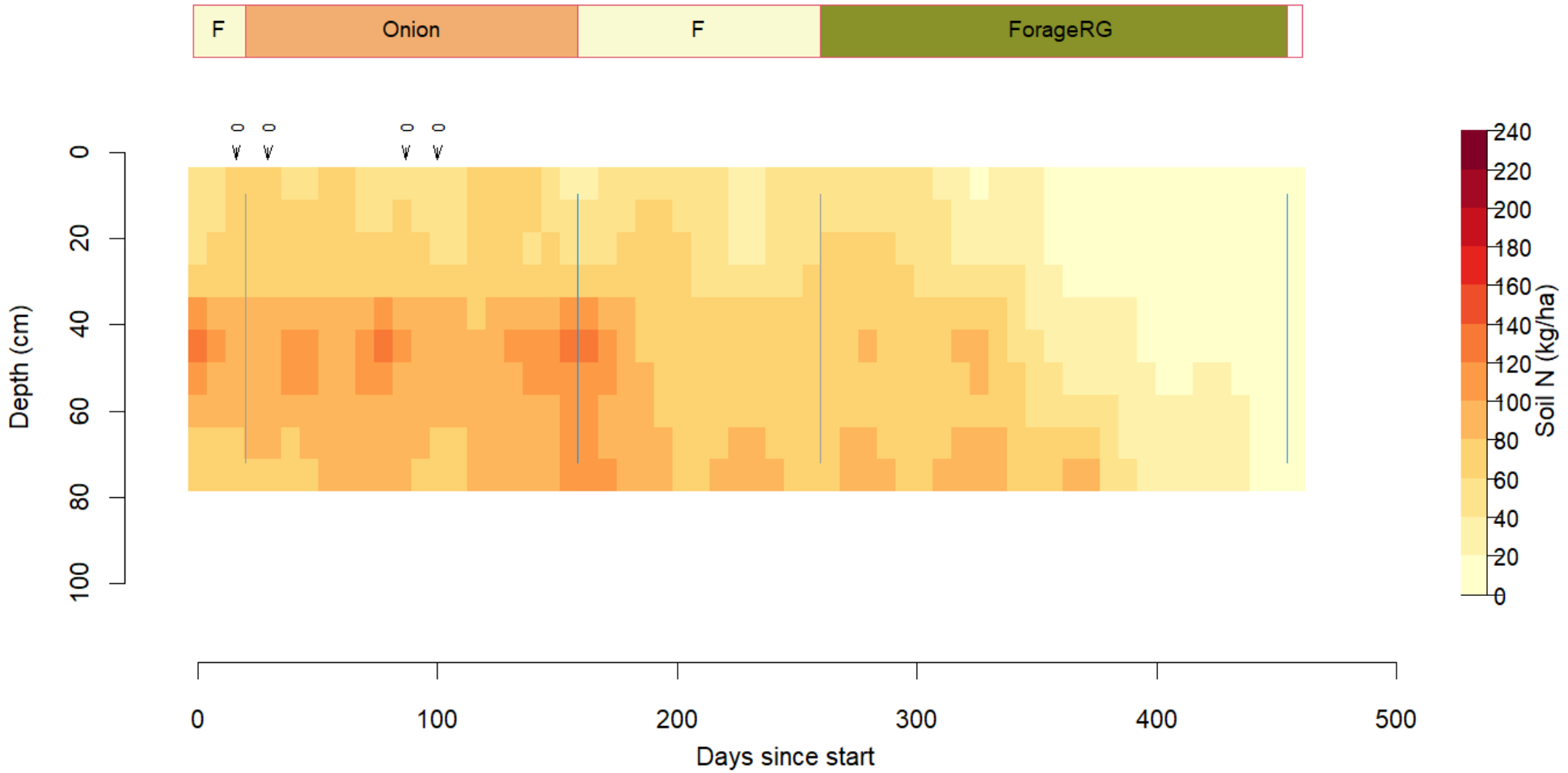


Figure 27. N1 treatment soil nitrate-nitrogen (N) interpolation plot to a soil depth of 90 cm across Rotation 3. Upper arrows represent N fertiliser application dates and amounts for the different crops in the rotation. The period between harvest and sowing of the subsequent crop is fallow period (F).

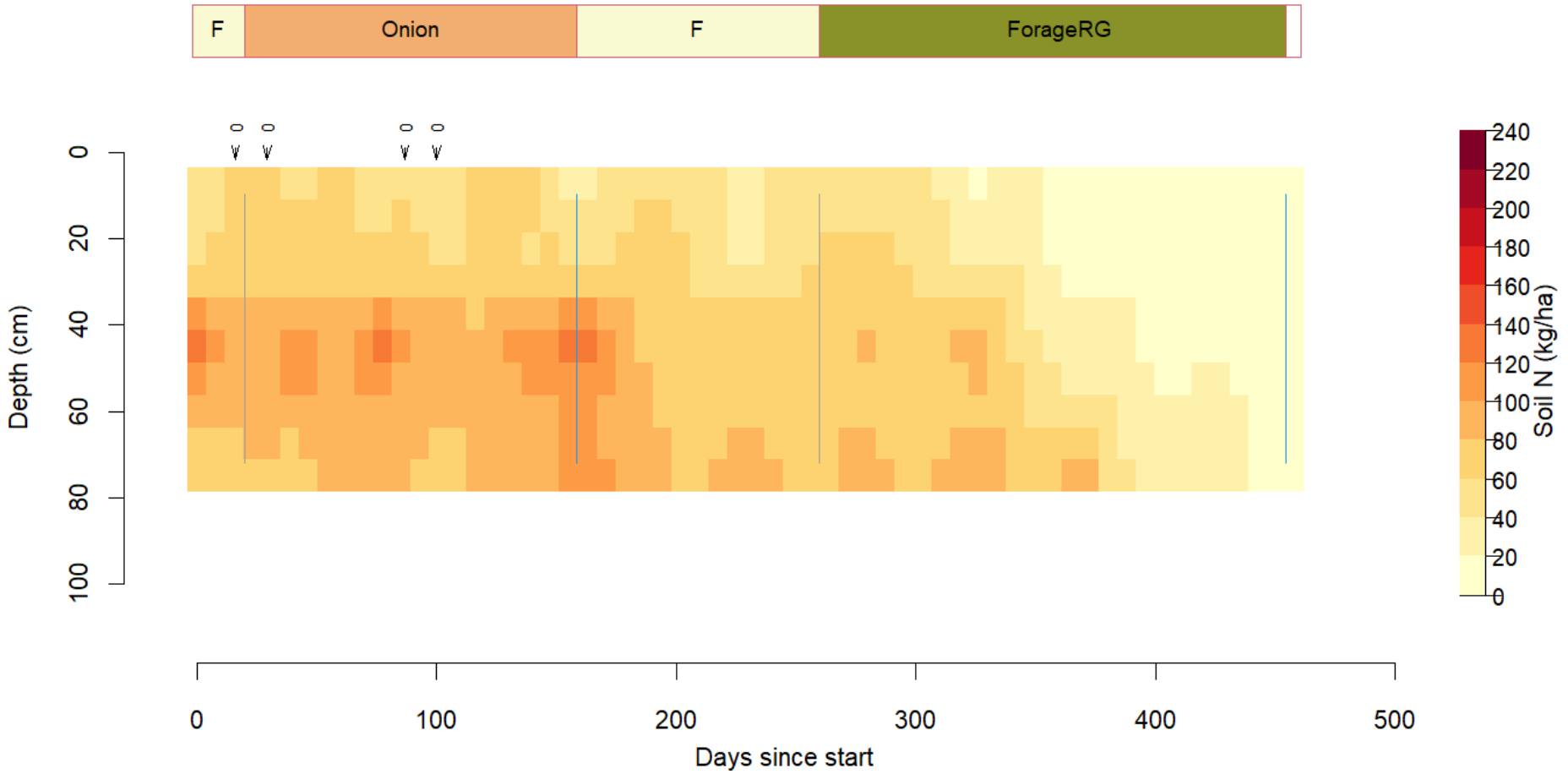


Figure 28. N21 treatment soil nitrate-nitrogen (N) interpolation plot to a soil depth of 90 cm across Rotation 3. Upper arrows represent N fertiliser application dates and amounts for the different crops in the rotation. The period between harvest and sowing of the subsequent crop is fallow period (F).

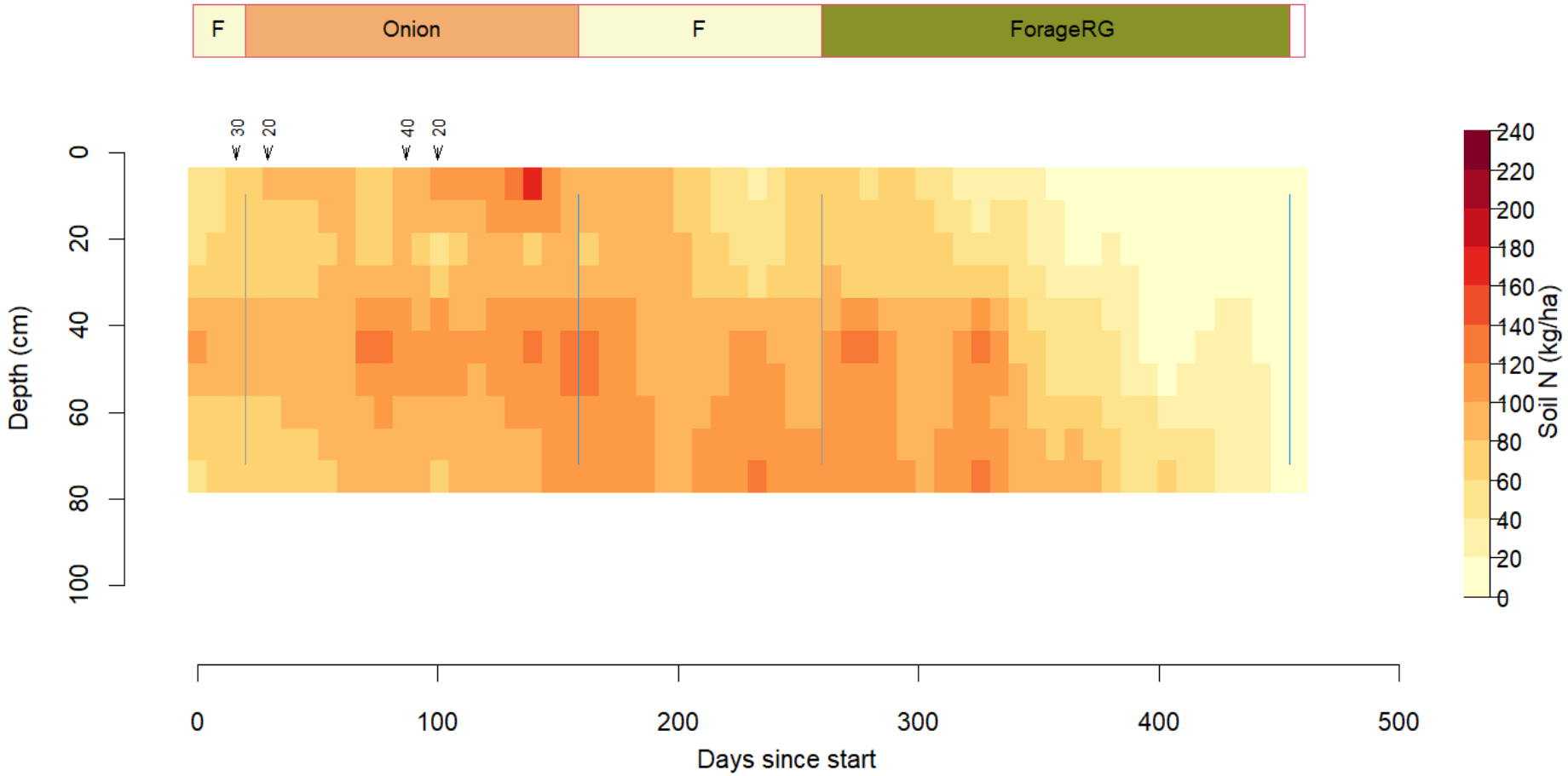


Figure 29. N3 treatment soil nitrate-nitrogen (N) interpolation plot to a soil depth of 90 cm across Rotation 3. Upper arrows represent N fertiliser application dates and amounts for the different crops in the rotation. The period between harvest and sowing of the subsequent crop is fallow period (F).

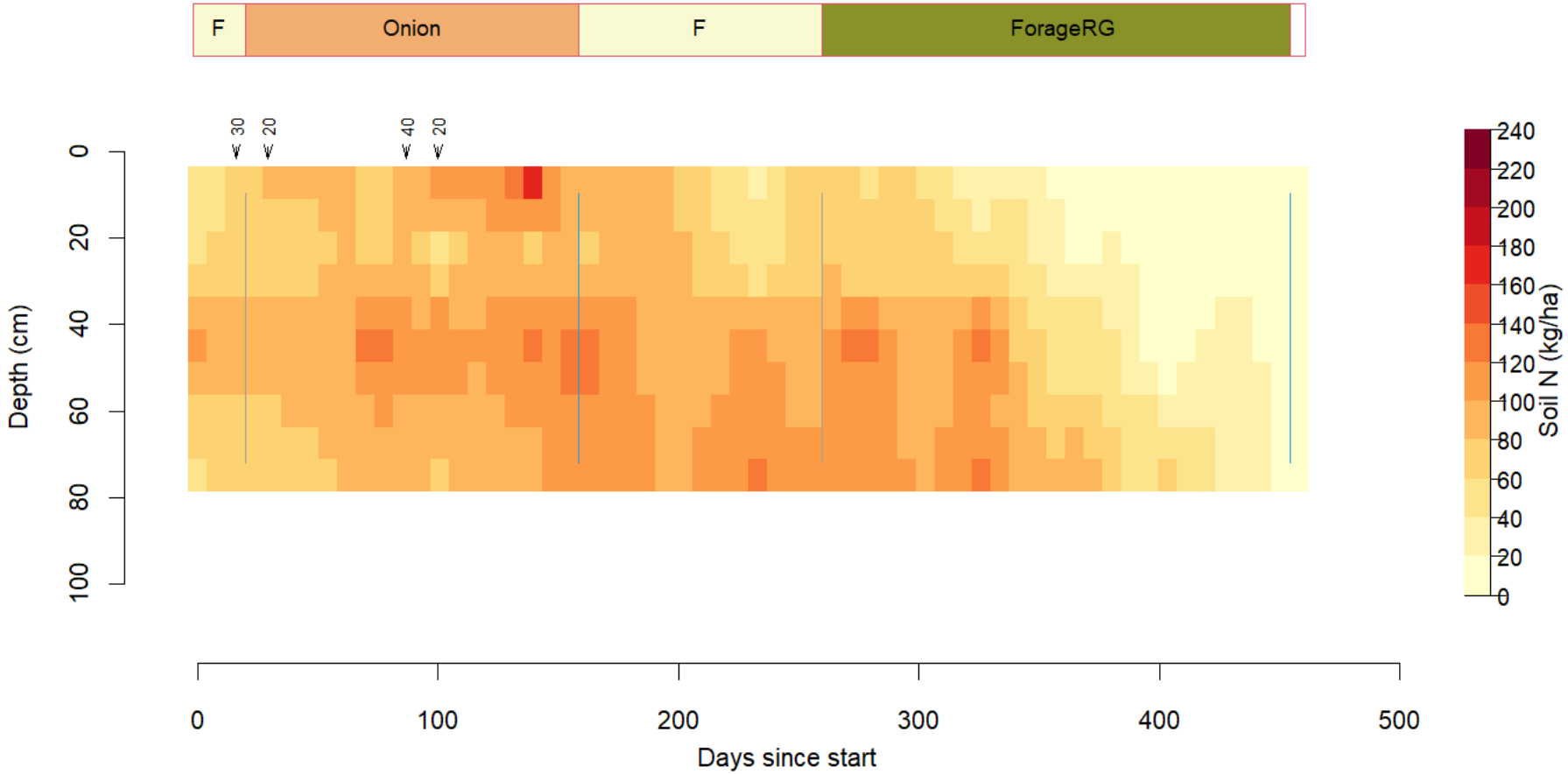


Figure 30. N4 treatment soil nitrate-nitrogen (N) interpolation plot to a soil depth of 90 cm across Rotation 3. Upper arrows represent N fertiliser application dates and amounts for the different crops in the rotation. The period between harvest and sowing of the subsequent crop is fallow period (F).

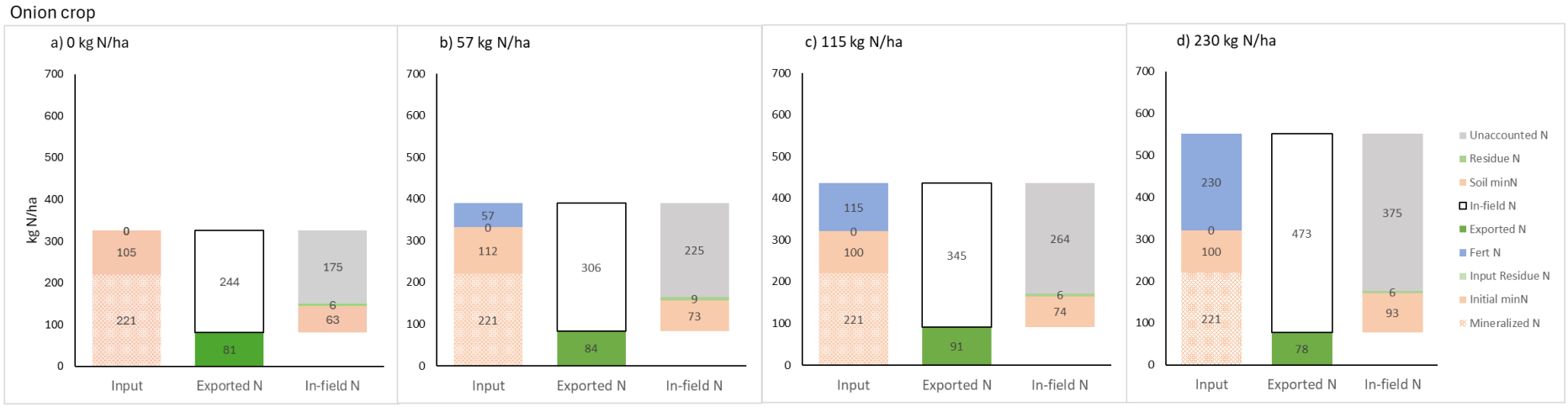


Figure 31. Nitrogen (N) balance of onion crop from Rotation 3 at different N rates. Onion crop was the variety 'Tilbury' sown on 7 Sep 2020 at The New Zealand Institute for Plant and Food Research Limited (PFR), Havelock North, Hawke's Bay

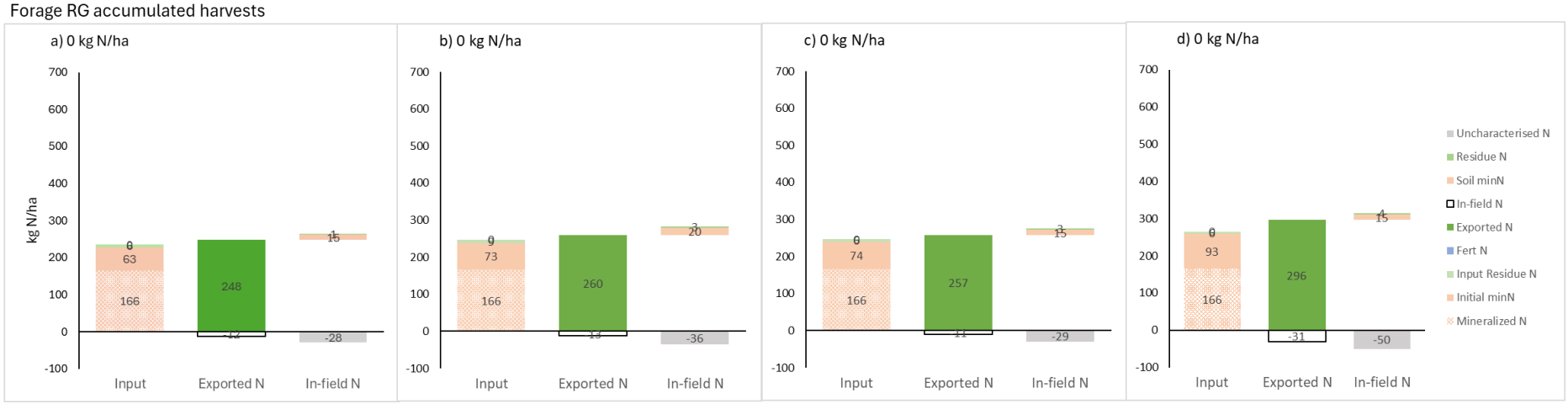


Figure 32. Nitrogen (N) balance of onion crop from Rotation 3 at different N rates. Forage ryegrass crop was a 50:50 mix of 'Asset' and 'Tama' ryegrass sown 2 March 2021 at The New Zealand Institute for Plant and Food Research Limited (PFR), Havelock North, Hawke's Bay.

2.3.4 Rotation 4.

Mineral N change and Uncharacterised N

The plots of interpolated soil mineral-N to depths of 90 cm for Rotation 4 are shown in Figures 33–36. Results show:

- There were significantly higher concentrations below 30 cm in the soil and this was relatively constant over the bulk of the season, and possibly associated with a high water table at this site. This was very pronounced in the N3 and N4 treatments. Some consideration to high water tables should be given in the management of N fertiliser in vegetable production systems.
- The mineral N content increased with fertiliser under pak choy, but then decreased, suggesting some uptake by the crop. However, in the N3 and N4 treatments this was not the case and mineral N remained high.
- Fertiliser application in cauliflower caused a significant increase in mineral N, particularly in the N4 treatment. There was a significant accumulation of mineral N below 30 cm under cauliflower and this was most pronounced in the N3 and N4 treatments.
- Under the forage ryegrass crop that received no fertiliser, the soil mineral N started to drop significantly both above 30 cm initially, and then below 30 cm. This was in part due to movement by excess rain, but also uptake by the crop.

Nitrogen balances

The calculated N balances for pak choy, lettuce, pea, cauliflower and forage ryegrass crops are shown in Figures 37–41. Some general observations from the N balances are:

- Export N accounted for 26% of the in-field N across all the treatments. The percentage of the total N output in the N1 treatment for onions and this decreased to 15% at the N4 treatment. The Uncharacterised N had a maximum of 152 kg N/ha that averaged 64% of the in-field N in pak choy.
- Export N of lettuce averaged 11% across all treatments, and the highest Uncharacterised N was 197 kg N/ha at the N4 treatments, which was 63% of the in-field N.
- Peas received no fertiliser treatments. The Export N varied with treatments from 7% at the N1 treatment to 10% at the N2 treatment. The Uncharacterised N at the N3 treatment was 56 kg N/ha or 23% of in-field N. In contrast, the residue was 104 kg N/ha, or 42% of the in-field N. Peas can contribute significant N to the system via residues.
- The Uncharacterised N in cauliflower increased form 38% of in-field N at the N1 treatment to 84% at the N4 treatment, suggesting an oversupply of N for the N4 rates. At the N3 treatment the Uncharacterised was 45% of in-field N,
- The forage ryegrass had a negative Uncharacterised N indicating it had used mineral N from below the 30 cm layer of soil used to estimate the N balance. This can also be seen in Figures 33–36 where soil mineral N under the ryegrass crop decreased over time, including below the 30 cm layer.

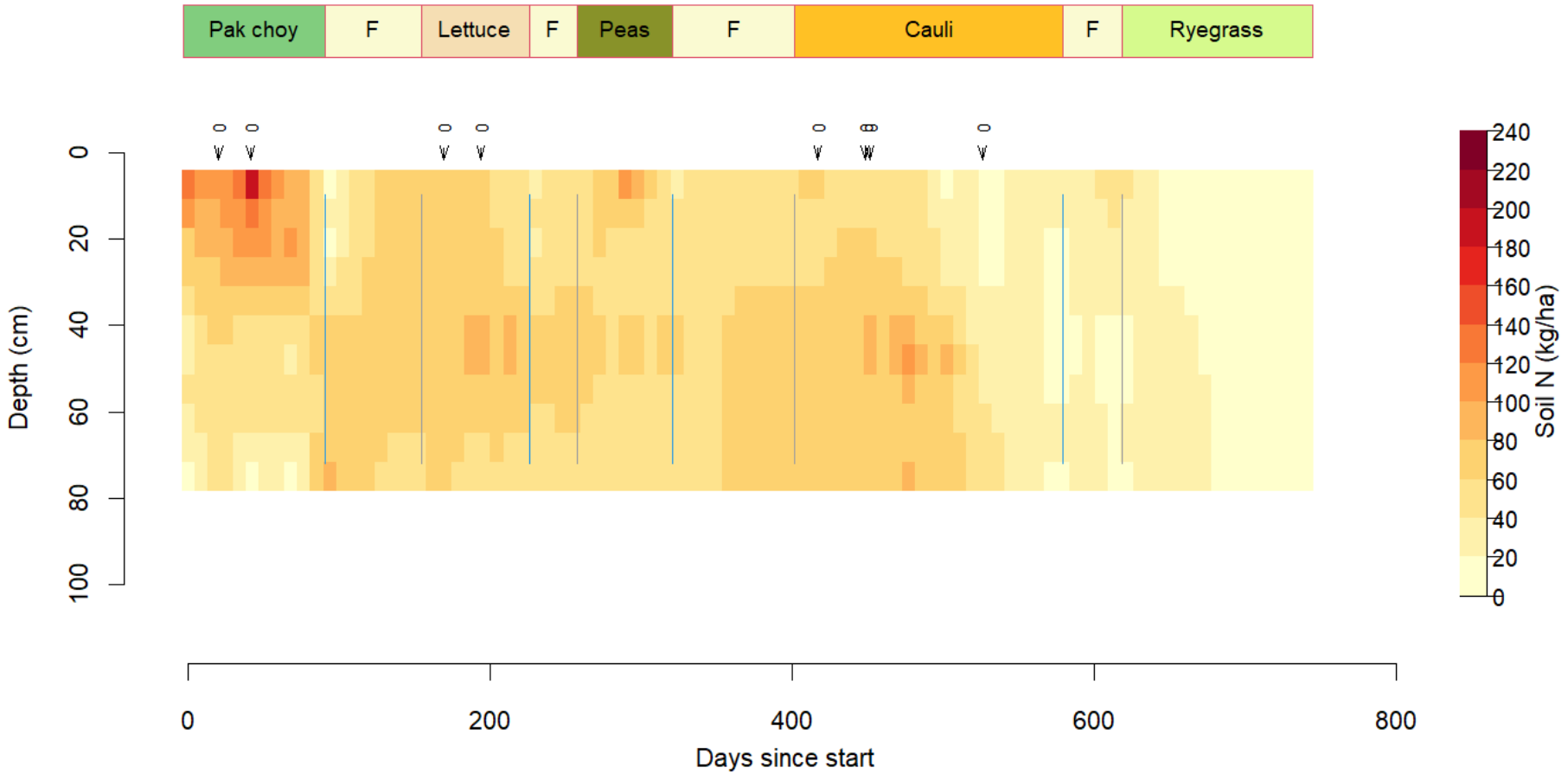


Figure 33. N1 treatment soil nitrate-nitrogen (N) interpolation plot to a soil depth of 90 cm across Rotation 4. Upper arrows represent N fertiliser application dates and amounts for the different crops in the rotation. The period between harvest and sowing of the subsequent crop is fallow period (F).

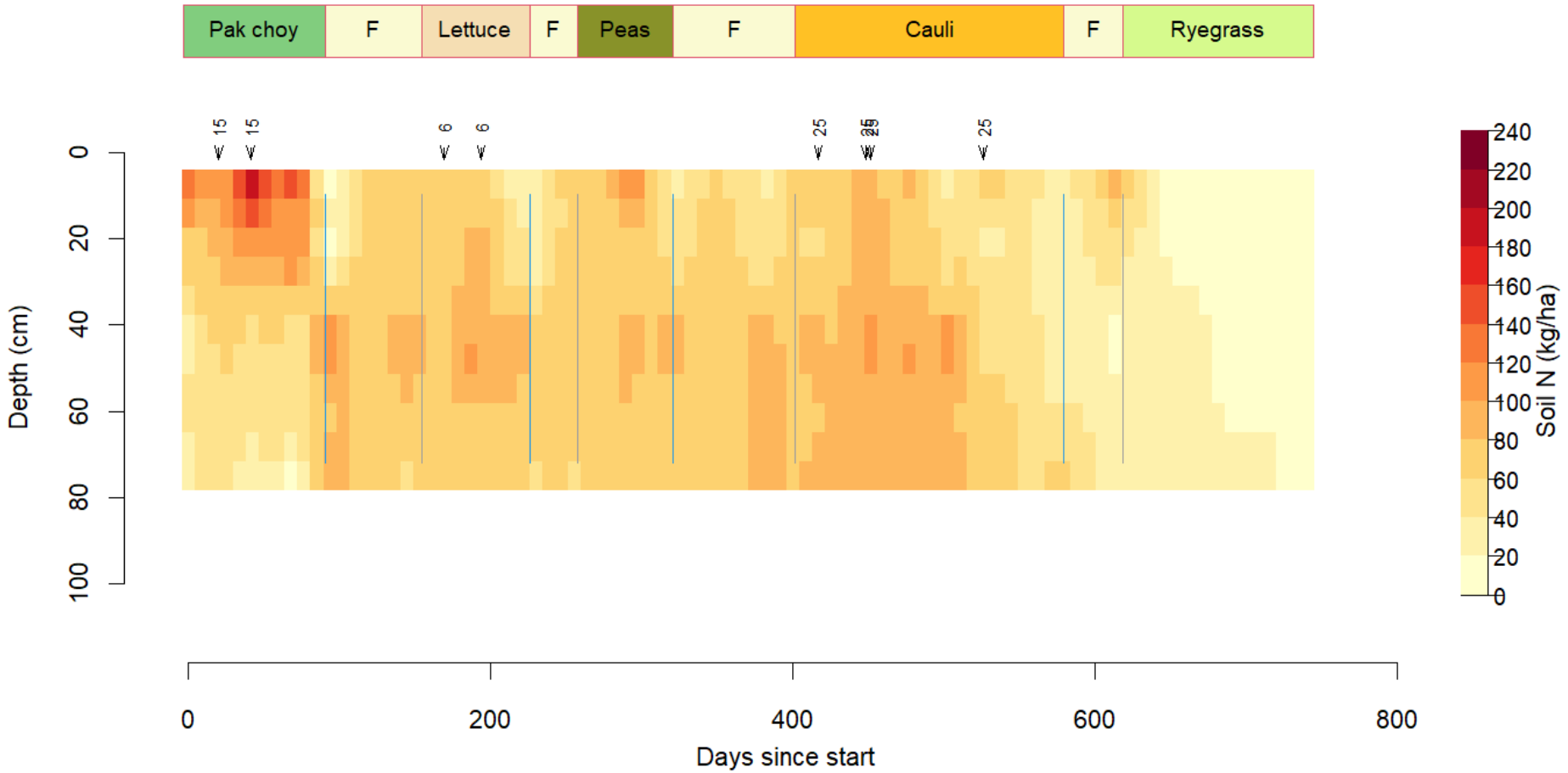


Figure 34. N2 treatment soil nitrate-nitrogen (N) interpolation plot to a soil depth of 90 cm across Rotation 4. Upper arrows represent N fertiliser application dates and amounts for the different crops in the rotation. The period between harvest and sowing of the subsequent crop is fallow period (F).

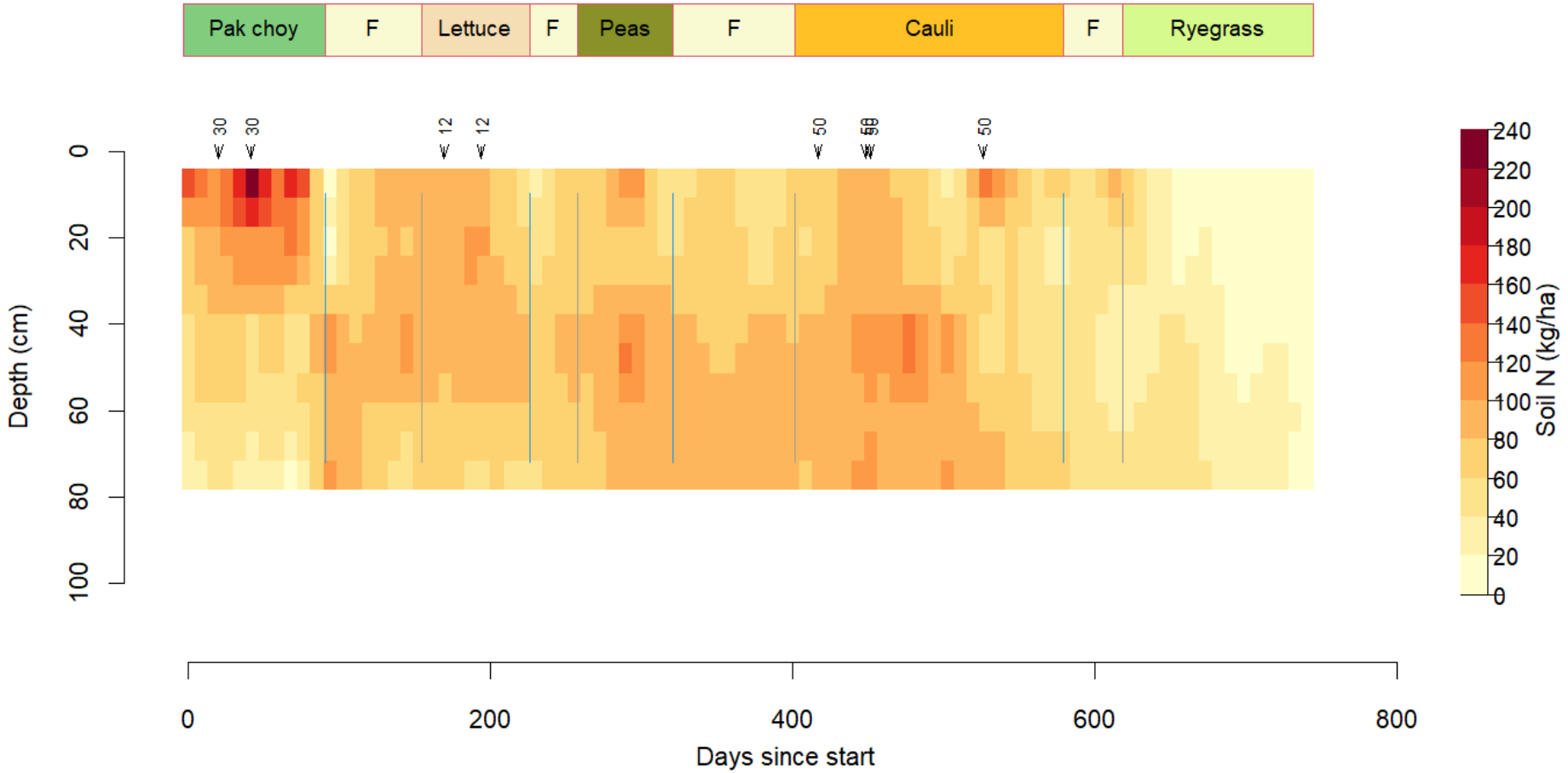


Figure 35. N3 treatment soil nitrate-nitrogen (N) interpolation plot to a soil depth of 90 cm across Rotation 4. Upper arrows represent N fertiliser application dates and amounts for the different crops in the rotation. The period between harvest and sowing of the subsequent crop is fallow period (F).

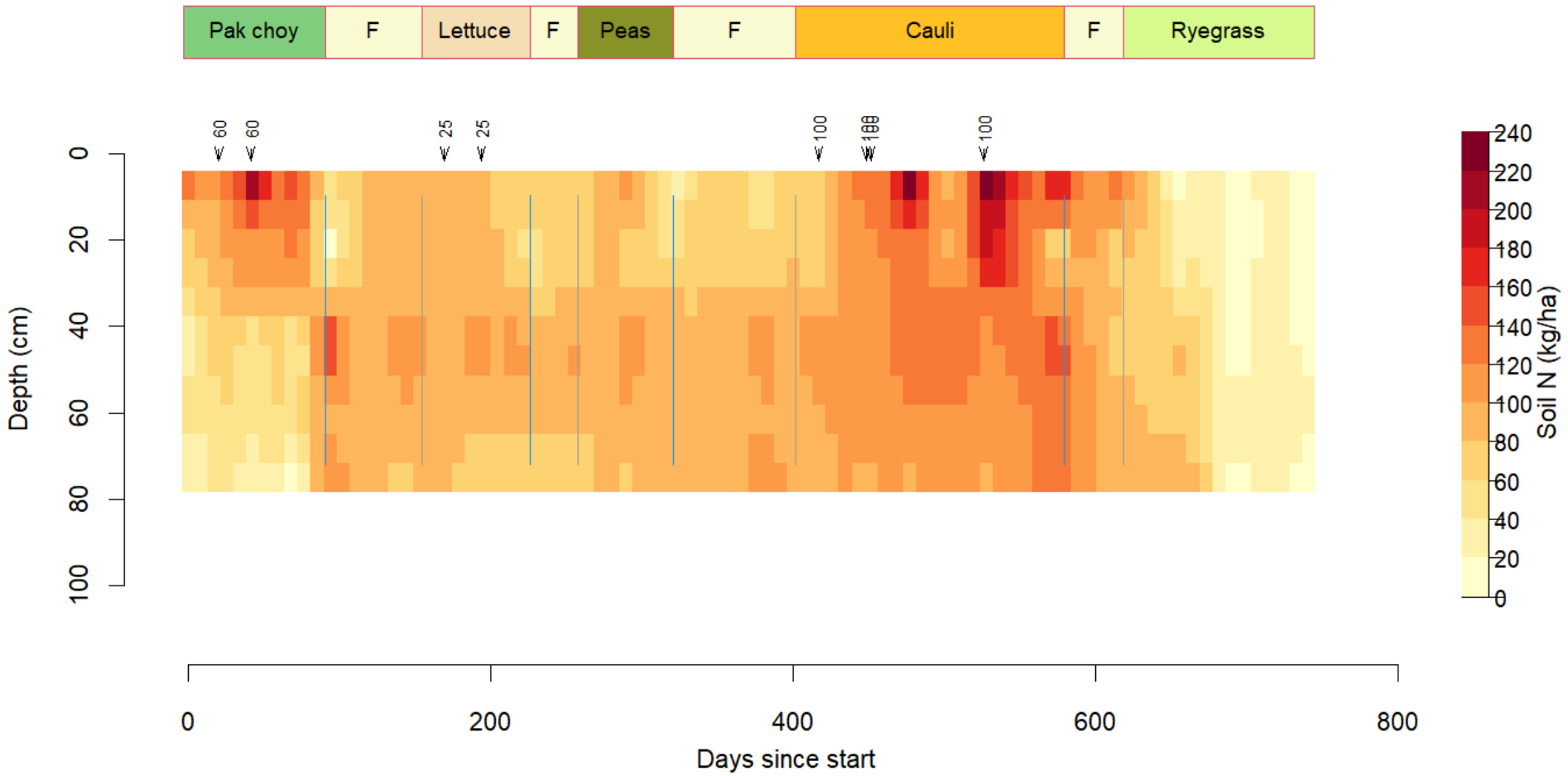


Figure 36. N4 treatment soil nitrate-nitrogen (N) interpolation plot to a soil depth of 90 cm across Rotation 4. Upper arrows represent N fertiliser application dates and amounts for the different crops in the rotation. The period between harvest and sowing of the subsequent crop is fallow period (F).

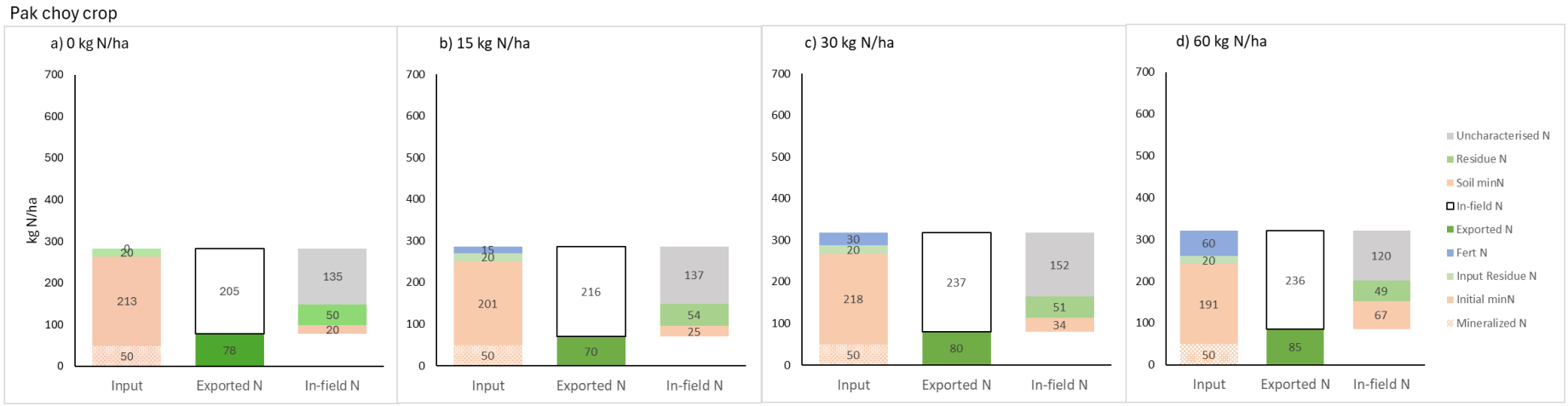


Figure 37. Nitrogen (N) balance of pak choy crop from Rotation 4 at different N rates. Pak choy crop was variety 'Shanghai' sown 7 December 2020. at The New Zealand Institute for Plant and Food Research Limited (PFR), Havelock North, Hawke's Bay.

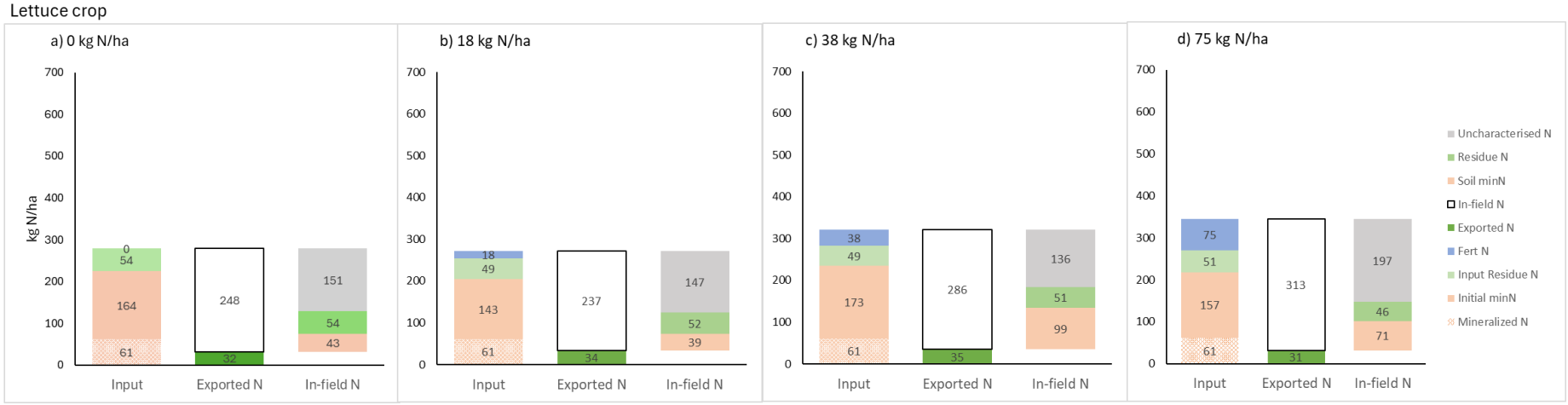


Figure 38. Nitrogen (N) balance of lettuce crop from Rotation 4 at different N rates. Lettuce crop was variety 'Contessa' sown 2 March 2021 at The New Zealand Institute for Plant and Food Research Limited (PFR), Havelock North, Hawke's Bay.

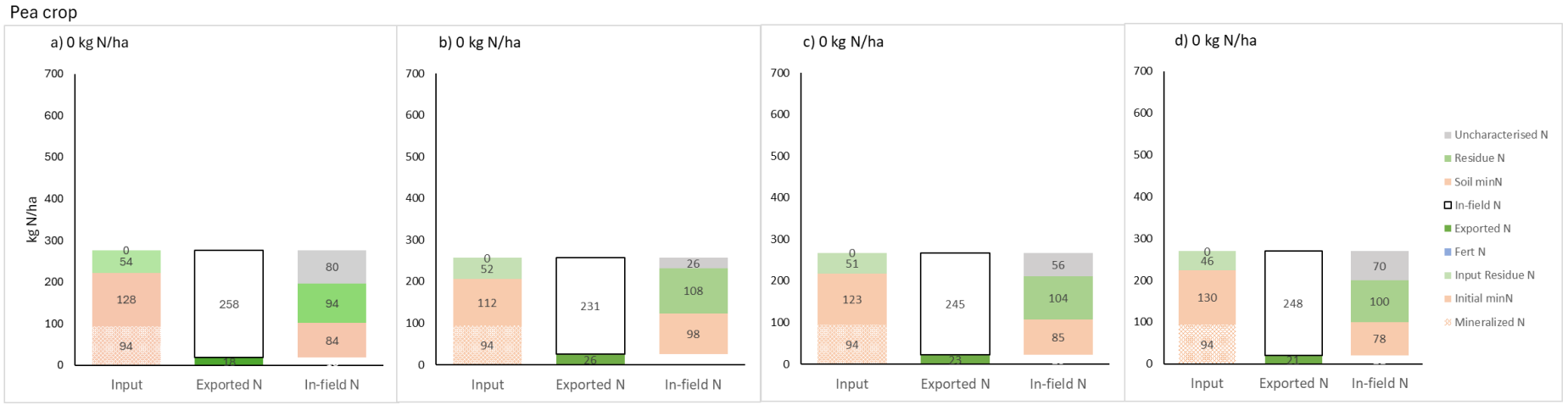


Figure 39. Nitrogen (N) balance of pea crop from Rotation 4 at different N rates. Pea crop was variety 'Ashton' sown 22 October 2021 at The New Zealand Institute for Plant and Food Research Limited (PFR), Havelock North, Hawke's Bay.

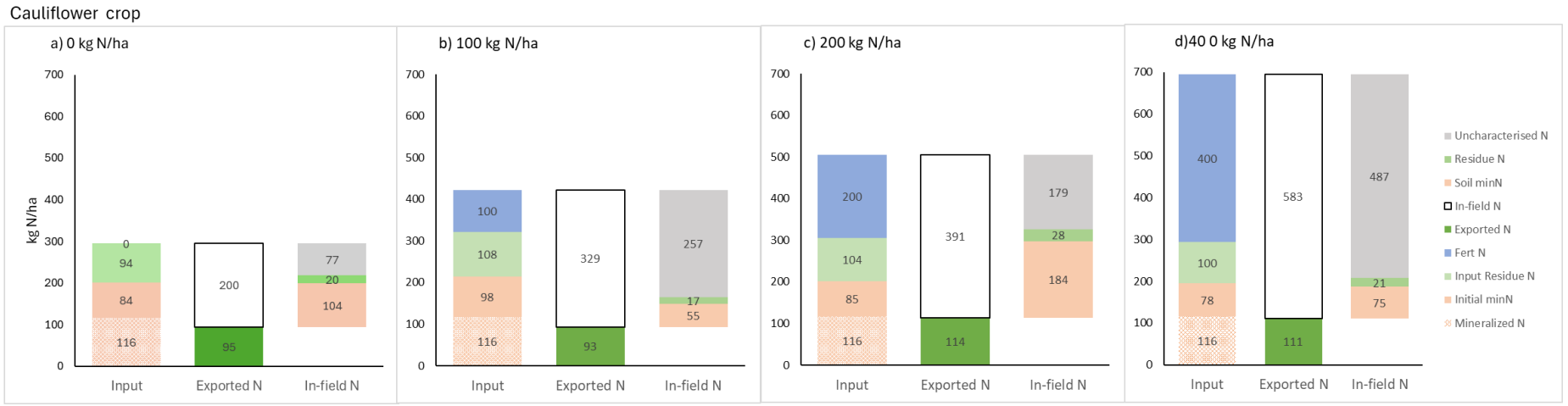


Figure 40. Nitrogen (N) balance of cauliflower crop from Rotation 4 at different N rates. Cauliflower crop was variety 'Casper' sown 6 May 2022 at The New Zealand Institute for Plant and Food Research Limited (PFR), Havelock North, Hawke's Bay.

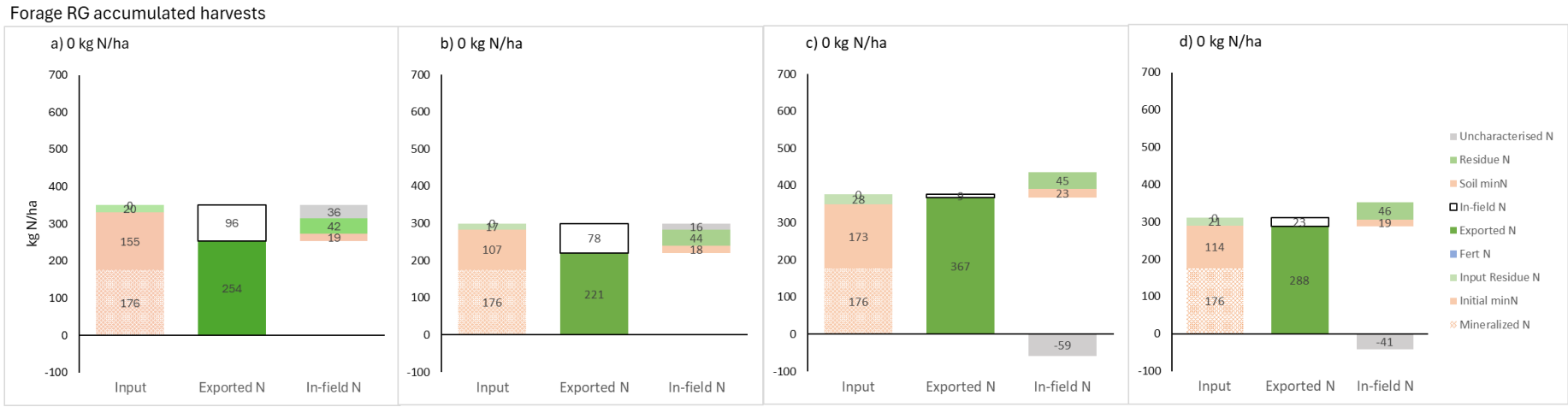


Figure 41. Nitrogen (N) balance of forage ryegrass crop from Rotation 4 at different N rates. Forage ryegrass crop was variety 'Winer Star II' sown 13 December 2022 at The New Zealand Institute for Plant and Food Research Limited (PFR), Havelock North, Hawke's Bay.

2.4 Application of results in management decisions

The potato crops in Rotations 1 and 2 were different varieties, grown for different markets and with different N management, and also quite different N balances (Table 6). There was a much higher potential for losses in Rotation 1 with an Uncharacterised N of 92 kg N/ha (51% of in-field N) compared with 31 kg N/ha in Rotation 2 (27% of in-field N) at the N3 treatment rate. This is a large difference in the N balance for crops that had good management fertiliser application.

Table 6. Comparison of potato crops in Rotations 1 and 2 with management, yield and Potential Environmental Nitrogen Loss (Uncharacterised N) of N3 treatment.

				N3 Treatment					
Rotation	Variety	Market	Method	Side-dress	Rate (kg N/ha)	Total N input (kg N/ha)	Yield (t/ha)	Exported N (kg N/ha)	Uncharacterised N (kg N/ha)
1	Russet Burbank	Processing	Potato Calculator	Pre-set time	221	414	72	236	139
2	'Agria'	Fresh	SVS Prototype	Checked with nitrate test strip	206	389	81	274	20

Differences in the Uncharacterised N levels between these two potato crops could be due to:

- Varietal – or seasonal – differences in yield, though both 'Russet Burbank' and 'Agria' are considered late maturing crops, 'Agria' tends to be a higher yielding variety (Misovic et al. 1997). The 'Agria' crop of Rotation 2 had a higher yield (significant with p=0.004) than Rotation 1, even though overall N supply was lower.
- Differences in N uptake. Exported N, another key parameter of the N balance differed between the two crops. The exported N was 236 kg N/ha for Rotation 1 at the N3 treatment (57% of total N input), and 274 kg N/ha (70% of total N) in Rotation 2. For total N uptake, the crop in Rotation 1 took up 69% of all N supplied, but this was 82% of all N supplied in Rotation 2.
- Differences in N management. While the crops received good management practice N rates, the management nevertheless differed, particularly in side-dressing timing and amount. In Rotation 1, the good management fertiliser rate was estimated with the Potato Calculator (Jamieson et al. 2006), with the total amount evenly split between side-dressings, timings of which were pre-set before sowing. In Rotation 2, good management fertiliser was estimated with the SVS prototype tool, which provides an estimate of N needed for the crop and suggests side-dressing application dates. Close to these suggested dates, nitrate test strips were used to obtain an indication of soil mineral-N content and to refine fertiliser recommendations. Based on this approach an additional 20 kg N/ha was provided to the crop at the last side-dressing, as soil mineral-N was lower than expected and crop demand was still high.

Good N management for a crop aims to best match supply with demand and this occurred for the Potato crop in Rotation 2 (compared N supply for potatoes in Rotation 2 shown in Figure 22, to that for potatoes in Rotation 1 shown in Figure 21). While estimating was a requirement of applied N based on likely yield and soil supply, within season adjustment seems to greatly improve the N balance. Future work should involve direct comparison, particularly of yield effects and N uptake and use effects on the N balance outcomes. The comparison of using SVS tool predictions, plus managing side-dress application rate and timing using nitrate test strips should be evaluated.

3 Workstream Two: Regional Monitoring

3.1 Summary

The regional monitoring programme provided monthly soil and plant biomass test data from nine operational outdoor vegetable production sites across the country (Table 8) over a period of three years, from late 2020 to early 2024.

Data collected from this workstream were used primarily to validate the model developed through Workstream 3 by comparing outputs from the model to real in-field data from commercial operations. Furthermore, data from regional monitoring were used to refine crop nitrogen content and yields used for default values within the model.

Data collected also had several side benefits, including furthering grower engagement with the SVS project through individualised reports to participating growers, NZ Grower articles, and case studies distributed to the wider industry.

Across the three years of sampling approximately 5,650 soil samples, 181 soil bulk density samples (82 x 0-15 cm, 83 x 15 – 30cm, and 8 each at 30 – 60 cm and 60 – 90 cm) and 463 plant biomass samples were collected. It was identified that there were data gaps in plant nitrogen content, so an additional 182 plant samples were taken from a priority list of crops across a range of growers and locations. In total 47 crops were grown across the nine monitoring sites over the sampling period, for an average of 1.7 crops grown per year per site.

Soil test and plant biomass results were collated and analysed. Survey results collected from the participating growers provided additional information such as planting and harvest dates, fertiliser usage, and where possible the yield from the sampled paddock.

This data were summarised and run through comparison tools developed by PFR to validate soil nitrogen and crop nitrogen uptake predictions made by the model developed in Workstream 3.

Additional data and photographs from the regional monitoring programme can be found in the appendix.

Table 8. Regional monitoring site information.

Site ID	Location	Soil texture	S-map soil family
1	Pukekawa (Waikato)	Clay	Onewhero/TeRaumoa
2	Pukekohe (Auckland)	Clay	Puni/Morrinsville
3	Tuakau (Waikato)	Clay	Puni/Morrinsville
4	Matamata (Waikato)	Silt	Otorohanga
5	Levin (Horowhenua)	Silt	Mandamus
6	Levin (Horowhenua)	Silt	Ngamoka
7	Hawke's Bay	Sand	Market Cross
8	Ashburton (Canterbury)	Silt	Wakanui
9	Leeston (Canterbury)	Silt	Templeton

3.2 Methodology and protocol

The general methodology of the regional monitoring programme was based on taking monthly soil and plant biomass samples at each site. Four principal monitors were each responsible for two or more sites.

The collected soil samples were sent to a commercial laboratory for analysis. From October 2020 to November 2022 the laboratory used was Eurofins, based in Penrose, Auckland. From late November 2022 until the final soil samples taken in March 2024 the laboratory used was ARL, based in Hawke's Bay. Analyses conducted on 0-15 cm and 15-30 cm core samples by each laboratory included a basic soil profile (pH, total N, total C, Olsen P, etc.), a mineral nitrogen profile (ammoniacal-N, nitrate-N, total mineral N), and a mineralisable nitrogen profile (Hot Water Extractable Nitrogen). Only the mineral nitrogen profile was tested for 30-60 cm and 60-90 cm core samples. Efforts were made to minimise the rate of mineralisation following sample collection, with ice packs sent during courier transport, or chilling if samples were kept overnight.

In the latter half of the programme, it was realised that this method of transporting samples was often insufficient to keep sample temperatures down, particularly during summer. Therefore, following advice from PFR, samples were frozen overnight prior to sending.

The collected plant biomass and soil bulk density samples were sent to PFR in Hawke's Bay (North Island sites) or in Canterbury (South Island sites). The samples received were then weighed, dried, and weighed again to determine dry matter content. N content was determined.

The sampling location at each monitoring site was a defined area, which was kept consistent over the course of the programme and within a given crop. In some cases (such as strip planting of broccoli), slight adjustments to the sampling area were made, but for the majority of the programme the same land area was sampled consistently at the same GPS coordinates.

3.2.1 Soil sampling protocol

A soil sampling protocol was developed and reviewed prior to sampling getting underway. Key features of this protocol have been summarised below:

- Soil samples were taken prior to fertiliser applications including side-dressings where possible.
- The sampling pattern and core locations remained consistent for the whole project. For most sites this took the form of a diagonal line of 100-150m across a section of paddock, with 10 evenly spaced sampling locations along the transect. The sampling locations were GPS tagged and marked physically and kept consistent for each subsequent sample collection including crop growth, cover crop and fallow periods. A more representative V or W-shaped transect was avoided due to some crops (e.g., broccoli) being planted in narrow strips, in some cases this necessitated moving the established transect, but this was not a common occurrence due to the layout of the transects.
- Soil samples were sent in bags that were placed in a polystyrene transport box with ice packs (initially) or frozen overnight and sent with ice packs (from late 2022). Soil samples were sent as soon as possible and couriered to ensure next day delivery to the laboratory.

- For each sample a minimum of 10 cores was collected, with a well-mixed composite subsample for each sampling depth sent for analysis.
- Soil samples were collected at three depths, 0-15 cm, 15-30 cm, and 30-60 cm. On most occasions a 60-90 cm sample was also collected, though this was not always possible due to ground conditions.
- Potato crops received special consideration, with sample depths adjusted based on sample position (ridge, shoulder, furrow). Ridge samples were adjusted by +5 cm, shoulder samples were standard, and furrow samples were adjusted by -5 cm.
- Where possible, considering the established sampling locations, samples were taken to be as representative of the crop in question as possible. For instance, samples on an onion crop were taken moving along the onion bed, so as not to bias the results if fertiliser were banded or crop uptake was greatest in one particular zone of the bed.

3.2.2 Soil bulk density sampling protocol

Bulk density sampling involved taking cores of 15 cm length with a defined volume from two layers of soil and measuring the weight of the dried soil. Key considerations when taking bulk density samples included:

- The aim was to take samples three times during the crop (beginning, middle, and end).
- Three samples were collected at each visit, for both 0-15 cm and 15-30 cm depths. Samples were kept separate for analysis, so that at each visit there were six total samples.
- Sampling was taken at the same points as plant biomass samples, typically points 2, 5, and 9 of the transect (beginning, middle, and end).
- For each site once during the programme a deep bulk density sample was taken, at 30-60 cm and 60-90 cm depth ranges.

3.2.3 Plant biomass sampling protocol

Plant biomass samples were collected at the same time as soil samples and included all crops grown at the site, including grass and other cover/catch/ecosystem service crops.

Key considerations when taking plant biomass samples during the programme included:

- Prior to sampling the bed or mound configuration was measured and recorded.
- Three samples were taken for production crops while five samples were taken for cover crops. Samples were taken on varying sides of the transect and staggered slightly with each visit to minimise bias in the results from previous sampling, and where possible the location of samples taken from prior crops was also accounted for. Typically, samples were taken at points 2, 5, and 9 of the transect for production crops, as with bulk density samples.
- The sampling area for each crop type was defined prior to commencement of sampling.
  - Potato: 2 ridges x 2m or 2 ridges x 1m.
  - Carrots, onions, broccoli, spinach on beds: 1 bed x 2m or 1 bed x 1m.
  - Row crops (maize, sweetcorn): 2.5m x 2 rows or 1m x 2 rows.
  - Squash and pumpkin: 2.5m x 2.5m hard quadrat (biomass outside the quadrat was discarded, which resulted in some partial samples).

- Plants were counted, excluding cover crops such as grass.
- Crops were partitioned depending on use. For instance, potatoes were separated into leaves & stem, tubers, and roots, while broccoli were separated into leaves & stem and head.
- Samples were weighed in field by partitioned component, and subsamples were then taken for sending to the lab.
- Only above ground biomass was accounted for with the exception of potato, onions, and carrots.
- The final pre-harvest sample for each crop was typically more thorough, with certain crops such as potatoes and onions graded into size categories (as specified by the participating grower). The residue component was also sampled and defined.

3.2.4 Equipment

Equipment required for sampling included:

- Auger/corer. Three general types were used, with multiple specific models (Figure 42).
- Sledgehammers. Several types were used, including wooden, plastic, metal with plastic cap, and copper head.
- Buckets for collection of soil and plant material.
- Soil moisture probes (2 per site).
- Petrol powered drill (clay soils) or electric hand drill (other soils) for installation of soil moisture probes.
- Weather stations and receivers.
- Laptop for collection of weather station data.
- Flags/markers for identifying sampling points along the transect.
- Mobile phone for collection of Bluetooth probe data and approximate (~1m) GPS tagging of sampling locations.
- Measuring devices (scales, tape measures).
- Secateurs, saws, and machetes for plant material collection.
- Safety equipment (eye protection, ear protection, safety vests, gloves, sun protection).
- Muscles.

Figure 42. Examples of auger and corer types used during programme. From left to right: Dutch-head auger, PFR closed tube corer, Open-sided corer (hammer-type), Open-sided corer (push-type), 30 cm step-probe, 15 cm step-probe.

3.3 Data collected

A significant quantity of data was collected over the course of the regional monitoring programme, summarised in Table 9.

Table 9. Data collected through regional monitoring.

Type	Source	Name	Unit	Frequency
Soil	Sampling/Lab	pH	pH units	Monthly
Soil	Sampling/Lab	Total nitrogen	%	
Soil	Sampling/Lab	Total carbon	%	
Soil	Sampling/Lab	Organic matter	%	
Soil	Sampling/Lab	Carbon:nitrogen ratio	-	
Soil	Sampling/Lab	Olsen P	mg/L	
Soil	Sampling/Lab	QT Calcium	MAF QT	
Soil	Sampling/Lab	QT Magnesium	MAF QT	
Soil	Sampling/Lab	QT Potassium	MAF QT	
Soil	Sampling/Lab	QT Sodium	MAF QT	
Soil	Sampling/Lab	Potentially available N	kg N/ha	
Soil	Sampling/Lab	Ammoniacal N	mg/kg	
Soil	Sampling/Lab	Nitrate N	mg/kg	
Soil	Sampling/Lab	Mineral N	mg/kg	
Soil	Sampling/Lab	Hot Water Extractable N	mg/kg	
Soil	Sampling/Lab	Hot Water Extractable Inorganic N	mg/kg	
Soil	Sampling/Lab	Hot Water Extractable Organic N	mg/kg	
Soil	Sampling/Lab	Bulk density	g/cm^3	3x per crop
Soil	Sampling	Nitrate-N (Nitrate Quick Test)	mg NO_3/L	Intermittently
Soil	Calculation	Nitrate-N (Nitrate Quick Test)	kg N/ha	
Soil	Calculation	Mineral N	kg/ha	Monthly
Soil	Calculation	Mineralisable N	kg/ha	
Plant biomass*	Sampling/PFR	Crop fresh weight	kg	Monthly
Plant biomass*	Sampling/PFR	Crop dry weight	kg	
Plant biomass*	Sampling/PFR	Dry matter content	%	
Plant biomass*	Sampling/PFR	Nitrogen content	%	
Plant biomass*	Calculation	Estimated crop yield	t/ha	
Plant biomass*	Calculation	Average nitrogen content	kg N/ha	
Weather	Weather station	Rainfall	mm	15 minutes
Weather	Weather station	Min/max temp	°C	
Weather	Weather station	Humidity	%	
Weather	Weather station	Wind speed	km/hr	
Weather	Weather station	Wind direction	-	
Weather	Weather station	Barometric pressure	hPa	
Soil moisture	Sentek/Aqua-check probes	Moisture	mm	15 minutes
Soil moisture	Sentek probes	Volumetric Ion Concentration	VIC	
Field	Observation	Site/crop condition	-	Monthly
Field	Measurement	Bed/mound configuration	m	Monthly
Grower data	Survey	Crop variety	-	Per crop
Grower data	Survey	Planted area	Ha	
Grower data	Survey	Planting date	-	

Type	Source	Name	Unit	Frequency
Grower data	Survey	Harvest date	-	
Grower data	Survey	Total harvested yield	t/ha	Monthly
Grower data	Survey	Marketable yield by grade	t/ha	Monthly
Grower data	Survey	Residue management	-	Per crop
Grower data	Survey	General crop comments	-	
Grower data	Survey	Fertiliser application date	-	
Grower data	Survey	Fertiliser name	-	
Grower data	Survey	Fertiliser content	NPKS	
Grower data	Survey	Fertiliser application rate	kg/ha	
Grower data	Survey	Cultivation date	-	
Grower data	Survey	Cultivation type	-	
Grower data	Survey	Irrigation type	-	
Grower data	Survey	Irrigation date	-	
Grower data	Survey	Irrigation quantity	Mm	

* For whole crop and by partitioned components.

3.4 Challenges

As with any field research several issues arose during the programme, from factors both inside and outside of the control of the regional monitors.

3.4.1 Soil sampling

The first and most pervasive issue to occur, which ran the course of the programme, was in soil sample collection. This problem was particularly acute for the North Island sites around the Pukekohe growing hub (Sites 1-3) with clay-based soils. This problem was partly due to the inherent nature of clay soil (becoming wet and sticky in wet conditions, and dry and rock-like in dry conditions), and also partly due to both the auger/corer design and the design of the sledgehammers. Initially for the upper North Island sites, the Dutch-head auger was used (Figure 42 – Corer model A) which involved a twisting action to collect soil into the open head. This resulted in two issues, the first being frittering of the soil from out of the head, particularly for the 0-15 cm layer in drier conditions. The second problem was the increased potential for contamination between soil layers.

PFR had designed 1 m long steel closed tube corers (Figure 42 – Corer model B), which they then organised the manufacture and distribution of. This had the advantage of minimising contamination from the sides of the sampling hole, and also was generally easy to take samples at depth on lighter soils. Unfortunately, on the clay-based soils around the Pukekohe growing hub, these corers tended to become jammed, with the collected soil unable to pass through the top opening between the handle – a particularly acute problem during wet winter months. In dry summer months, these corers also struggled to penetrate the clay, with sledgehammers often required even for the initial 0-15 cm sample. Retrieving the corer from deep samples (60-90 cm) was also often quite difficult, as the handle and leverage was low to the ground and the tube-shaped corers tended to get stuck with suction force at the base of the sampling hole.

Furthermore, the Type B corers were also liable to deform at the top exit hole between the handles. Therefore, sledgehammers had to be selected with a head softer than the steel of the corer. Plastic tipped metal sledgehammers were used successfully, as were, eventually, copper-headed

sledgehammers. Wooden sledgehammers were also used successfully for a time, before eventually disintegrating under the frequent impact stress.

Several other models, including open-sided corers (Figure 42 – Corer models C & D) and step probes (Figure 42 – Corer models E & F). This was for the purpose of testing auger and corer types to determine which would be the most convenient for use by growers to facilitate simple and convenient soil testing and to encourage further uptake of testing, and the nitrate quick test in particular.

Therefore, over the course of the programme and particularly for sites 1-3, a mix of auger/corer models were used, depending on the ground conditions. Several corers were destroyed over the course of the programme, all of them in the Pukekohe growing hub sites (Figure 43).

Another persistent issue was sample temperature. Initially, samples were sent straight after sampling alongside ice packs. This was found to be insufficient at keeping samples cool and may have resulted in some samples having additional mineralised nitrogen. Discussions with PFR and the commercial laboratories resulted in the decision to freeze samples overnight prior to sending, which resolved this issue in most cases.

There was initial concern that thawing the frozen samples may result in a spike of mineralised nitrogen, but based on prior testing by PFR this was judged a minimal risk in comparison to over-temperature samples potentially mineralising nitrogen during transit.

Figure 43. Examples of damaged and destroyed sampling equipment.

3.4.2 Weather stations

From the beginning of the programme, two TESA weather pro weather stations were installed at each site. These consisted of a station, mounted outside, and a receiver terminal, located inside or in a weather resistant container. These stations provided patchy data and tended to fail frequently, mostly due to moisture getting into the receiver terminal. As there was no way to interchange receivers and stations, a broken receiver rendered the entire station useless.

The weather stations also attracted significant quantities of spiders, whose webs jammed up the wind sensors and rainfall collector. Within two years most of the weather stations had broken, and the patchwork data obtained from them was difficult to work with.

Backup weather data was obtained using the National Institute of Water and Atmospheric Research (NIWA) Virtual Climate Station Network (VCSN). VCSN is, as the name suggests, a network of 150 automatic climate stations, with data interpolated between individual stations so that an approximated climate summary can be obtained for any site within New Zealand, with historical data back to 1972. Unfortunately, over the course of the programme the previously free of charge VCSN was first monetised and subsequently became unavailable for public access. Data requests could be made directly to NIWA, but the cost of extracting relatively large datasets was considerable. NIWA also offers the CliFlo service for access to the National Climate Database, this was used to some extent, but data were incomplete for several sites and so this was not relied upon for the primary weather data.

The compromise solution to this was to utilise the HortPlus MetWatch service. MetWatch comprises approximately 94 weather stations in every region of the country, with high levels of data completeness. Unfortunately, data from these stations are not interpolated, and several monitoring sites were located some distance from the nearest MetWatch station. The greatest distance was approximately 29 km between site 8 and its nearest MetWatch station, though all other monitoring sites were within 8 km of the nearest station, with six sites within 4 km. The closest station was coincidentally located at the same location as the monitoring site.

To deal with the variety of sources, data from the weather stations, VCSN stations, CliFlo, and Metwatch stations were merged to provide a continuous overview of rainfall at each site throughout the programme. While not ideal, this was sufficient to help identify potential significant nitrate leaching events, which could also be supported by the soil moisture probe data.

3.4.3 Soil moisture probes

The programme design called for two soil moisture probes to be installed alongside each crop to provide data on changes in soil moisture and Volumetric Ion Content (VIC). It was anticipated that these data could be used to predict leaching events and identify risk hotspots throughout the rotation. Two models of probe were used. The first of these were Sentek probes, supplied by Fruition Horticulture. Data from these Bluetooth based probes were downloaded via Bluetooth to a mobile phone, from where it was transmitted to the Sentek database where it can be analysed. Sentek probes required installation by the regional monitor, using petrol powered or battery powered drills alongside a simple installation kit.

The second model of probes were Aqua-Check.

For the majority of the programme, the installation and data acquisition from these probes was successful, though some problems were encountered.

Issues with installation of the Sentek probes arose before the monitors became familiar with the correct installation methods, particularly on the clay soils of sites 1-3. The primary installation issue was drilling a hole that was too wide, resulting in the probe not having complete contact with the surrounding soil and therefore providing incomplete readings.

Another issue was related to communication with the participating growers. Because harvest of a given crop is often dictated by rapidly changing weather and market conditions, the planned harvest date is often bought forward by up to several weeks. This resulted in the unfortunate decapitation of two probes early in the programme, after which probes were removed well in advance of harvest – a compromise which resulted in some loss of potential data acquisition, especially when, as is also common, harvest was delayed by several weeks.

3.4.4 Grower surveys

Participating growers were surveyed periodically to collect crop data and fertiliser inputs. The survey data, particularly for nitrogen fertiliser inputs, were critical for preparing plant nitrogen uptake curves, soil mineral nitrogen curves, and nitrogen budgets for the regional monitoring data for validation against the model.

3.5 Results

This section contains selected analysis from data collected from the regional monitoring. Regional monitoring data collected from Workstream 2 was primarily used to test the model and tool developed in Workstream 3 as well as form the basis for many of the extension materials used to promote grower engagement with SVS and increase the level of knowledge within the industry on soil nitrogen testing.

In total, from October 2020 to February 2024 approximately 5,650 soil samples were collected and processed. In addition, just under 300 additional Nitrate Quick Test samples were also collected and processed. Conversion of mineral nitrogen results to a field scale was accomplished using 181 bulk density samples that were collected periodically at all sites. Alongside the soil test data 463 plant biomass samples were also collected as part of the regular monitoring, with an additional 182 plant biomass samples collected from other sites.

3.5.1 Mineral nitrogen

Mineral nitrogen data were collected in units of mg/kg and converted to a field scale kg N/ha using field bulk density samples. The nitrate-nitrogen and ammoniacal-nitrogen fractions were also tested and reported for all samples.

Changes in mineral nitrogen at each site could be linked to management decisions such as crop in paddock and fertiliser applications, as well as environmental conditions such as weather and point in

season. Table 10 shows the average quantity of mineral nitrogen for each sampled crop alongside the range in brackets, demonstrating that for most crops mineral nitrogen levels in each layer fluctuate significantly. Figure 44 is a graphical representation of the data in Table 10 for the top 15 cm. Note that for both Table 10 and Figure 44 the crops are not presented in rotation order and are not intended to show changes over time. When the maximum and minimum values for each crop by depth layer are compared, there is an average of a 12-fold difference in maximum and minimum mineral nitrogen quantities within a crop, in one particular outlier this difference was nearly 70-fold. This underscores the central extension message to growers of the necessity of regular testing, as a test taken at one point in a crop's growth cycle or in an overall rotation is unlikely to have any relevance at another point in the season and could be highly misleading.

The specific magnitude of mineral nitrogen quantities in the soil, while still of value, is therefore less important than the rate of change in mineral nitrogen and what promotes these changes. Extensive prior research has shown the following factors typically promote changes in mineral nitrogen, and these have been observed and supported by the data collected through regional monitoring:

Factors promoting mineral nitrogen increase:

- Nitrogen fertiliser application (direct addition to mineral nitrogen pool)
- Warm and wet climate (increased mineralisation)
- Cultivation (increased mineralisation)
- Crop residue breakdown (direct addition to mineral nitrogen pool and soil organic nitrogen pool)
- Nitrogen fixation by legume crops (direct addition to mineral nitrogen pool).

Factors promoting mineral nitrogen decrease:

- Crop uptake (direct reduction in mineral nitrogen pool)
- Immobilisation (movement of mineral nitrogen into organic nitrogen pool)
- Leaching (direct reduction in mineral nitrogen pool)
- Denitrification (direct reduction in mineral nitrogen pool).

Each of these factors have been considered in isolation in the following sections, though it must be noted that within a crop-soil system these factors are all working together, often synergistically or in opposition to produce changes in overall soil nitrogen status. This section should not be considered a complete statistical analysis and should not be used to draw conclusions on causation of changes, instead it is intended to summarise observations in mineral nitrogen changes from isolated factors.

For a more comprehensive breakdown of the factors promoting changes in soil and crop nitrogen pools please refer to the sections on Workstream 1 (intensive field trials) and Workstream 3 (model development).

Table 10. Average mineral nitrogen level by soil layer, crop, and region. Range in brackets.

Crop	Region	Number of sampling dates	Mineral nitrogen (kg N/ha) – mean and range			
			0-15cm	15-30cm	30-60cm	60-90cm
Ryegrass (2 crops)	Pukekawa	20	6.6 (0 - 34.3)	5.4 (1 - 25.8)	14.1 (2.7 - 49)	36.5 (4.6 - 91.4)
Fallow	Pukekawa	8	22.2 (4.2 - 53.7)	14 (4.2 - 28.1)	24.1 (10.9 - 49)	-
Onions	Pukekawa	6	20.6 (4.6 - 39.6)	12.1 (6.3 - 17.4)	24 (16.3 - 32.6)	41.5 (25.1 - 61.7)
Barley	Pukekohe	4	7.9 (4.8 - 12.7)	4 (1.1 - 6.9)	11.7 (5.5 - 22)	22.4 (15.8 - 29)
Potato	Pukekohe	8	56.8 (4.6 - 315.7)	35.9 (7.5 - 162.6)	36.6 (15.7 - 79.9)	38.5 (15.8 - 65.9)
Fallow	Pukekohe	13	18.3 (4.5 - 46.1)	15.4 (4.5 - 39.3)	27.3 (5.5 - 55.1)	31 (15.8 - 44.8)
Cauliflower	Pukekohe	4	28.3 (5.4 - 51.7)	29.6 (6.2 - 60.8)	57.1 (30.3 - 71.6)	51.8 (36.9 - 73.8)
Onions	Pukekohe	6	27.8 (3 - 76.7)	15.1 (8.1 - 29.1)	34.9 (24.8 - 52.3)	43.5 (31.6 - 63.2)
Mustard	Tuakau	5	18.9 (3 - 33.9)	13.9 (1.3 - 39.5)	24.2 (8.3 - 44)	37.2 (14.9 - 49.6)
Fallow	Tuakau	14	17.1 (4.2 - 32.5)	14.8 (2.9 - 32.2)	23.4 (6 - 44)	25 (7.4 - 39.7)
Carrot	Tuakau	7	8.2 (2.4 - 20.3)	9 (2.9 - 14.6)	36.2 (11 - 82.5)	33.9 (5 - 57.1)
Onions (2 crops)	Tuakau	13	57 (10.2 - 95.5)	28.6 (6.9 - 60.4)	51.7 (22 - 129)	53.6 (34.8 - 86.9)
Maize	Matamata	5	80.9 (58.2 - 123.8)	47.9 (19.7 - 80.2)	58 (41.4 - 75.5)	38.4 (31.7 - 46.4)
Potato	Matamata	6	47.2 (28.7 - 73.6)	45.5 (23.1 - 81.5)	30.9 (17.3 - 56)	19.7 (3.7 - 39)
Fallow	Matamata	7	31.1 (4.4 - 54.9)	33.8 (11.6 - 73.1)	55 (36.6 - 78)	37 (22 - 63.5)
Cauliflower	Matamata	4	35.3 (6.4 - 71.2)	36 (13.3 - 62.1)	58.5 (48.7 - 65.8)	34.2 (26.8 - 41.5)
Onions	Matamata	7	23.7 (8.8 - 49.7)	15.5 (4.9 - 24.7)	26 (9 - 51.2)	31 (7.6 - 80.5)
Clover	Matamata	5	12.1 (6.3 - 20.6)	12.9 (5.3 - 30.5)	23 (5.1 - 51.2)	21.3 (6.3 - 29.3)
Crop	Region	Number of sampling dates	Mineral nitrogen (kg N/ha) – mean and range			
			0-15cm	15-30cm	30-60cm	60-90cm
Potato (2 crops)	Levin	17	27.4 (8.9 - 119)	36.5 (9.1 - 210.7)	33 (8.3 - 109.6)	16.5 (2.6 - 51.3)
Fallow	Levin	2	24.6 (12.3 - 37)	18.7 (13 - 24.4)	31.1 (20.8 - 41.5)	29.9 (29.9 - 29.9)
Grass	Levin	7	8.5 (3.2 - 24)	6.7 (0 - 18.4)	12.8 (6.9 - 20.8)	14.7 (8.5 - 25.6)
Onions	Levin	8	10.7 (4.9 - 21.1)	10.6 (6.6 - 16.6)	22.9 (17.3 - 27.7)	28.8 (21.4 - 42.7)
Maize	Levin (2)	6	14.3 (6.4 - 30)	11.3 (6.8 - 18.1)	20.3 (13 - 30.4)	24.6 (12.9 - 34.3)
Fallow	Levin (2)	6	27.7 (3.4 - 109)	32.9 (7.7 - 147.4)	29 (8.7 - 47.8)	26.6 (8.6 - 38.6)
Grass	Levin (2)	8	9.1 (0 - 23.5)	8.2 (0 - 15.3)	17.4 (8.7 - 34.7)	17.7 (0 - 38.6)
Cabbage	Levin (2)	3	72.7 (39 - 91.9)	28.7 (21.5 - 39.1)	43.4 (17.4 - 65.2)	15.7 (8.6 - 21.4)
Watermelon	Levin (2)	3	51.3 (13.4 - 105.9)	32.3 (6 - 73.3)	26.9 (8.3 - 45.7)	18.5 (13.2 - 25)
Parsley	Levin (2)	7	37.8 (11.9 - 63.6)	30.3 (10.9 - 75.9)	39.7 (17.4 - 87.7)	22.3 (12.9 - 42.4)
Maize	Hawke's Bay	2	81 (78.4 - 83.6)	63.6 (61.3 - 65.9)	32.8 (22.7 - 42.8)	18.6 (11.7 - 25.5)
Fallow	Hawke's Bay	3	47.8 (29.6 - 60.8)	152.3 (28.3 - 376.1)	57.8 (34.7 - 91.4)	32.6 (15.8 - 50.4)
Grass (3 crops)	Hawke's Bay	12	20.7 (6.2 - 35.2)	24.5 (6.1 - 102.3)	18 (3.2 - 41)	14.4 (3.2 - 22.1)
Squash (3 crops)	Hawke's Bay	9	44.8 (20.1 - 87.3)	42.9 (14.2 - 65.6)	67.4 (15.8 - 132.3)	44.6 (12.6 - 113.4)
Potato	Ashburton	6	90.7 (25.1 - 219.6)	63.3 (22.6 - 130.6)	54.2 (39.6 - 79.1)	63.2 (31 - 146.3)
Fallow	Ashburton	9	48.5 (17.3 - 138.6)	24.9 (13.1 - 39.3)	31.3 (8.8 - 65.9)	29.5 (8.9 - 57.6)
Wheat	Ashburton	9	26.9 (7.4 - 98.6)	17 (7.7 - 42.6)	26.4 (0 - 57.1)	29.1 (0 - 53.2)
Peas	Ashburton	4	35.5 (14.9 - 67.5)	45 (9.6 - 83.8)	40.4 (16.3 - 74.7)	53.2 (19.1 - 110.8)
Carrots	Ashburton	6	78.3 (22.5 - 149.8)	46 (18.7 - 88)	47.7 (29.5 - 75.6)	65.7 (31 - 167.5)
Pumpkin	Leeston	5	54.2 (20.4 - 112.9)	41.1 (14.5 - 126.5)	32.1 (15.8 - 81.9)	15.8 (12.6 - 18.9)
Fallow	Leeston	4	33.8 (20.3 - 59.1)	44.8 (31.9 - 71.7)	53.8 (10.4 - 104)	27.6 (7.2 - 47.3)
Turf Grass	Leeston	16	20.6 (3.8 - 61.1)	18.3 (2 - 68.8)	17.1 (0 - 50.4)	14.0 (3.2 - 25.2)
Onions	Leeston	3	115.5 (99.2 - 145.6)	88.4 (63.6 - 111.8)	67.1 (64.6 - 70.2)	99 (92.6 - 107.7)
Broccoli	Leeston	3	37.4 (14.7 - 74.6)	32.4 (15.8 - 60.4)	133.2 (9.1 - 362.3)	45.2 (15.8 - 104)

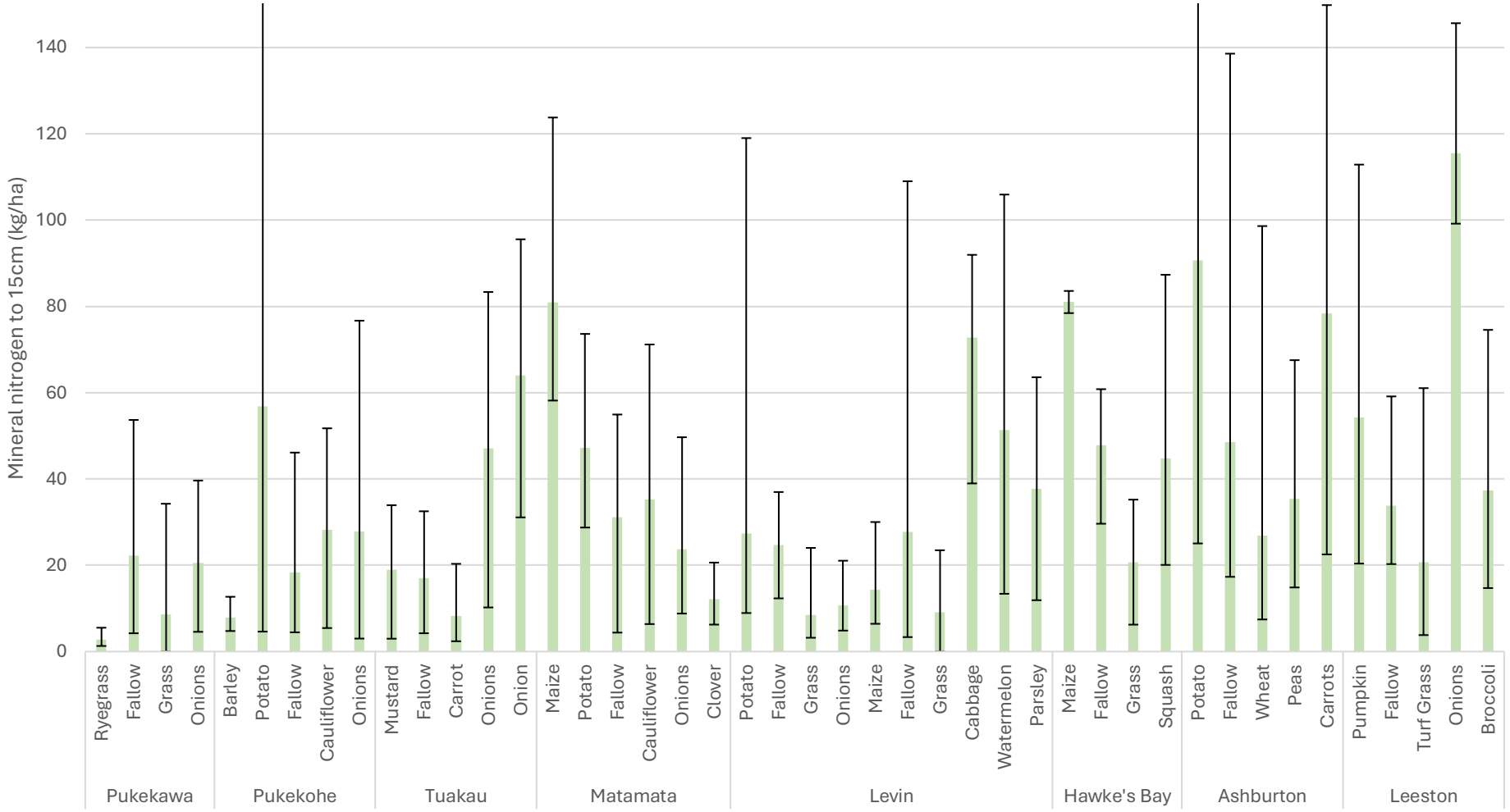


Figure 44. Average mineral nitrogen in top 15 cm by crop and region. Range represented by bars.

Mineral N: Nitrogen fertiliser

This section summarises observed changes in mineral nitrogen levels after nitrogen fertiliser application. The analysis in this section considers nitrogen fertiliser in isolation from other factors so should be as a summary of observations and not a claim of direct causation.

This analysis considers the effect on mineral nitrogen test results in the top 30 cm from fertiliser applications of greater than or equal to 30 kg N/ha. A comparison between test data from a minimum of two weeks to a maximum of four weeks following application is made to the closest test sample prior to application. A maximum difference of six weeks between the previous and subsequent tests from the fertiliser application was also implemented to minimise the potential of other factors (e.g., enhanced, or reduced mineralisation) significantly skewing the results.

Interestingly, the difference in mineral nitrogen to 30 cm was frequently negative between the samples taken either side of the fertiliser application – this would indicate that for most sites, fertiliser was being applied to match crop uptake, without leading to significant accumulations in the soil. No patterns could be observed when broken down by quantity of nitrogen in the pre-application sample, not even when grouped against quantity of fertiliser applied.

Negative differences, i.e. a loss of mineral nitrogen between the two sampling points after a fertiliser application, occurred on four of the sites. Each of these negative changes occurred during the peak of crop uptake with high N-demand crops (potatoes, carrots) and were then either followed by an additional fertiliser application or by harvest. This is demonstrative of good practice, providing enough fertiliser to match crop uptake without resulting in excess nitrogen accumulation, which would increase the risk of nitrate leaching.

Significant positive differences, i.e. a gain in mineral nitrogen between the two sampling points after a fertiliser application, of over 50 kg N/ha in the top 30 cm were relatively rare occurrences, happening only five times across five of the monitoring sites. Only one of these had a significant accumulation of greater than 100 kg N/ha. In this case, the extreme magnitude of change (+460 kg N/ha) and the proximity of the subsequent sample to the fertiliser application indicates a high likelihood of having sampled through a fertiliser band, and this result can therefore be discarded.

What this analysis shows, in isolation from other soil, crop, and climate factors, is that most fertiliser applications on regional monitoring sites were made with good practice and did not lead to an undue risk of leaching. Large accumulations in nitrogen in the top 30 cm appear more likely to be primarily driven by mineralisation, crop residue breakdown, and rotation management than by fertiliser application.

Mineral N: Nitrogen mineralisation

Mineralisation from the soil organic nitrogen pool can have a significant impact on the quantity of the mineral nitrogen pool in the soil, especially in the top 30 cm. Mineralisation is a process undertaken by soil bacteria where nitrogen mobilised from soil organic matter is broken down into the mineral forms of nitrate-nitrogen and ammoniacal-nitrogen which are then available for plant uptake. The soil bacteria undertaking this process typically thrive under warm and moist (but not waterlogged) conditions, and so mineralisation typically occurs more rapidly in late spring, summer, and early autumn.

The regional monitoring test programme took Potentially Mineralisable Nitrogen measurements for the 0-15 cm and 15-30 cm soil layers, with these results predicting the volume of mineral nitrogen expected to mineralise over a specific time period under laboratory conditions. Part of the model developed in Workstream 3 converts these results into the quantity of mineral nitrogen expected to mineralise under *actual* field conditions over the crop growth period.

Table 11 shows the estimates for mineralised nitrogen over the crop growth period for crops from the regional monitoring programme. On average across all regional monitoring crops analysed, not accounting for losses, the average quantity of mineral nitrogen mineralised during crop growth, as predicted by the Workstream 3 sub-model, was 86 kg N/ha, ranging from 32 kg N/ha to 175 kg N/ha.

Table 11 also shows the proportion of the total crop nitrogen that could have been supplied by the mineralised nitrogen – ignoring losses due to leaching and through other pathways. This was determined by dividing the estimate of mineralised nitrogen against the total crop nitrogen uptake. On average across all crops, the mineralisation sub-model predicts that 47% of total crop nitrogen requirement could be met through mineralisation when potential losses are not factored in.

While this shows the large organic matter mineralisation component, it must be emphasised that crop nitrogen requirements are not linear, with most of the demand coming at the peak of the growth phase. Therefore, while mineralisation may supply a large quantity of nitrogen it may not supply enough during critical growth phases, justifying the necessity of applying fertiliser to match daily rather than total plant demand. This is accounted for within the tool as mineralisation is added to the soil pool in a daily timestep based on climate data, but at a nitrogen balance level it is inaccurate to look only at the quantity of nitrogen mineralised while not accounting for timing – therefore the percentage supply figures in Table 11 are indicative of potential supply only.

The ability of the soil to satisfy plant requirements is also heavily dependent on the crop type and time of the season. For example, a cauliflower crop grown over 100 days in winter will not be able to draw upon significant quantities of mineralised nitrogen due to the short duration and cold and often waterlogged soil conditions. Therefore, in the example in Table 11, only 9% of the total crop requirement could be met by soil mineralisation, even without accounting for potential losses. Meanwhile, for onion crops grown from spring through to mid-summer, mineralisation could have supplied on average 68% of the total crop nitrogen requirement.

Location also plays a significant role in mineralisation due to soil and climate factors. The same crop grown over the exact same period and with the exact same PMN test result could see major differences in the quantity of mineralised nitrogen if grown in Pukekohe instead of in Canterbury, or if grown on Brown soils instead of Allophanic soils. These differences can be significant, with some scenarios showing a more than doubling of the estimate of nitrogen mineralised when the location or soil order is modified.

Table 11. Mineralised nitrogen (0-30 cm) over the course of crop growth as predicted by Workstream 3 sub-model.

Crop	Region	Planting date	Harvest date	Initial PMN (mg/kg)	Model estimate of mineralised nitrogen (kg N/ha)	Proportion of total crop N **potentially** supplied by mineralised nitrogen (%)
Onions	Pukekawa	13/06/2021	17/01/2022	16	48.8	74%
Ryegrass (2)	Pukekawa	01/05/2022	15/03/2023	31	126.7	163%
Potato	Pukekohe	22/12/2022	01/05/23	66	97.6	58%
Cauliflower	Pukekohe	02/04/2022	13/07/2022	21	31.8	10%
Onions	Pukekohe	14/07/2021	04/02/2022	24	69.2	49%
Carrot	Tuakau	07/04/2021	18/11/2021	38	121.2	50%
Onions	Tuakau	04/07/2022	10/01/2023	62	167.6	-
Onions	Tuakau	18/07/2023	25/01/2024	25	69.8	-
Maize	Matamata	21/10/2021	27/04/2022	31	39.4	16%
Potato	Matamata	10/10/2023	19/02/2023	52	48.1	24%
Cauliflower	Matamata	23/03/2021	22/07/2021	66	64.6	19%
Onions	Matamata	24/07/2022	01/03/2023	34	54.4	34%
Clover	Matamata	29/03/2023	19/09/2023	45	58.6	57%
Potato (2)	Matamata	10/10/2023	19/02/2024	67	92.2	37%
Potato	Levin	04/11/2020	28/05/2021	33	74.6	37%
Onions	Levin	13/06/2021	18/02/2022	35	112.9	75%
Maize	Levin (2)	13/11/2020	25/04/2021	38	74.4	56%
Cabbage	Levin (2)	23/12/2021	20/04/2022	66	87.4	39%
Watermelon	Levin (2)	15/12/2022	22/03/2023	74	89.7	67%
Ryegrass	Hawke's Bay	05/04/2021	05/07/2021	51	56.2	37%
Ryegrass (2)	Hawke's Bay	20/03/2022	25/09/2022	33	66.4	53%
Ryegrass (3)	Hawke's Bay	01/05/2023	25/10/2023	71	119.9	-
Squash	Hawke's Bay	12/12/2020	19/03/2021	62	55.4	42%
Squash (2)	Hawke's Bay	03/12/2021	15/03/2022	56	53.1	41%
Squash (3)	Hawke's Bay	01/12/2022	01/04/2023	85	91.6	-
Potato	Ashburton	24/09/2020	23/03/2021	98	138.8	37%
Wheat	Ashburton	21/04/2021	19/02/2022	59	145.1	40%
Peas	Ashburton	27/09/2022	04/02/2023	94	102.1	33%
Oats	Ashburton	10/04/2023	04/08/2023	93	100.6	84%
Carrots	Ashburton	11/09/2023	15/03/2024	52	89.8	42%
Pumpkin	Leeston	20/11/2020	19/04/2021	60	69.3	29%
Turf Grass	Leeston	20/05/2021	22/02/2022	85	175.0	83%
Broccoli	Leeston	28/12/2022	15/03/2023	98	67.8	23%
Onions	Leeston	20/08/2023	01/03/2024	67	121.1	83%

Mineral N: Cultivation and crop residue breakdown

Crop residue breakdown can lead to significant increases in soil mineral nitrogen and in some cases can also lead to a decrease in soil mineral nitrogen due to immobilisation.

Being able to make better use of this 'free' or 'recycled' nitrogen would be valuable to growers when planning their rotations and fertiliser inputs, as would understanding any immobilisation effect from high C:N ratio residues.

A comparative analysis was conducted between mineral nitrogen test samples taken before harvest and test samples taken up to one month after harvest during the subsequent fallow period to determine the immediate impact of residue decomposition. As with the analysis in other sections, this does not consider other factors such as increased mineralisation or leaching that may also occur during the same interval.

In total, 26 crops from the regional monitoring programme were analysed, and from these it was found that on average there was a 140% increase in mineral nitrogen from pre-harvest through to the following fallow period. This ranged from a decrease of 46% (-10 kg N/ha) on an onion crop to a 517% increase (54 kg N/ha) following a cauliflower crop harvest. Grass, brassica, potato, and other vegetable crops tended to have much larger mineral nitrogen increases following harvest, at 14, 21, 31, and 16 kg N/ha on average respectively. In contrast, grain crops such as wheat, barley, and maize tended to see an initial decrease in mineral nitrogen in the top 30 cm following harvest, though the average reduction was less than 5 kg N/ha.

Table 12 shows the potential residue as identified from each of the main crops sampled in the regional monitoring programme.

Crop residue has been highlighted as a key area for further data collection in future work in this area, with plans to integrate any additional data into the SVS Tool in the future.

Mineral N: Crop uptake

Crop uptake is, unsurprisingly, often the single biggest pathway for decreases in mineral nitrogen levels in the soil. Uptake of nitrogen is highly dependent on crop type and yield. Table 12 shows the nitrogen uptake of selected crops from the regional monitoring at the final biomass sample.

Not all crop nitrogen uptake results in a permanent loss of mineral nitrogen from the system, with leftover crop residue eventually breaking down and releasing nitrogen to the mineral or organic pools. The quantity of residue is also dependent on crop type and yield, with certain brassica crops such as cauliflower and broccoli leaving significantly more crop nitrogen behind as residue than an onion crop for example.

Table 12. Total crop uptake at final biomass sample.

Crop	Region	Total crop uptake (kg N/ha)	Removed from field (kg N/ha)	Potential residue (kg N/ha)
Onions	Pukekawa	65.8	54.5	11.2
Ryegrass (2)	Pukekawa	77.8	77.8	Minimal
Potato	Pukekohe	167.9	110.9	57.0
Cauliflower	Pukekohe	331.6	135.5	196.2
Onions	Pukekohe	140.3	117.8	22.5
Carrot	Tuakau	244.0	87.2	156.8
Maize	Matamata	250.5	249.0	Minimal
Potato	Matamata	202.1	74.6	127.5
Cauliflower	Matamata	168.9	-	-
Onions	Matamata	160.4	136.7	23.7
Clover	Matamata	103.7	0.0	103.7
Potato (2)	Matamata	238.3	198.5	39.9
Potato	Levin	201.3	172.5	28.9
Grass	Levin	24.6	0.0	24.6
Onions	Levin	151.0	124.0	27.0
Maize	Levin (2)	132.1	132.1	Minimal
Cabbage	Levin (2)	226.0	110.7	115.3
Watermelon	Levin (2)	134.0	75.5	58.4
Parsley	Levin (2)	16.0	16.0	Minimal
Maize	Hawke's Bay	361.2	361.2	Minimal
Grass	Hawke's Bay	150.5	0.0	150.5
Grass (2)	Hawke's Bay	125.2	0.0	125.2
Potato	Ashburton	373.3		
Wheat	Ashburton	359.9		
Peas	Ashburton	307.8	307.8	0.0
Oats	Ashburton	238.2	-	-
Carrots	Ashburton	327.7	216.7	111.0
Pumpkin	Leeston	235.3	167.4	67.8
Turf Grass	Leeston	211.6	75.8	135.8
Broccoli	Leeston	291.5	84.7	206.8
Onions	Leeston	243.6	203.5	40.1

Mineral N: Leaching

Nitrate leaching was not directly monitored within the regional monitoring programme, though the soil moisture probes that were installed in some crops could give a general sense of leaching potential through measurement of VIC.

A full report (Hosie, 2024) was commissioned which analysed the soil moisture changes and potential nutrient movement for several probe installations on sites 1-7. Table 13 shows a summary of the assessed leaching risk during these installation periods at each site. In general, when crops are in the

ground the lower profile nutrient accumulation is usually not significantly elevated, resulting in reduced risk of leaching – supporting the hypothesis that (in general) most significant leaching events occur post-harvest.

Table 13. Soil moisture VIC measurement summary from select installations.

Site number	Soil texture	Installation period	Crop	Drainage	Leaching below active root zone	Lower profile nutrient accumulation risk
1	Heavy	July 2022 – Oct 2022	Ryegrass	Mod	High	High
2	Heavy	Feb 2023 – May 2023	Potato	Mod-well	Low	Low
3	Heavy	Aug 2023 – Jan 2024	Onion	Mod-well	Moderate	Moderate
4	Medium	Aug 2022 – Jan 2023	Onion	Mod-well	Moderate	Moderate
5	Medium	Dec 2022 – Apr 2023	Potato	Mod-well	Low	Low
6	Medium	Dec 2022 – Mar 2023	Watermelon	Mod-well	Low	Moderate
7	Heavy	Dec 2022 – Apr 2023	Buttercup squash	Mod-well	High	Low

3.5.2 Potentially mineralisable nitrogen

The content in this section originates from Stenning, 2023. This report summarised the PMN data collected up to that point in the regional monitoring programme. The full report is available upon request.

PMN: Background

PMN data was collected in Workstream 2, as Hot Water Extractable Nitrogen (HWEN) samples taken monthly at each site at 0-15 cm and 15-30 cm sample depths. These results are reported back as Hot Water Extractable Inorganic Nitrogen (HWEIN) and Hot Water Extractable Organic Nitrogen (HWEON) in mg/kg. The latter is scaled to Potentially Mineralisable Nitrogen (PMN) using the closest bulk density sample collected by the regional monitors and analysed by PFR, as well as the sample core length. Scaling HWEON results to kg N/ha ourselves using our own bulk density measurements was the most consistent approach when comparing different laboratory result formats. This same methodology was applied to the mineral N results.

Three different laboratories have been used throughout the regional monitoring, with each reporting results in different formats and units. Eurofins was used from October 2020 to October 2023 after which the programme switched to ARL. Following the cyclone damage to the ARL testing laboratory, this work was subcontracted to Hill's.

PMN: Laboratory issues

Several assumptions have been made to account for inconsistent laboratory reporting:

1) **Detectability limits for Nitrate-N (mg/kg), Ammoniacal-N (mg/kg) and Mineral N sum (mg/kg):** After the switch to ARL detectability limits were reported as < 0.5 (Nitrate-N and Ammoniacal-N), <1 and <2 (Mineral N). These have been interpreted as 0.2 mg/kg for results of < 0.5 and < 1, and as 1.0 mg/kg for results of <2.

2) **HWEIN re-calculation:** ARL/Hill's report HWEIN in units of kg N/ha using their own bulk density measurement from the collected sample. As they cannot know the volume used to collect each sample this measurement will be less accurate than the ones collected by the regional monitors and analysed by PFR. Therefore, HWEIN in units of mg/kg was back calculated using the laboratories bulk density and sample core length, before being re-calculated to units of kg N/ha using our own bulk density measurements.

3) **Detectability limits for HWEON:** ARL/Hill's have high detectability limits for HWEON (aka PMN) measurements, with results under 30 mg/kg being reported as < 30. Despite this, they also report PMN in kg N/ha units for these results, sometimes including a less-than sign and sometimes without. The differences between field scaled PMN results for 0-15 cm and 15-30 cm are often quite large and cannot be explained by bulk density. Therefore, it has been assumed that the equation used by ARL/Hill's to generate results in kg N/ha use the raw mg/kg result.

   Therefore, for sample results reported as < 30 we converted the PMN figure from kg N/ha to mg/kg by dividing by bulk density and core length. This produced figures that sometimes exceeded the detectability limit of 30 mg/kg.

PMN: Summary of data

There were 439 samples with HWEN/PMN results from the primary sampling across the nine sites, with an average of approximately 25 distinct sample collections for each site between October 2020 and June 2023.

For the majority of sample collections two of the four collected soil depth layers (0-15 cm and 15-30 cm) were analysed using the Hot Water Extractable Nitrogen Test.

Figures 45-47 show changes in PMN across the timespan of the project for each of the regional monitoring sites. What is immediately apparent from these graphs is the presence of significant outliers. Most sites seem to have one or several higher than usual PMN readings distributed across seasons, though with a notable cluster in the second half of 2022. The cause of these outliers is currently unclear. For Table 14 and Figure 34 we applied an incl./excl. rule. PMN results which are greater or lesser than the average for each site multiplied or divided by 3 are excluded.

What is also apparent is the relatively even split between HWEON results taken from 0-15 cm and those taken at 15-30 cm, though this can vary significantly within individual samples. Typically, PMN levels are slightly higher in the top 15 cm, on average accounting for 55% of the total PMN to 30 cm (range: 7% - 89%). There is the potential to include a scaling calculation within the SVS tool that converts any PMN results input for the 0-15 cm layer only to 0-30 cm, this should be investigated further.

Table 14. Average PMN results to 30cm (kg N/ha) for each season by site and across entire project.

Site	Project		Spring		Summer		Autumn		Winter	
	Mean	Median	Mean	Median	Mean	Median	Mean	Median	Mean	Median
1	70	67	65	67	80	82	74	66	63	63
2	79	71	70	66	93	85	55	53	110	80
3	102	84	102	101	112	85	94	79	96	71
4	128	130	136	137	134	138	120	108	111	112
5	160	152	162	160	166	155	175	161	130	127
6	188	166	150	158	198	196	222	158	170	166
7	179	172	201	183	180	173	166	158	154	166
8	279	284	318	323	318	313	250	194	226	222
9	306	309	345	321	306	299	285	301	278	285

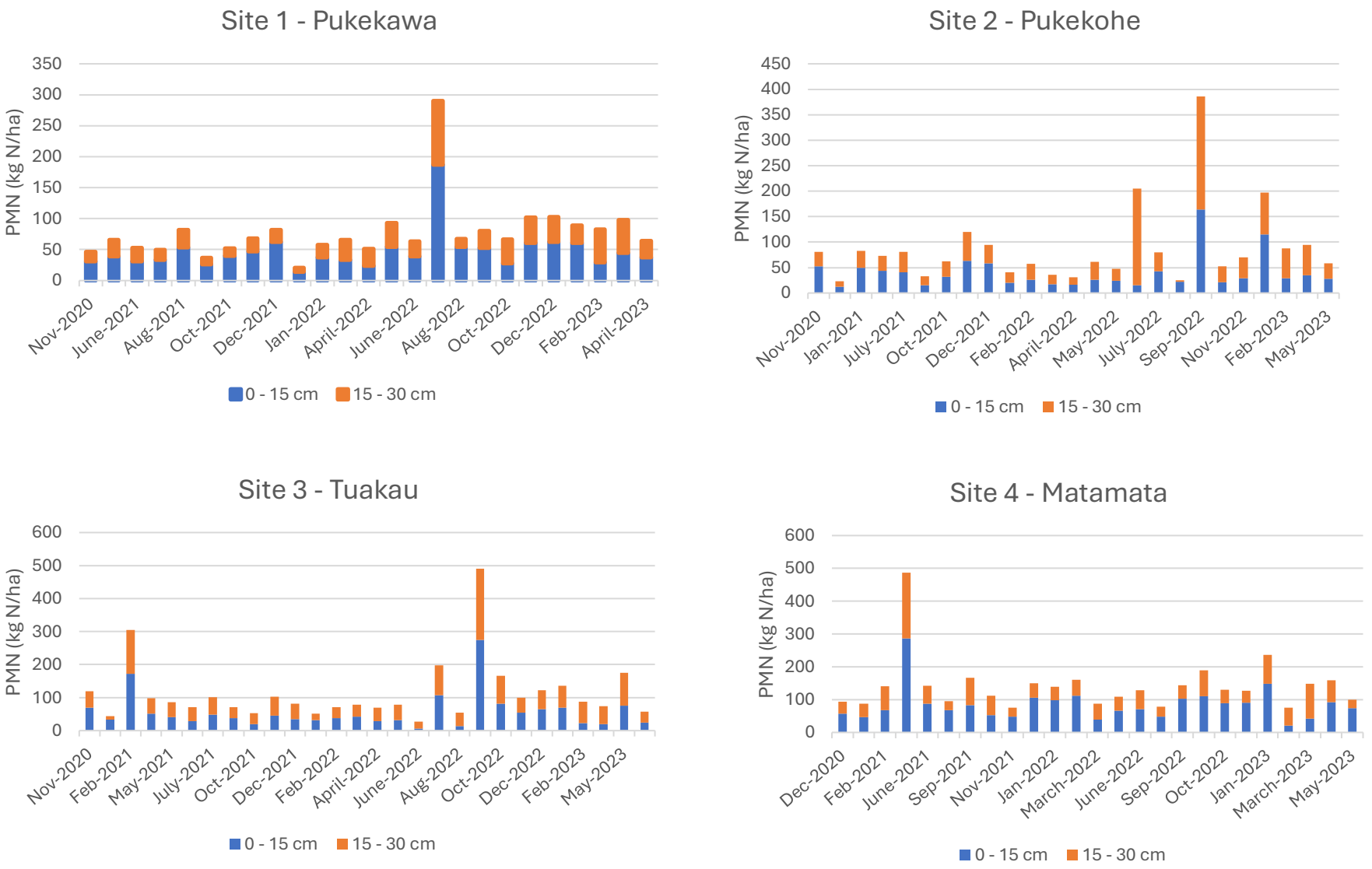
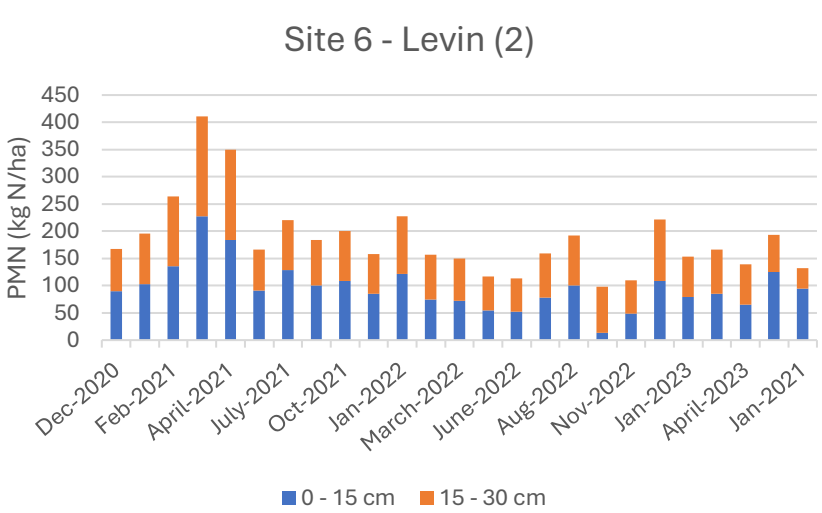
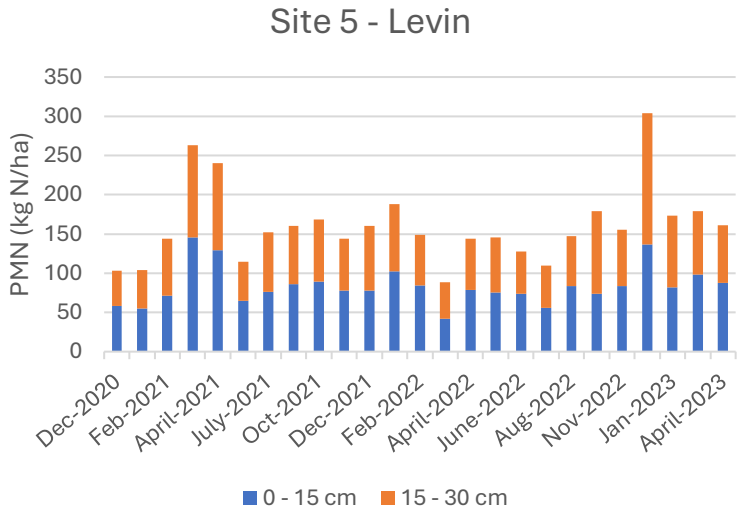
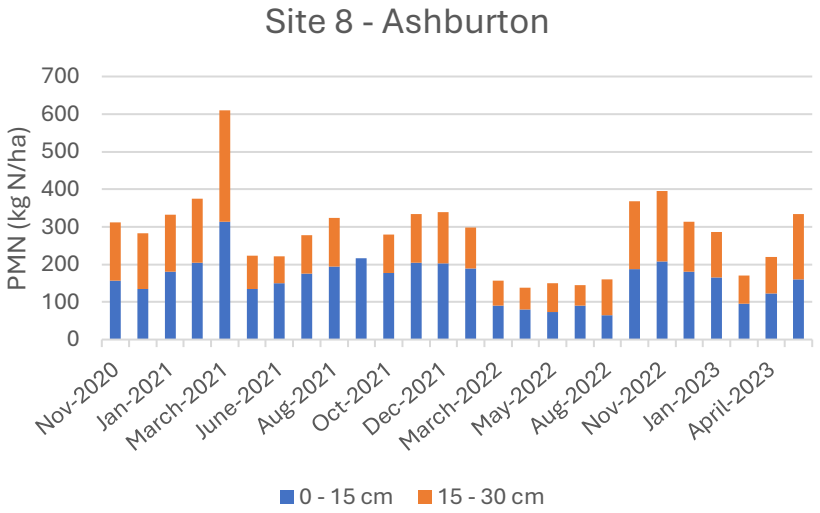


Figure 45. Calculated PMN by trial site for Sites 1 – 4.







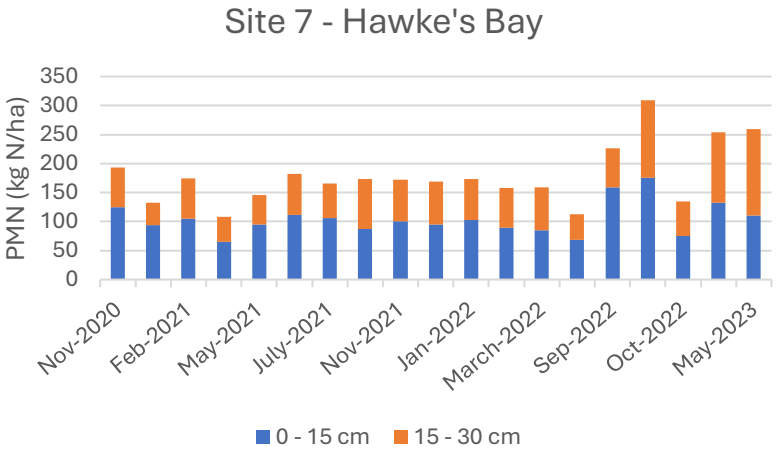


Figure 46. Calculated PMN by trial site for Sites 6 – 8.

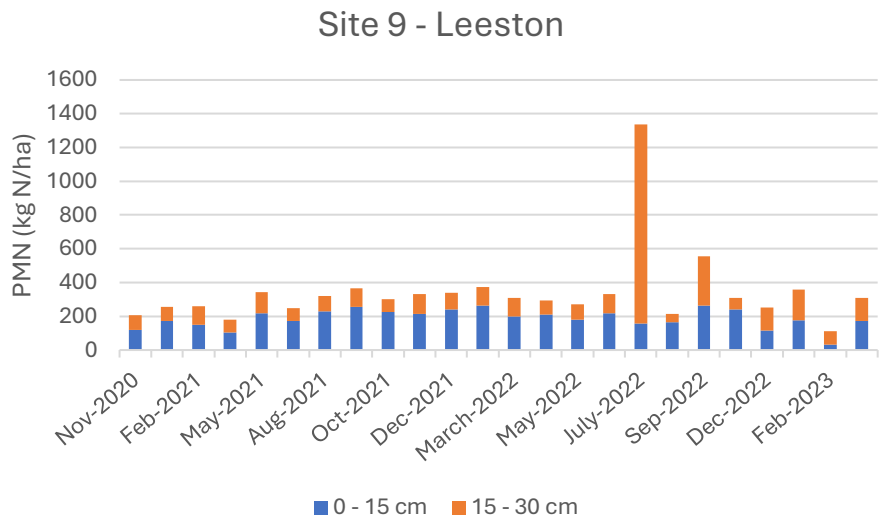


Figure 47. Calculated PMN by trial site for Site 9.

Figure 48 shows the mean PMN results to 30 cm for each site. Across almost all sites, except for Site 2 in Pukekohe – the winter months have a noticeably lower mineralisation rate than other seasons, with the difference between the winter average and the whole site average ranging from -19% to -5% (+38% at Site 2) and averaging -7% across all sites. The reverse is true for the summer averages, which range between 0% and +18% greater than the whole project mean, averaging +8% across all sites.

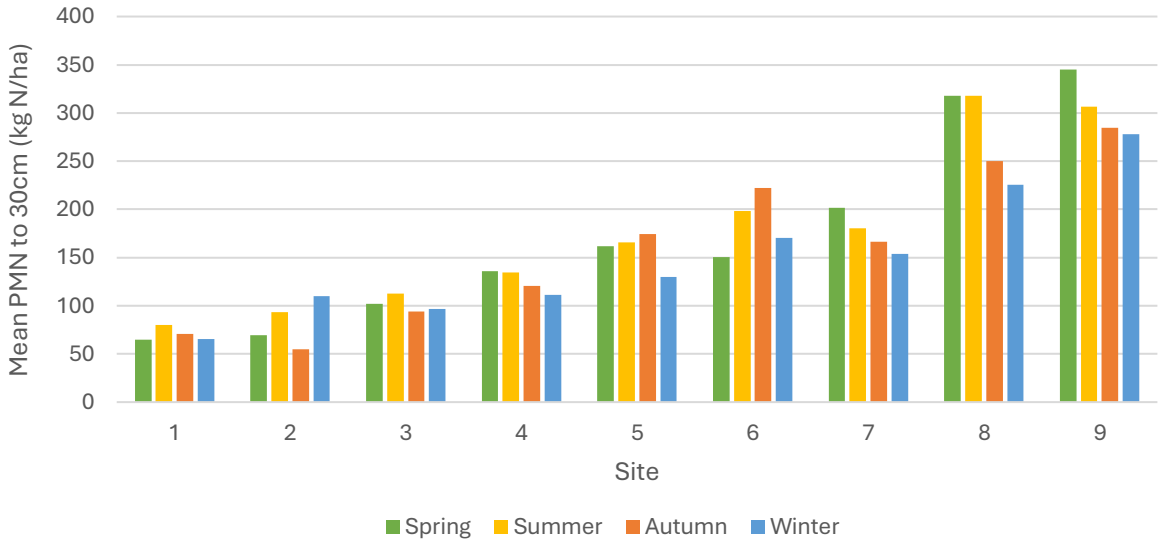


Figure 48. Average PMN to 30 cm by season and by site (outliers removed).

Figure 49 shows the means, medians, and quartiles for PMN results to 30 cm across sites from three of the primary New Zealand growing regions. Sites in the Pukekohe growing hub have the lowest average PMN levels across all seasons, likely due to soil depletion from over a century of intensive vegetable production. Canterbury sites have the highest average PMN levels across seasons. Outliers have skewed some of the means (indicated by X), especially in winter. Canterbury sites have the largest outliers.

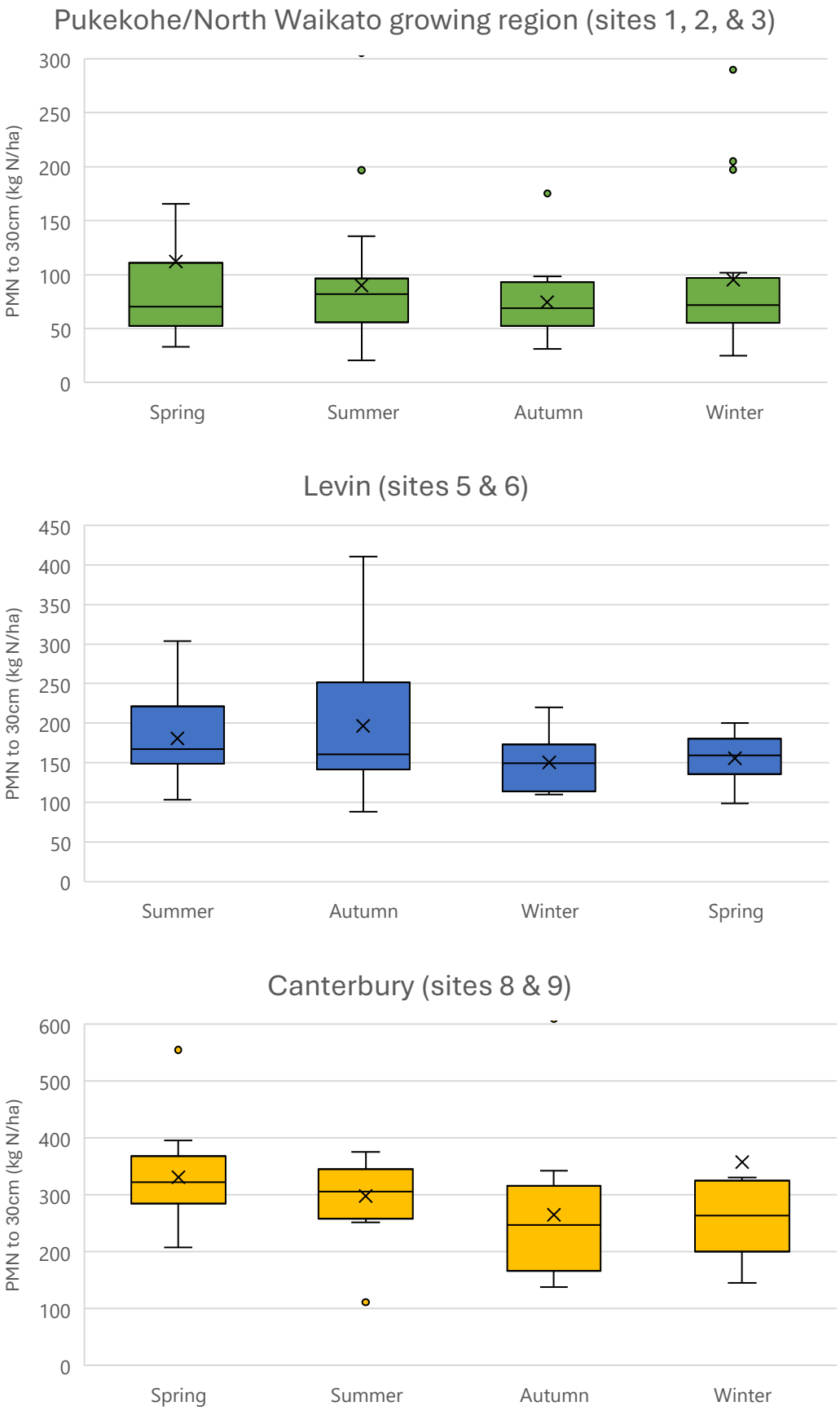


Figure 49. Boxplots for averages across three regions (excluding Matamata and Hawke's Bay).

3.5.3 Nitrate Quick Test

The Nitrate Quick Test is a rapid and affordable method for determining soil nitrate status. The Nitrate Quick Test strips are similar to the litmus strips used for pH testing but are coated with a chemical that changes colour when it reacts with nitrate. A simple colorimetric scale is used to quantify the nitrate concentration in the soil sample. This is in mg nitrate/litre of soil solution, which can then be converted into more useful kg nitrate/ha figure through the SVS Tool or using conversion tables.

Because the Nitrate Quick Test is so easy to use it has been heavily promoted to New Zealand growers by PFR, the V R & I Board, and the Foundation for Arable Research (FAR) among others. The latter organisation produced an excellent user guide which was used as the first resource for growers throughout the SVS programme: link.

The SVS programme promoted the Nitrate Quick Test heavily throughout the Workstream 4 extension work and at most grower workshops. To improve grower confidence in the accuracy and reliability of these tests, comparison samples were taken at several sites during the first half of the regional monitoring programme period. This allowed for side-by-side testing of soil samples using the Nitrate Quick Test and standard laboratory KCl extractions.

The content in this section originates from Stenning, 2022. This report summarised the side-by-side comparative analysis performed on standard commercial laboratory nitrate test results and nitrate quick test results from samples collected through the regional monitoring programme from October 2020 to June 2022. The full report is available upon request.

Nitrate Quick Test - Executive Summary

- 232 Nitrate Quick Tests were taken between Oct 2020 and June 2022.
- There is a strong correlation (R^2 = 0.69) between Nitrate Quick Test and laboratory nitrate KCl extraction results.
- The average difference between the two test types is approximately 8 kg N/ha less (5.4 mg NO_3-N/kg dry soil).
- 11% of samples had Nitrate Quick Test results differ by 20 kg N/ha or more from laboratory comparisons. The largest observed difference was approximately 70 kg N/ha.
- Extrapolating Nitrate Quick Test results for the 0 – 15 cm layer to a 30 cm root depth results in an 11% difference when compared to samples taken at 0 – 30 cm. This ranges between 65% under-estimation to 78% over-estimation.
- Assuming that < 30 kg N/ha to 30 cm constitutes a low leaching risk, 48% of laboratory samples and 38% of Nitrate Quick Test samples would show a low risk of nitrate leaching.
- There is no observed correlation between pre-planting mineral nitrogen levels and quantity of base fertiliser applied.
- Ammonium accounts for an average of 33% of total mineral nitrogen. Two sites had average ammonium concentrations of > 50% of total mineral nitrogen.
- Ammonium concentrations increase with soil depth, soil pH, C:N ratio (peaking at a ratio of 13:1), and during the months of October – May.
- In-field spatial variability presents a challenge to growers, with a single site measured variability of ±20 kg N/ha based on sample location along the transect.

Nitrate Quick Test - Introduction

The Nitrate Quick Test has been used as part of the SVS Workstream 2 regional monitoring trials. Workstream 2 afforded a good opportunity to benchmark the Nitrate Quick Test ("Quick N") results, as obtained in field conditions, against commercial laboratory nitrate-nitrogen soil test results (using the standard KCl extraction method).

Nitrate Quick Test - Methodology

Quick N tests have been taken since October 2020 across sites 1-4 of Workstream 2. The sites are located in Pukekohe, Tuakau, Pukekawa, and Matamata. The Quick N tests were conducted following the Foundation for Arable Research's (FAR) *Quick Test Mass Balance Guide*[1].

Soil cores were collected across the same sampling points and transects as the regular Workstream 2 laboratory samples. The cores were broken up and thoroughly mixed within the same bucket. Ideally, the soil would have been sieved and mixed to ensure as much variability was removed between the sub-samples sent to the laboratory and those used for Quick N. Unfortunately, due to the heavy clay soils on the Pukekohe-Pukekawa sites, sieving is often impractical.

The sub-samples used for the Quick N tests were then taken back to the office and stored in the fridge or processed immediately. If stored in the fridge they were processed the next day. This was to ensure that there was minimal difference in the time that the laboratory and Quick N subsamples spent at room temperature, to reduce the quantity of nitrate mineralised after sampling.

Initially, the results obtained on the Quick N test strips were interpreted by eye, however from April 2022 results were interpreted with a colour chart and the MQuant StripScan app. Generally, there was relatively little difference in interpretation.

Once results were obtained as mg NO_3/L, they needed to be converted into mg NO_3-N/kg dry soil for accurate comparison with the laboratory samples. This was done using the soil correction table in the FAR guide. The FAR guide provides a simple method to determine soil moisture, however in some instances this was subjective, introducing another element of variability into the results.

While sample collection, sub-sampling procedure, test procedure, and result interpretation and conversion were all done as accurately as possible, it was recognised that the Quick N test is designed to be used in the field, and its results should be used in practice to give relatively broad indications of available nitrate.

[1] https://www.far.org.nz/resources/quick-test-mass-balance-tool-user-guide.

Nitrate Quick Test – Results

232 tests were taken between October 2020 and June 2022, covering depth ranges of 0-15 cm, 15-30 cm, and 30-60 cm. There were 26 individual sampling dates across the four locations, for most of these dates three tests were conducted for each depth range.

For each date and depth, the test results were averaged and compared to laboratory results. Overall, there is a strong correlation between laboratory results and results obtained by the Nitrate Quick Test (Figure 50).

Generally, the Quick N test returns a smaller quantity of nitrate than the typical laboratory KCl extraction, with the gap between results increasing as the quantity of nitrate increases. This is to be expected as the Quick N testing protocol is unlikely to extract the same level of nitrate from a given sample as a full laboratory test.

The average difference between the two test types is approximately 5.4 mg NO_3-N/kg dry soil, which translates to approximately 8.5 kg N/ha difference when using a standard bulk density of 1.05 g/cm^3. This difference is absolutely within the level of confidence the Quick N test is supposed to provide and would be unlikely to have an effect on management practice decisions.

Of the 74 aggregated samples (date + depth range), 8 (11%) returned a difference of greater than 20 kg N/ha. The largest observed difference was 67 kg N/ha. In this instance, the Quick N test could have potentially convinced the user to implement different practices than if they had relied on a standard soil test. The next largest observed difference was 36 kg N/ha.

Assuming that a variation of below 20 kg N/ha is acceptable, this gives Quick N tests an approximate 90% success rate from the 232 samples taken. It was first thought that the largest discrepancies could be accounted for by the variability introduced by difficulties in accurately sub-sampling clay loam soils, however, 7 of the 8 most variable results came from the single sandy loam soil on Site 4 – which was sieved and thoroughly mixed prior to sub-sampling. Site 4 also had the longest distance between site and laboratory, so while efforts were made to keep the samples cool different rates of mineralisation may have been a factor driving these differences.

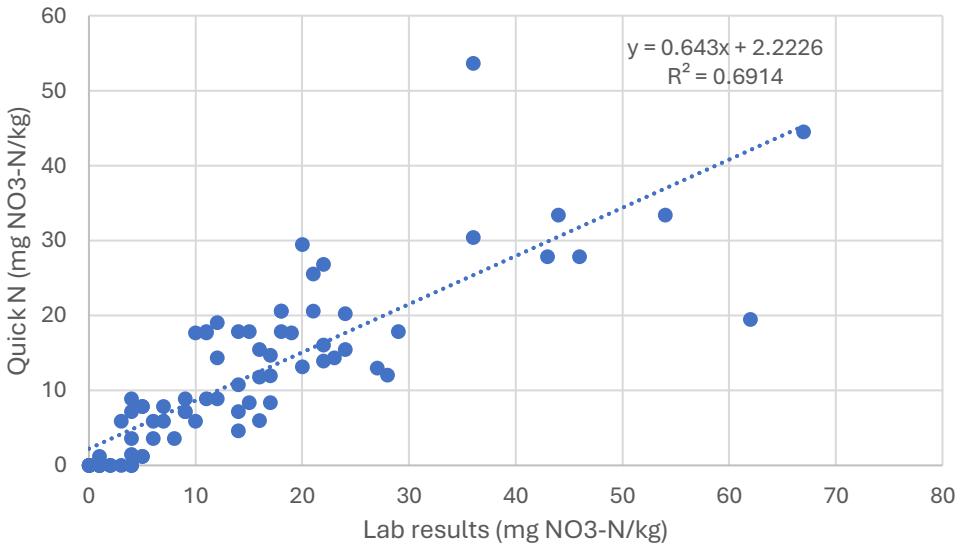


Figure 50. Correlation between laboratory and Quick N results.

Relative risk

It is anticipated that most growers will be using Quick N tests to provide an approximate guideline of nitrate levels in the soil prior to planting a crop or fertiliser side dressing. An analysis was therefore conducted on 'categories,' the broad levels of nitrate present in the soil that may trigger a certain management practice.

Three categories were designed for this analysis (Table 15). Table 15 also describes potential decisions a grower could make following a Quick N result in each category if the test was taken pre-planting. Note that these are examples and real practices would be dependent on multiple factors including crop, soil, time of year, and climate.

Table 15. Quick N risk categories

Category	Quick N result (kg N/ha to 30 cm)	Example practice at planting (crop dependent)
Low	0 - 30	Apply base fertiliser
Medium	30 – 100	Apply side dressing(s) later in season
High	>100	Take another Quick N test later in season before applying fertiliser

Figure 51 demonstrates that most test results (aggregated to 30 cm and converted to kg N/ha) are within the low or medium categories. The results of this analysis show that the majority (54%) are within the medium category, while only a small minority (8%) are high. When this analysis is performed on the more numerous laboratory mineral nitrogen (KCl extraction) dataset the same pattern is present, albeit with a larger proportion in the low-risk category (Figure 52). All Quick N tests were taken during crop growth periods, so the example practices listed in Table 15 should only be considered as hypotheticals.

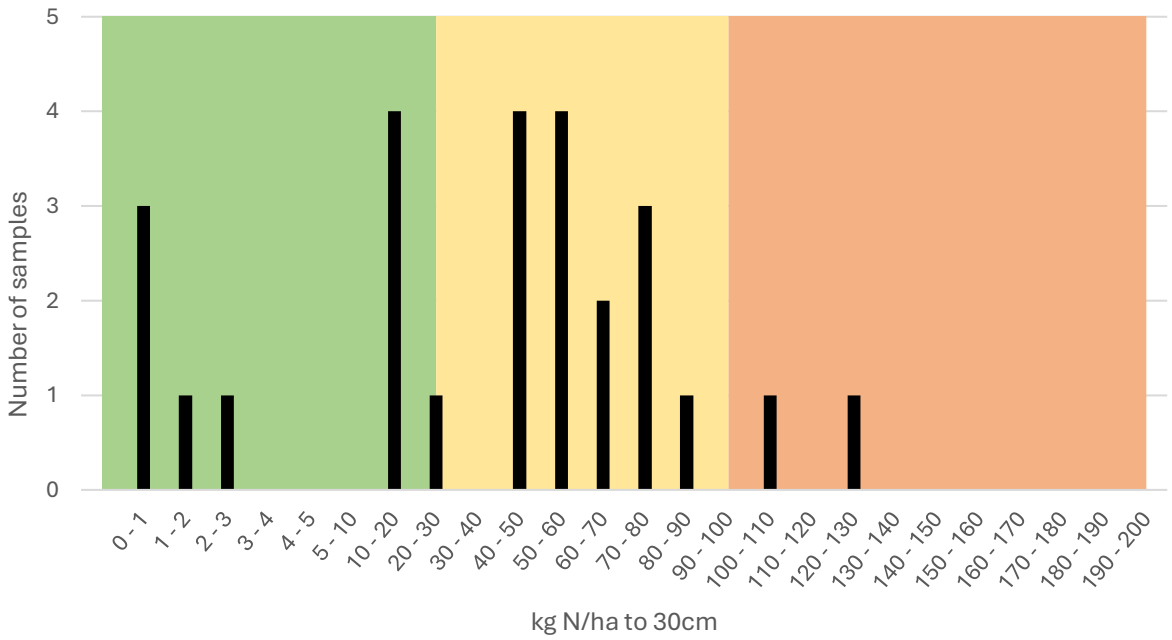


Figure 51. Category distribution from Quick N test results.

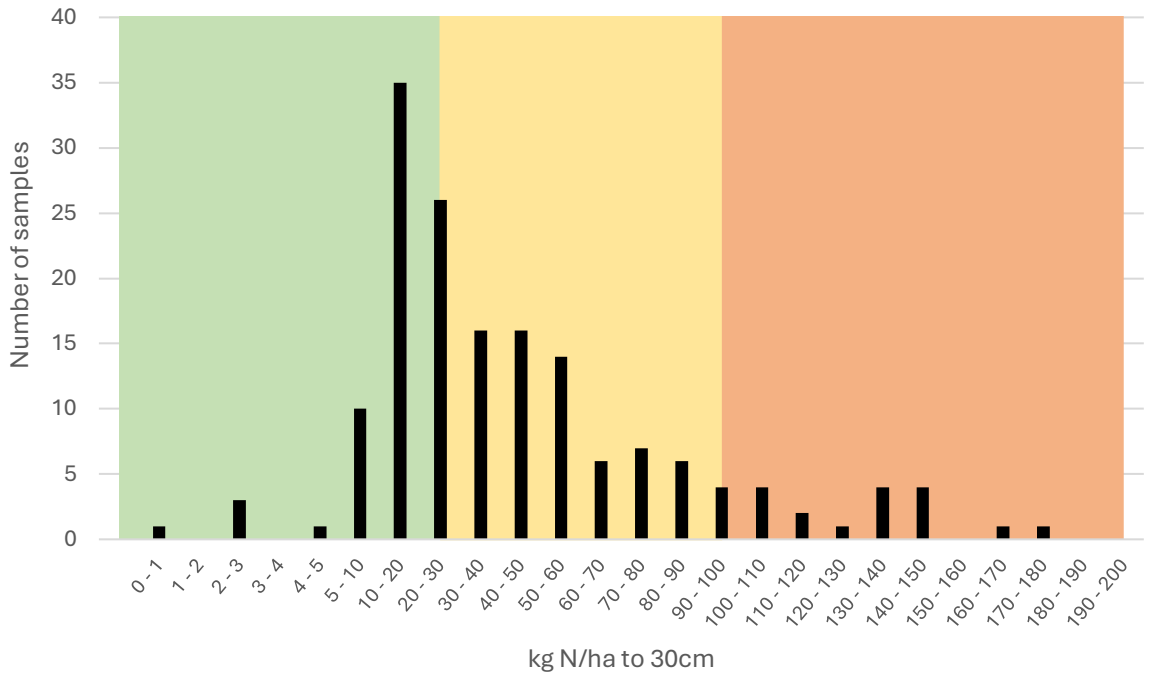


Figure 52. Category distribution from laboratory mineral nitrogen results (KCl extraction).

Using laboratory nitrate results (KCl extraction), an analysis on pre-planting soil nitrate to 30 cm was conducted. As KCl extraction and Quick N nitrate results are well correlated, and growers have both as metaphorical tools in the toolbox, the following section could apply to results from either methodology. The key concept is what hypothetical management practices a grower could implement following a soil nitrate result in each of the categories.

Across the 9 sites there were 16 crops for which pre-planting samples were obtained a month or closer prior to planting. The pre-planting samples were taken on average 22 days before planting (range 4 – 32 days).

There was a significant range in soil mineral nitrogen to 30 cm across these 16 pre-planting samples, with an average of 44 kg N/ha (range 8 – 108 kg N/ha). This range in plant available soil nitrogen pre-planting highlights the importance of monitoring, so growers can best match soil nitrogen supply to plant requirements.

Nitrate Quick Test - Practical considerations

Workstream 2 has provided an opportunity to take Quick N samples alongside the existing sampling transects at four trial sites, following an established protocol. In reality, it is unlikely most growers would be able to sample every block pre-planting. It would also be unlikely that the grower would be willing or able to take 10 or more samples across a transect to a depth of at least 30 cm.

A grower is more likely in practice to select several paddocks deemed high risk, whether that is due to soil type, crop rotation, or historical soil test results, in which to do their Quick N testing.

Taking a representative sample is critical. Aspects to consider that will reduce the representativeness are the impact of taking less than 10 cores, and a core depth of 15 cm (using a footrest soil corer). With this in mind, it is necessary to understand the likely impact of sub-optimal sampling, as well as

any mitigations that can be implemented to maximise practical utility of the tests while minimising loss of accuracy.

Due to the nature of nitrate in soils, a Quick N test result from one field cannot be used as a stand in for the quantity of soil nitrate in another field, especially if there has been a different crop and management history between the two. Nevertheless, even if not testing all fields growers can still benefit by using Quick N tests to better understand nitrate behaviour in their cropping systems. Over several years and crop rotations, growers can build a picture, mentally or on computer software, of nitrate flows in their soils, building confidence in management practices that will result in better optimised and justified nitrogen fertiliser use.

Nitrate Quick Test - Sampling depth

The active rooting depth for most vegetable crops is approximately 30 cm, though this can vary widely. Therefore, the pool of available nitrogen in the top 30 cm of soil is critical for maintaining crop growth and obtaining the desired yield.

On most soils, it is practical to obtain soil cores to 30 cm. However, taking cores deeper than 15 cm does take more time, and most standard soil corers are footrest style models fixed to take 15 cm samples from pasture. However, footrest style corers with sampling depths of 30 cm do exist.

An analysis was conducted to see if the 0 – 15 cm mineral N test results could be extrapolated to give a reasonably accurate kg N/ha figure to 30 cm. This involved comparing the 0 – 30 cm result (taken using soil samples to 30 cm) with doubling the 0 – 15 cm soil layer.

The results of this analysis can be seen in Figure 50. There is a strong correlation between the 15 cm tests scaled to 30 cm and the soil tests taken to 30 cm. However, extrapolating the 0 – 15 cm results to 30 cm over-estimates the amount of soil nitrate in the 0 – 30 cm zone. Where there was between 50 – 100 kgN/ha the 15 cm either under or overestimated by an average of 18 kgN/ha, while this increased to a difference of 45 kgN/ha at soil N levels of over 100 kgN/ha.

While the average difference is 11%, this hides a large range of -65% (underestimated) and up to 78% (overestimated) difference.

Based on the available dataset it is likely that sampling to 15 cm and then extrapolating the results to 30 cm could be enough to adversely affect management decisions, particularly once the quantity of mineral nitrogen is greater than 100 kgN/ha.

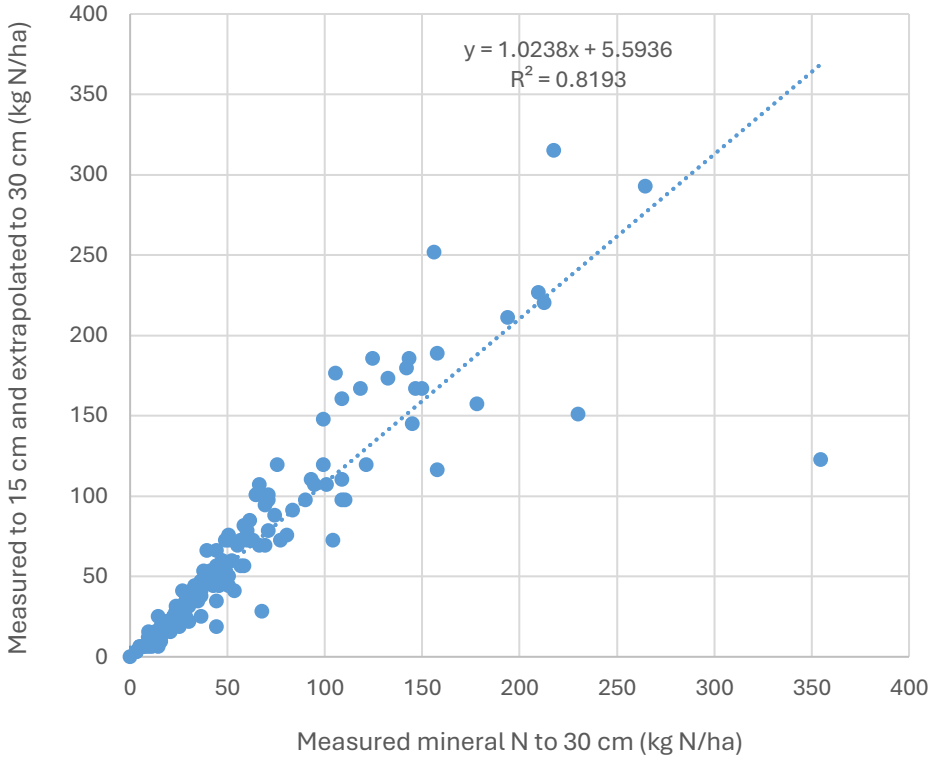


Figure 53. Correlation between nitrate-nitrogen per hectare from Quick N tests taken to 0 – 15 cm scaled to a 30 cm depth, and standard Quick N tests taken to 30 cm.

Nitrate Quick Test - Detection of ammonium

Plant available nitrogen, or mineral nitrogen, is present in the soil in two forms: nitrate and ammonium. The Quick N test can be used to rapidly determine the quantity of nitrate nitrogen in a given soil layer, but it does not detect ammonium.

In most aerobic soils ammonium is rapidly converted to nitrate through the process of nitrification.

Not accounting for ammonium will under-estimate the quantity of available nitrogen in the soil. There are many factors[2] that affect nitrification rates, including:

- Soil pH: acidic conditions (pH < 5.5) can inhibit nitrification
- Soil moisture: Overly saturated or overly dry soil can inhibit nitrification
- Soil temperature: Soil temperature below 25° C or above 35° C can inhibit nitrification
- Soil aeration: Poorly aerated or compacted soil can inhibit nitrification.

It would be expected that the greater the rate of nitrification, the smaller the proportion of ammonium, as it is used up by soil microbes in the process of producing nitrate.

[2] https://www.ctahr.hawaii.edu/mauisoil/c_nutrients01.aspx

The other source of ammonium is nitrogen mineralisation. There are many factors that affect nitrogen mineralisation[1], including:

- Soil moisture: Overly saturated or overly dry soil can inhibit nitrification
- C:N ratio: Net mineralisation occurs when C:N ratio is less than 20:1
- Soil temperature: Soil temperature below 25° C or above 35° C can inhibit nitrification
- Soil aeration: Poorly aerated or compacted soil can inhibit nitrification.

Across all laboratory samples analysed from the Workstream 2 regional monitoring sites, the average proportion of mineral nitrogen in the ammonium form was 33% across all soil layers. Two sites have average ammonium concentrations over 50%.

Figure 51 below shows that there does appear to be a noticeable seasonal influence on ammonium concentrations, with warmer and drier months having on average a greater proportion of ammonium. The October - May period has an average of 35% ammonium across all sites, while the May – October period has an average of 26% ammonium.

The cooler soil temperature and greater incidence of saturation above field capacity in the winter months would point towards a lower rate of nitrification, and therefore a greater proportion of soil ammonium, and yet the opposite appears to be happening. This is likely because the same conditions also inhibit nitrogen mineralisation, the process by which organic nitrogen is converted to ammonium.

Wet, anaerobic, and cold soils inhibit the activity of soil microbes, reducing the quantity of ammonium that is mineralised from the organic nitrogen supply in the soil.

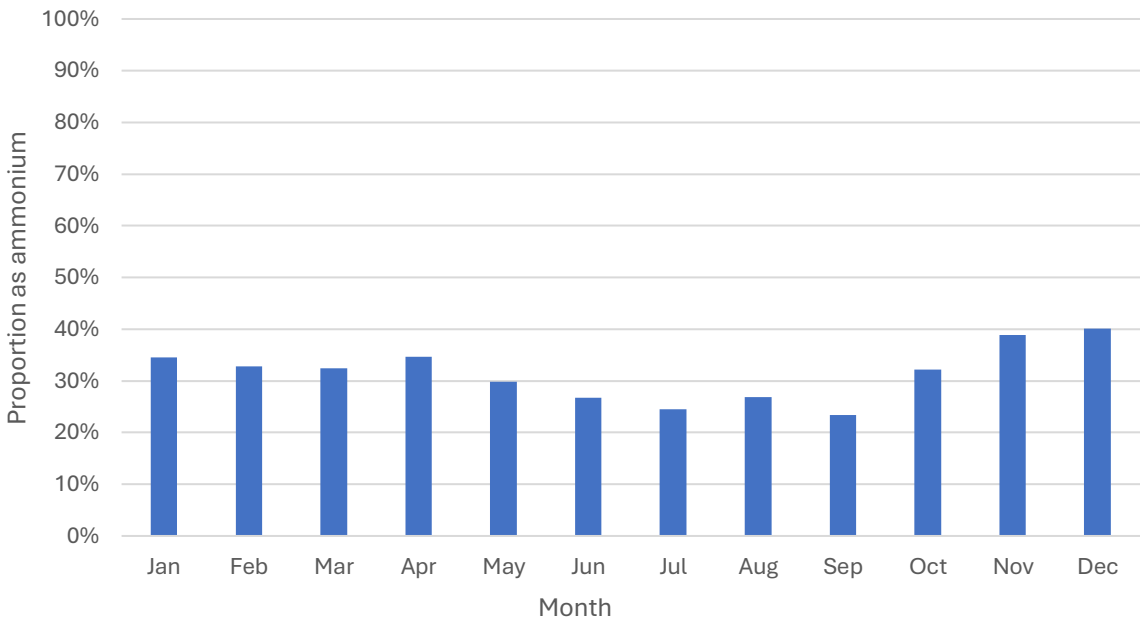


Figure 51. Average proportion of total mineral nitrogen as ammonium by month.

Interestingly, there appears to be a strong correlation between soil depth and proportion of mineral nitrogen as ammonium (Figure 52). As the depth into the soil increases, the average proportion of ammonium increases.

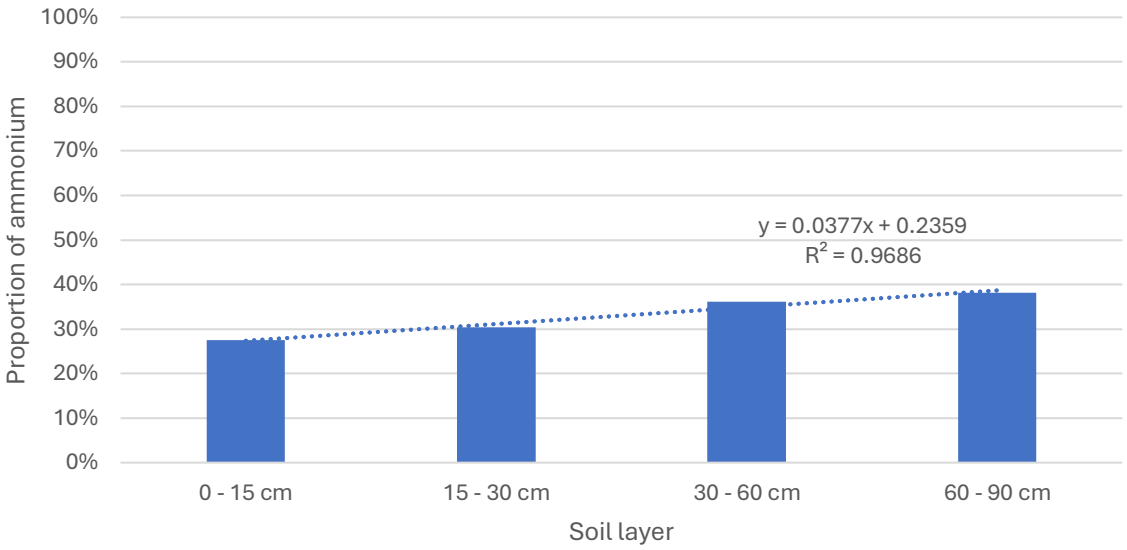


Figure 52. Average proportion of total mineral nitrogen as ammonium by soil layer.

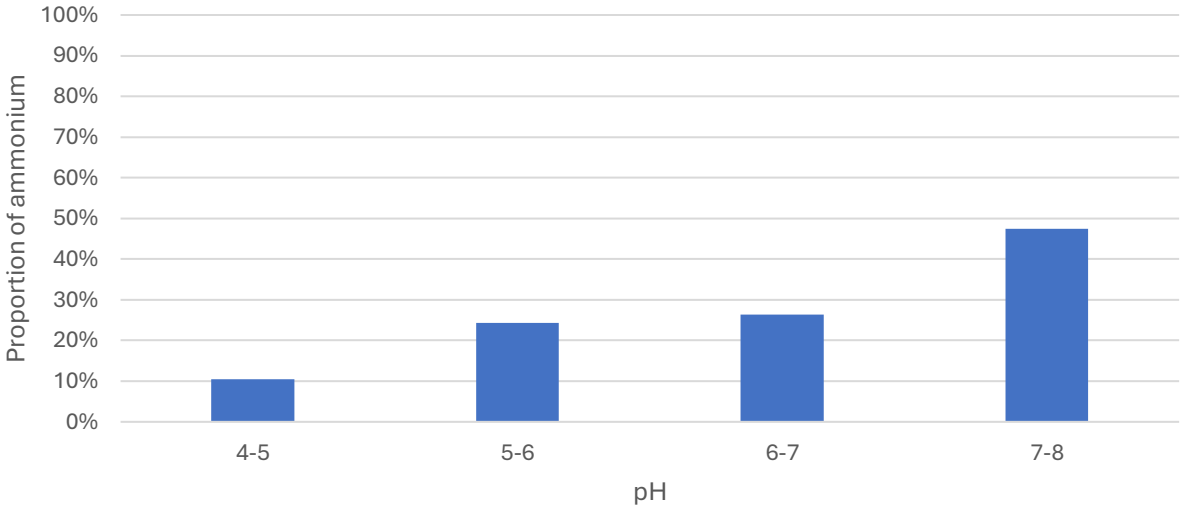


Figure 53. Average proportion of total mineral nitrogen as ammonium by pH range.

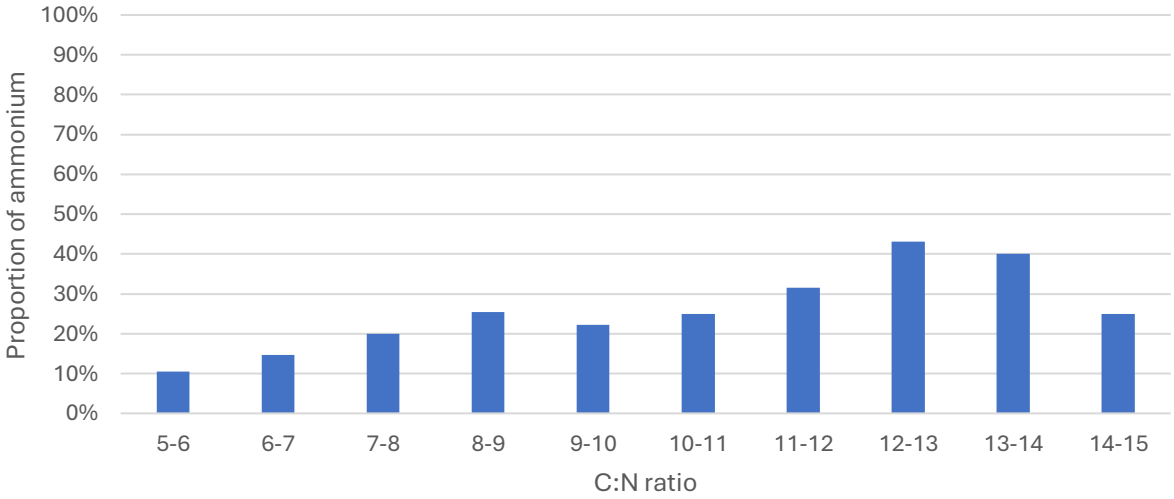


Figure 54. Average proportion of total mineral nitrogen as ammonium by C:N ratio.

As with soil depth, the proportion of ammonium seems to increase alongside pH (Figure 53) and the C:N ratio (Figure 54) but the proportion of ammonium decreases once the C:N is greater than 14.

It is quite clear that the soil ammonium pool, while normally accounting for a third or less of total mineral nitrogen, can still contain a large quantity of plant available nitrogen, while also acting as a pool of potential nitrate as it undergoes nitrification. Because the Quick N test does not account for ammonium, it will be important to ensure growers and technical advisors understand the potential "hidden" pool of nitrogen within the soil and find a way to account for it.

However, it should be noted despite this that ammonium itself, due to its attraction to soil surfaces, is largely immobile. Therefore, the Quick N test still provides a measure of leaching risk from soils at a point in time.

Nitrate Quick Test - Sampling variability

If due to time constraints best practice soil sampling cannot be followed (i.e., 10+ cores across a representative transect) it is important to understand how the soil variability within a given field can affect the representativeness of the results.

A preliminary analysis was conducted on Site 1, with samples taken at 3 depth ranges to 60 cm at the beginning, middle, and end of the transect. The results need to be treated with caution as it is only based on one site. However, Figure 55 on the next page shows that for mineral nitrogen 8 of the 9 results were within 5 kgN/ha of the full transect figure. When mineral N increased to > 50 kgN/ha one sample was 16 kgN/ha higher than the full transect figure. There are multiple sources of variability which build upon each other, so reducing as many sources of variability as possible is the goal.

3.6 Additional biomass sampling

Midway through the programme there was a realisation that the crop nitrogen content and yield default values underpinning the model required more supporting data, particularly for certain crops and different varieties of potato.

A straightforward and inexpensive method of obtaining these data was to take pre-harvest samples at several commercial sites around the country. In total 182 additional biomass samples were taken from commercial properties around Pukekohe and in Canterbury.

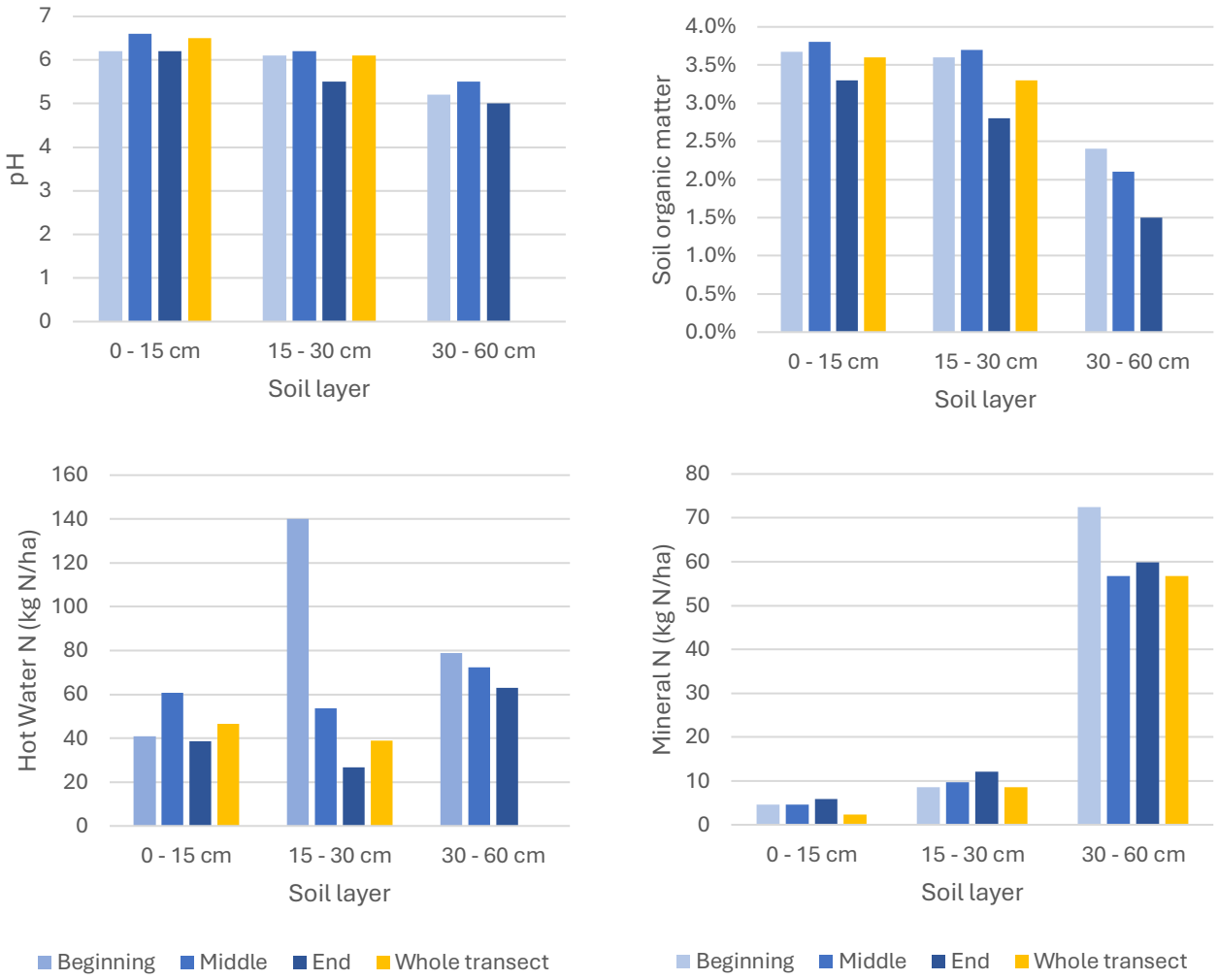


Figure 55. pH (top left), organic matter (top right), Hot Water Nitrogen (bottom left), and mineral nitrogen (bottom right) by soil sample location. Transect locations are beginning, middle and end, plus the whole transect (10 locations).