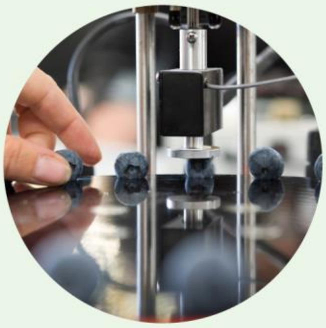







PFR SPTS No. 26449

Sustainable Vegetable Systems – annual report 2024

Searle B, Brown H, Khaembah E, Sharp J, Maley S, Dellow S, van der Weyden J, Arnold N, Sorensen I, Husband E, Beare M, Husheer S

November 2024

Report for:

Potatoes New Zealand Incorporated
Sustainable Vegetable Systems

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November 2024

Contents

Executive summary

Sustainable Vegetable Systems – annual report 2024

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November 2024

The vegetable production sector in Aotearoa–New Zealand is actively seeking to implement and adopt more sustainable production practices, with key emphasis on managing nitrogen (N), a key management factor in the complex vegetable production system for its effect on economic and environmental outcomes.

The aim of the Sustainable Vegetable Systems (SVS) is to address this complexity in the management of N by:

- Understanding and quantifying the N dynamics in the complex vegetable production systems of Aotearoa-NZ
- Developing a tool with these data that will help growers determine the best rate of N fertilizer that maximises crop yield and results in improved environmental outcomes.

To achieve these goals, the project had four interlocking workstreams (WS). WS1 provided data from controlled experiments to understand and quantify the N dynamics of a system, as well as understanding factors contributing to the N balance of a crop. WS2 provided data from commercial fields for further validation of a model developed in WS3 using data from WS1. WS4 provided grower interaction and feedback on data analysis implications and tool usability.

Workstream 1.

Intensive measurements of soil and crop system N dynamics were recorded for crops within four different rotations; two of these rotations were based in Canterbury and two in Hawke's Bay. Measurements occurred over time for each crop and included soil mineral N content, residue return, soil mineral N made available through mineralisation and different rates of fertiliser. We also measured crop growth and crop N content over time to estimate crop N uptake. At harvest we measured crop marketable yield, and any residue left in the field, together with their N contents. This allowed an estimate of crop N removed from the field in yield, and any returned to the system through crop residue.

A **crop N balance** in response to applied N for the different crops was devised to:

- Understand how the system is functioning and provide the approach that the tool developed in WS3 uses to implement predictions of N supply to the crop
- Help with management decisions as it considers all the key inputs and outputs of N from the system. A contribution of the N balance is a component referred to as Uncharacterised N – an indication of N that could move out of the crop growing system and become unavailable to the crop.

Data analysis of N balance outcomes showed that if more N was provided than needed for best yield outcomes achievable under the environmental conditions, then Uncharacterised N increased regardless of the crop. This result indicates that if best management practice is implemented for N supply to crops, then best environmental outcomes are also being applied.

The **soil and crop N dynamics** captured changes in soil and crop N content over time. These data:

- Were used for model development in WS3
- Indicate that better matching of N supply to N demand gives a better N balance outcome
- Show significant input from previous crop residues can have significant consequences on N balances. While estimates of N release from residue for crop availability are implemented in the tool, further improvements based on additional measurements across a range of residue types and soils is recommended
- Provides strong evidence for use of the tool and in-season management. This evidence comes from the potato crop grown in Rotation 1 at best management practice, that had higher Uncharacterised N results (139 kg N/ha) than the potato crop grown in Rotation 2 (20 kg N/ha) when amounts applied were similar. In Rotation 2, the SVS tool prototype was used to estimate N requirements for the crop which proved to be best management practice rates, but timing and amounts of side-dressing were checked using nitrate test strips, rather than relying on the tool's predictions. This provided a more sensitive response to in-season weather conditions and soil mineralisation supply, better matching N supply to crop demand.

The SVS tool, building on the relationships gained from WS1 data, provides best management practices for N, indicating an amount, and suggesting side-dressing timings and rates. Adjusting the suggested side-dressing by using nitrate test strips can further improve outcomes. It is suggested that further work across a wider range of crops and conditions be implemented to confirm the value of adjusting side-dressings using real time values of soil N rather than estimated values.

Workstream 2

Data for all the commercial fields were collated and evaluated and subsequently used for validation of the model developed in WS3.

Components for a N balance were measured in all crops and rotations. The variability of hot water extractable organic nitrogen (HWEON) used for estimating how much N is mineralised over the season was significantly higher in WS2 compared to WS1. Establishing a robust protocol for HWEON testing was required. For current practice, growers should take HWEON samples as determined by a sowing schedule: a spring sample for spring sown crops, and an autumn sample for autumn sown crops.

Workstream 3

Model development

- Data were used in SCRUM-APSIM and the model developed adequately captured the dynamics of plant growth and N uptake, predicting the effect of water and N supply on growth. Accurate prediction of plant-related variables was supported by model performance indicators, which showed good to very good prediction rating (R^2=0.75–0.91).

- The model captured the general trends of water content in different layers of the soil profile, with the exception of the surface layer (0–20 cm; Table 1). The exposure of the top layer of the soil profile to management practices such as cultivation and hilling of potatoes create variability and uncertainty in soil moisture measurements.

- Soil mineral N was accurately predicted except for the deepest evaluated layer (120–150 cm). While there was noticeably high variability among replicates in measured data, comparison of soil mineral N to 60 and 120 m depth indicated greater under-prediction at the Hawke's Bay sites partly explained by the high water table at these sites.

- Overall, the accurate prediction of soil N uptake, soil mineral N and soil moisture provides confidence in the ability of SCRUM-APSIM to simulation N leaching from crop rotations. A high water table is likely to introduce uncertainty in predictions.

Model testing

The model was tested using data from WS2. There was generally good agreement between the model's predictions and the field observations. In some instances, there was not good agreement, and this is associated with three main reasons:

1. Not accounting for luxury N uptake by cereal, grass and green manure crops. This did not affect accuracy of recommendations for these crops but does affect the model's ability to demonstrate effectiveness of these crops to mitigate higher N conditions in a rotation. Adding luxury N uptake mechanisms to a future version of the model would enable this.
2. Under prediction of crop N uptake and soil N. This could be caused by under prediction of mineral N entering the system from predicted mineralisation of soil or plant organic matter, or over prediction of losses. Further testing would be required to build confidence in this component of the model.
3. Over prediction of soil N occurred in some situations. This could be caused by an over prediction of mineralisation or an under prediction of leaching. From the data collected it is not possible to attribute an exact cause to these over and under predictions. Future work should evaluate this and take into consideration any water table movement as well.

Workstream 4

Extensive discussions with growers provided feedback that directly contributed to model development and tool design. A key aspect of this is providing visibility of soil N data and allowing soil N data to be altered within season.

In summary, the project has developed a new tool that contributes to N management in vegetable systems. The tool predicts the N requirement for crops and predicts best management rate. Additionally, the tool has a powerful feature where in-season recommendations respond to actual measured data. Experimental evidence suggests this is key for further improving economic and environmental outcomes.

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1 Background

1.1 Project objective and structure

The Sustainable Vegetable Systems (SVS) project seeks to understand and quantify the nitrogen (N) dynamics in vegetable production within Aotearoa–New Zealand. This aim of the project is to provide a tool that will help growers determine the best rate of N fertilizer for their crop that maximizes the yield and results in improved environmental outcomes through reduced excess applications. The project consists of four Workstreams to integrate results and achieve these objectives (Figure 1).

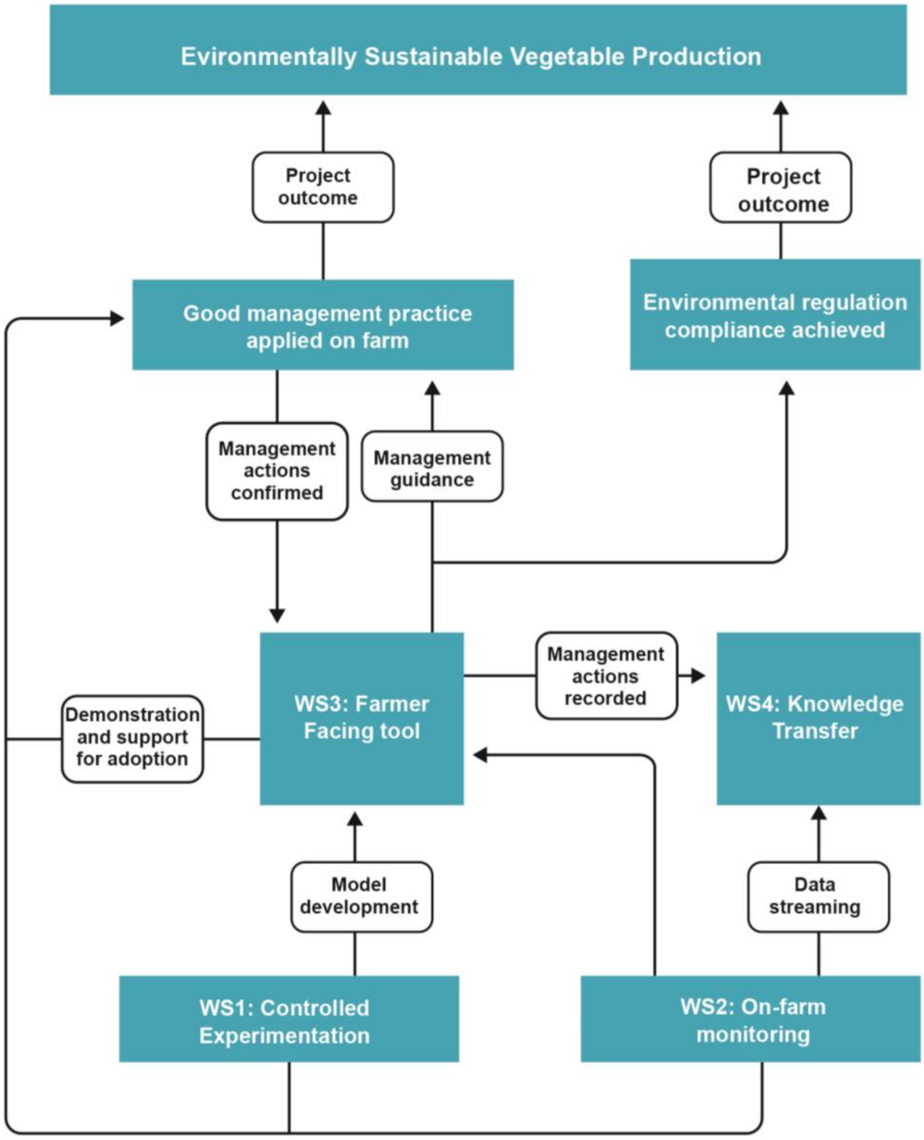

Figure 1. Overview of Sustainable Vegetable Systems (SVS) project, identifying Workstreams (WS) 1 to 4 and connections between them.

To reduce the losses of N from a crop production system, a simple approach is to match the N supply to that required for uptake by the crop in a way that results in saleable yield and quality. In practice this is not straightforward as knowledge is needed of crop uptake of N, the factors driving it and understanding the supply of N from the soil over time to the crop. Measurement and quantifying the different components that contribute to crop N uptake and soil N supply across vegetable crops is needed to be able to predict demand and supply. These data were collected in Workstream (WS) 1 across a range of crops and rotations.

A simple measure of N losses can be derived from a N balance where the inputs and outputs of the system are quantified. This approach helps to integrate the complex dynamics of the crop soil system and shows the beneficial effects of N additions for yield as well as a potential for losses. Whilst this approach has been used for other crops such as cereals (Cassman et al. 2002; Congreves & Van Eerd 2015; Eagle et al. 2020; Beare et al. 2023) to determine the amount of N fertiliser to be applied that minimises environmental losses, it is not been applied in vegetable crops. With the data obtained and analysis across the different workstreams, we have now developed this for vegetable crops. Usually, fertiliser is considered for an individual crop, but the N dynamics are also influenced by the proceeding crop and can influence the crop that follows it, and this is particularly so in vegetable crops that can leave residues with often significant supply of N for the following crop. With this in mind, we have used different rotations to obtain the measurements to understand N dynamics in a vegetable system.

A N balance is usually a retrospective look at how the crop used N during growth. However, decisions on fertiliser to be applied need to be made before the crop is sown, or during growth. For this, predictions of crop N requirements are required. The data from WS1 provide these base data and are used within WS 3 to develop a model of crop N uptake. This forms the basis of the tool for managing fertiliser applications and improving sustainability outcomes.

The data needed to calculate the N balance are often difficult and expensive to obtain and realistically could not form part of a commercial production routine. Hence, the tool will also be validated with data collected from commercial fields in WS2.

Apart from good data collection and modelling, success requires continuous interaction between growers and model developers to ensure that any tool developed is usable, practical and farmer friendly. This is the focus of WS4 (Figure 1), which is facilitating interaction between growers involved in WS2 and those involved in WS1 and 3 to improve the tool functionality and usability, as well as evaluate outcomes in farmers' fields.

In this report we summarise the data from WS1, particularly from the point of view of N balance calculations. We consider soil N inputs, the uptake of N by the crop, estimate the components of the N balance and consider implications for applying the N balance to understanding crop system dynamics. We report on the calibration of the model implemented in WS3 using WS1 data and the validations using WS2 data and consider implications for use of the tool as well as issues for further research and development to ensure sustainable vegetable cropping systems, and on activity of technology transfer in WS4.

2 Data collection

2.1 Workstream 1. Experimental data

Overview

The experiments in Workstream 1 provide data to understand the movement of N within a dynamic vegetable crop rotation, as well as the data that undergirds the coefficients needed for model development.

There were four different rotations within this programme of work consisting of different crops These crops were chosen with input from the SVS Technical Panel (growers and commercially active agronomists from different regions of the country), identifying key vegetable crops where information was most needed in terms of crop N uptake and response to applied N fertiliser. The SVS Technical Panel also gave input into crop management. The crops were grown at the research farms of The New Zealand Institute for Plant and Food Research Limited (PFR) in Canterbury (Lincoln) and Hawke’s Bay (Havelock North). Rotations 1 and 2 were sown at the Lincoln site, and Rotations 3 and 4 at the Havelock North site (Figure 2). Details of crop variety, sowing dates and fertiliser N are given in Appendix 1, Tables A1–A4.

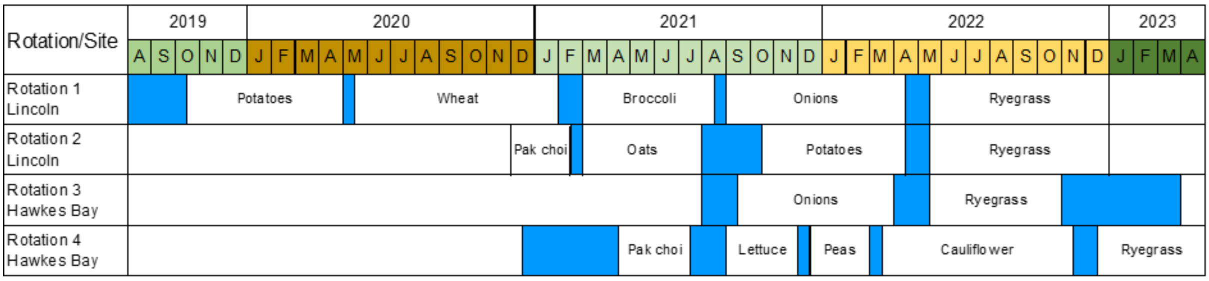

Figure 2. Rotations and crops grown in Workstream 1. Blank areas represent fallow periods between crops. Rotations 1 and 2 are grown at The New Zealand Institute for Plant and Food Research Limited (PFR) farm at Lincoln, Canterbury and Rotations 3 and 4 grown on PFR farm at Havelock North, Hawke’s Bay.

Experimental design and treatments

Each rotation experiment consists of four rates of N fertiliser and two rates of irrigation, replicated four times. This gives a total of 32 plots in each rotation (128 plots in total across all four rotations). Each experiment is set with a split-plot design, with irrigation rate as the main plot and N rate as the sub-plot. The first irrigation treatment (Irrig1) was applied to ensure that soil moisture deficit did not trigger yield reduction, or drainage. Irrigation was applied to replace lost water to a deficit of 15–20 mm below field capacity to accommodate for potential rainfall events during the season. The second irrigation treatment (Irrig2) applied 10% additional irrigation over and above the Irrig1 treatment, so that the soil deficit was closer to field capacity and increased the likelihood of drainage with potential rain events.

The N fertiliser rates varied from crop to crop (Appendix 1, Tables A1–A4). One N treatment reflected what is considered as a good management rate, and this rate was based on soil test of mineral N and potentially available N, and determined by consulting literature and tools (e.g., Potato Calculator, Nutrient Management Handbook for Vegetables) that provide good N management fertiliser rates. The final rate was confirmed in discussion with the SVS Technical Panel. The number and timing of side-dressings were also confirmed with the SVS Technical Panel. In some cases, where soil N supply is 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. Thus, treatment rates were:

- N1 (no fertiliser applied, except to some crops as per Technical Panel discussion),
- N2 (half the recommended good management rate),
- N3 (the good management rate),
- N4 (double the good management rate).

Each N treatment plot stayed consistent across the duration of the rotation – hence a N3 plot consistently received the N3 treatment rate for all crops, except for catch crops that received no applied N fertiliser. Decisions on fertiliser also included application rates of phosphorus, potassium and other nutrients depending on soil tests and SVS Technical Panel input.

Soils and climate

Soil types were determined using S-map (Lilburne et al. 2012). The soils for Rotation 1 and 2 were Templetonf (Sib 1a.1 and 2a.1) deep to moderately deep, and moderately well drained silt loam. In contrast, the soil for Rotations 3 and 4 was a Flaxtonf (Sib 69), a deep, poorly drained, silty loam over clay soil. Soil physical characteristics were measured at each rotation site to a depth of 1.5 m. This included determining textural properties for each horizon layer in the soil profile, as well as bulk density, infiltration rates, saturated water content, the drained upper and lower limits for each horizon layer. Soil physical properties are summarised in Appendix 2.

Records of temperature and rainfall were obtained from meteorological stations within a 1 km radius of the experimental sites and are shown in Figure 3 to Figure 6. Temperature during growth did not differ greatly between rotations, averaging 13 and 13.6°C in Rotation 1 and 2 in Canterbury and 14.3 and 13.9°C for Rotation 3 and 4 in Hawke’s Bay. Temperature was slightly above the long-term average in each rotation (Table 1).

There was higher overall rainfall at the Hawke’s Bay site compared to Canterbury (Figure 4, Figure 6).There was one large rainfall event in Canterbury (July 2022), and only five months where cumulative rainfall was over 100 mm during Rotations 1 and 2 in Canterbury. There were eight months with over 100 mm for Rotations 3 and 4 at Hawke’s Bay the rotations received almost twice as much rainfall as average. This included the rainfall associated with Cyclone Gabrielle in February 2023. Overall, there was a greater rainfall than the long-term average experienced in the Hawke’s Bay rotations, but less rain than the long-term average experienced for the Canterbury rotations (Table 1). With the poor drainage soil, there were often elevated water table levels during Rotations 3 and 4 (Appendix 3).

Table 1. Summary of temperature conditions and accumulated rainfall experienced for the duration of the rotations in Canterbury and Hawke's Bay and long-term (LT – for the last 20 years across the same duration as the experiments) for each region. Records were collected from the beginning of the first crop sown until the last crop was harvested of each rotation in each region.

	Canterbury		Hawke's Bay	
	Rotation 1	Rotation 2	Rotation 3	Rotation 4
Start date	22 Oct 2019	7 Dec 2020	25 Sep 2021	22 Apr 2021
End date	4 Jan 2023	4 Jan 2023	29 Nov 2022	19 Apr 2023
Mean °C	13.0	13.6	14.3	13.9
Min °C	-3.7	-3.5	-3.1	-3.5
Max °C	37.2	37.2	30.8	30.8
Days above 30 °C	15	7	3	3
LT mean °C	12.2	12.1	13.5	13.5
Accumulated Rain mm	1955	1347	1197	2238
LT Accumulated Rain mm	1937	1263	800	1379

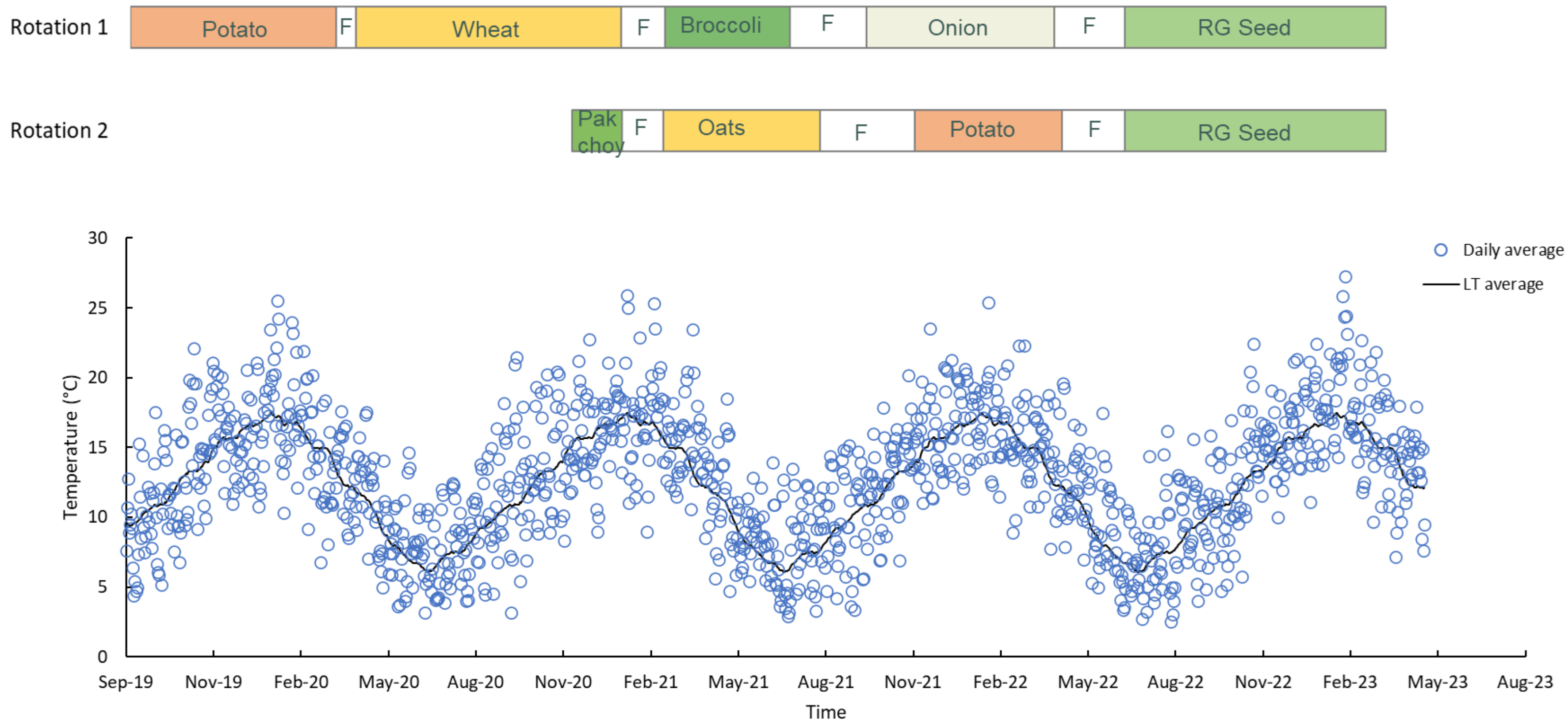

Figure 3. Daily temperature and 20-year long term daily average (LT average) during growth of crops in Rotation 1 and 2 grown at The New Zealand Institute for Plant and Food Research Limited farm in Lincoln, Canterbury. RG Seed crop is Rye grass seed.

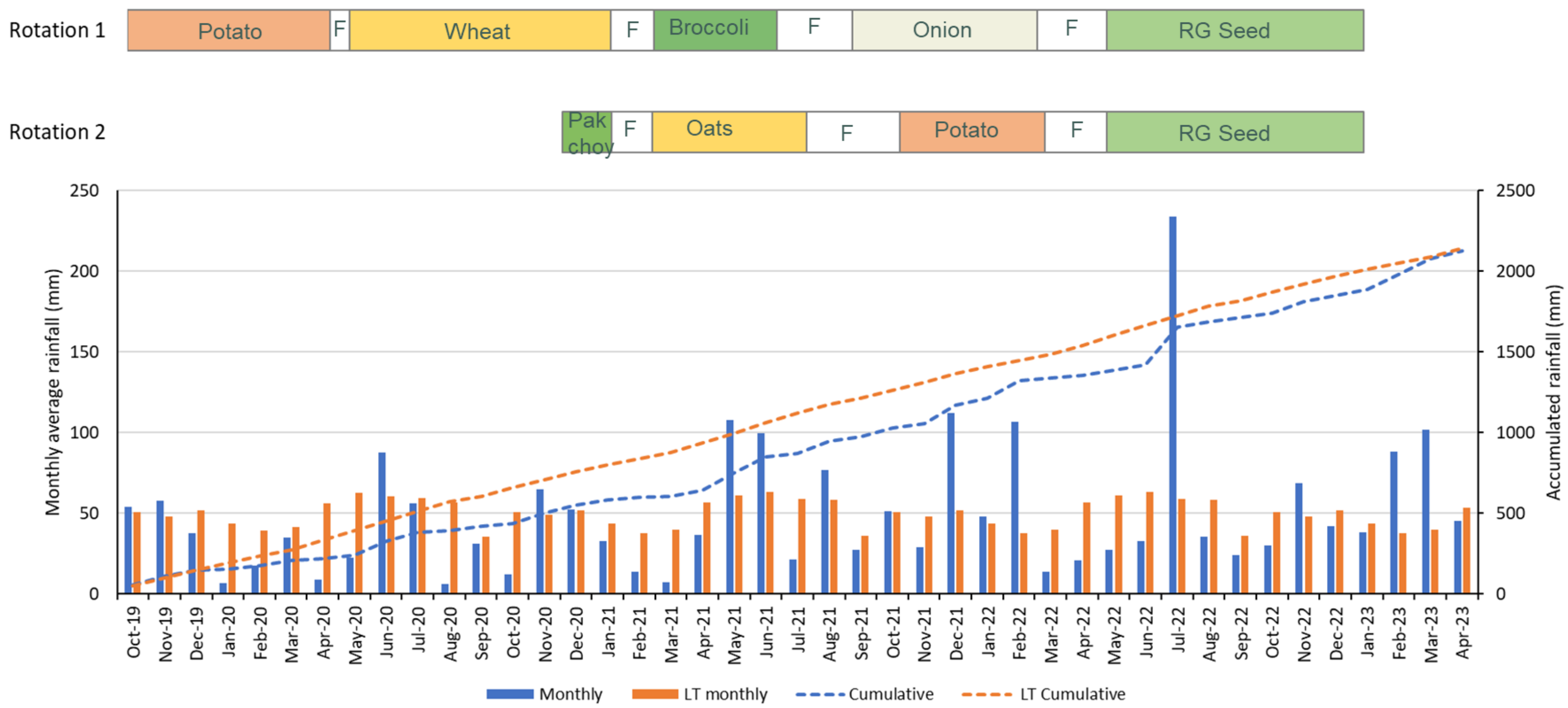

Figure 4. Monthly average and accumulated rainfall long-term (LT – 20-year) average during growth of crops in Rotation 1 and 2 grown at The New Zealand Institute for Plant and Food Research Limited farm in Lincoln, Canterbury. RG Seed crop is Rye grass seed.

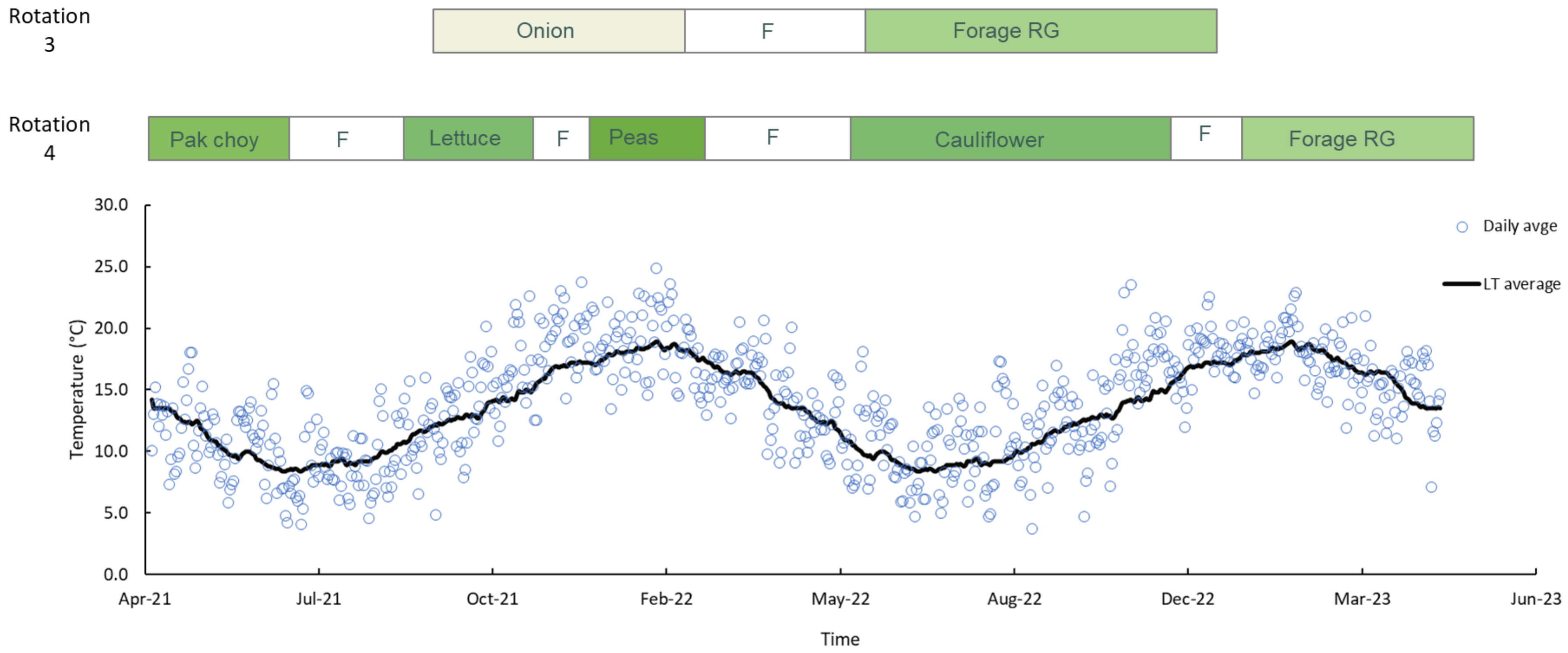

Figure 5. Daily temperature and 20-year long term daily average (LT average) during growth of crops in Rotation 3 and 4 grown at The New Zealand Institute for Plant and Food Research Limited farm in Havelock North, Hawke's Bay. Forage RG is Forage ryegrass crop.

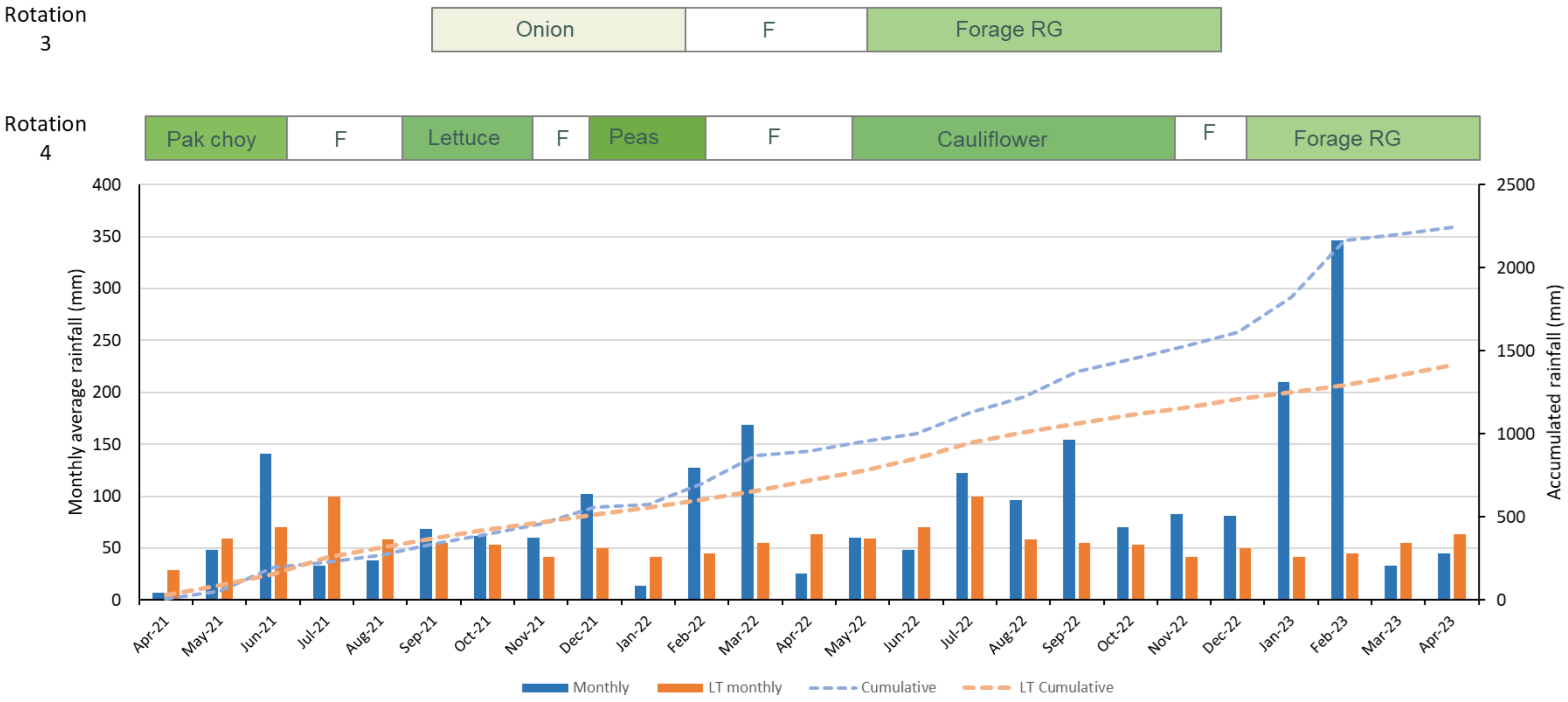

Figure 6. Monthly average and accumulated rainfall long-term (LT – 20-year) average during growth of crops in Rotation 3 and 4 grown at The New Zealand Institute for Plant and Food Research Limited farm in Havelock North, Hawke’s Bay. Forage RG is Forage ryegrass crop.

Data collection

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, dried samples were ground, and total carbon and N % were determined by an automated dry combustion method using a Leco TruMac CN analyser (Leco Corporation, MI, USA). From these data, the total amount of N taken up by the crop, and the amount in marketable yield and crop residue was calculated, 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 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. Soils cores for each depth were combined and passed through a 4 mm sieve. Mineral-N concentrations were determined by 1 hour extraction of 5 g field-moist sieved soil shaken with 25 mL of 2 M KCl. The extracts were then centrifuged and filtered through Whatman 42 papers and analysed for ammonium (NH_4^+ -N) and nitrate (NO_3^-N) on a Lachat QuikChem 8500 Series 2 Flow Injection Analysis System (Lachat Instruments, Loveland, Colorado, USA). 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) by analysis via commercial labs.

Prior to planting, soil samples from 0–15 and 15–30 cm depths are also collected and analysed for soil mineralisable N. This was carried out using the HWEON test (Curtin et al. 2017; Beare et al. 2023), where 4 g of air-dried soil was shaken for 30 min with 40 mL of cold (room temperature) water. The samples were then placed in an 80°C water bath for 16 h before being centrifuged and filtered. Inorganic nitrogen (NO_3-N and NH_4-N) was measured on a Lachat QuikChem 8500 Series 2 Flow Injection Analysis System (Lachat Instruments, Loveland, Colorado, USA). The HWEON results were used to calculate the amount of N that could potentially become available during the growth of the crop based on algorithms implemented in the project “Mineralisable N to improve N management” (Beare et al. 2023). In Rotation 1 and 2, HWEON was collected from N1 and N3 plots only, in Rotation 3 and 4, HWEON was collected from all plots.

Soil bulk density was measured to a depth of 150 cm at the start of each rotation, and measured once during crop growth to a depth of 0–15 and 15–30 cm. These values were 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 contents at further depths (20–40, 40–60, 60–80, 80–100, 100–120, 120–140, and 140–160 cm) were measured with a neutron probe.

Using the soil water content and rainfall data, likely drainage events were estimated and when drainage may have been more than 15 mm, leachate samples were collected using ceramic cups at depths of 60 and 120 cm. These samples were analysed for ammonium (NH_4^+ -N) and nitrate (NO_3^-N) on a Lachat QuikChem 8500 Series 2 Flow Injection Analysis System (Lachat Instruments, Loveland, Colorado, USA).

Nitrogen balance

The N balance used in this project is shown in (Figure 7) and is the difference between all the inputs and outputs of N within the crop-soil system. The N balance was calculated for the top 30 cm of soil.

As inputs we considered:

> ***Soil mineral-N at the 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). Most balances use a depth of 30 cm as deeper samples are not easily or routinely collected from fields.
>
> ***Soil mineralisable N***. This is a measure of the N that will be released from the soil via mineralisation. We have used the HWEON test to predict the amount of potentially mineralisable N at each site and applied soil temperature and water content coefficients to predict the in-field N mineralised during the growth of each crop following the methods described by Beare et al (2023). Samples were collected to a depth of 30 cm as there is little mineralisation below these depths.
>
> ***Previous crop residues***. For the first crop of each rotation, we estimated this from knowledge of the previous crop and recorded values of residue levels. Otherwise, we used measured values of N content and biomass to estimate total N uptake of the 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.

The outputs considered were:

> ***Exported N***. The amount of exported N that leaves the field as yield.
>
> ***Residue N***. The amount of N that remains in the field after harvest; it is non-marketable crop material 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 through modelling. 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. There will be some residual mineral N in the soil after harvest, as crops are not effective at recovering all available N, and also mineralisation continues to add to the mineral N pool after crops senesce.
>
> ***Uncharacterised N***. The amount of N that could be lost during the crop growth period, it assumes that there is a mass balance of N in the system. This portion of N is made up of N that may have moved in water flow to below the 30 cm soil layer, or N that may be gaseous emission from the soil surface. Here we are estimating what the unaccounted-for N may be,

given the 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 7. The estimated outputs are separated into N exported from the field as marketable 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.

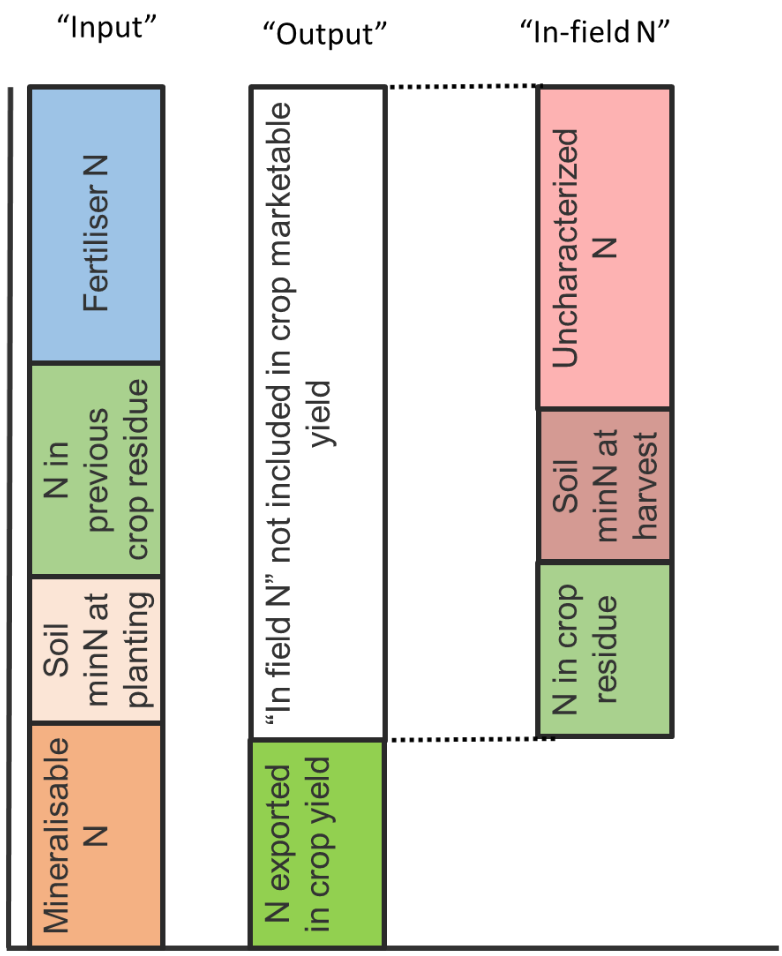

Figure 7. Nitrogen (N) balance components used in the Sustainable Vegetable Systems project.

Data analysis

Data were analysed by analysis of variance (ANOVA) using the glm procedure in R, set up as a split-plot analysis with Irrigation treatment as the main plot and N treatment as the sub-plot. To compare the effect of N, linear contrasts were developed to test the significance of treatments compared to the good management practice N3 (i.e. N1 vs N3, N2 vs N3 and N4 vs N3). The ANOVA model also included factors Rotation and Crop. Due to the inclusion of a wider range of factor levels and values in the ANOVA model such as Region and Crop we also calculated estimated marginal means (EMMS). EMMs help in understanding the main effects and interactions by providing means adjusted for other factors in the model. This allows for comparison of factor levels while controlling for other variables in the model, making it easier to interpret the effect of specific factors. Invariably, EMMS were not different to estimated raw means, and raw means are reported throughout the report.

A Principal Component Analysis (PCA) evaluating Rotation, Crop, Irrigation and Nitrogen treatment effect on N balance outcomes was also used to identify key drivers of N balance for more sustainable outcomes.

2.2 Workstream 2. Commercial field data

Workstream 2 data were collected from commercial fields by regional agronomists identified by the SVS Technical Panel and used to validate the model developed from Workstream 1 data. A total of nine sites were selected across Auckland, Waikato, Manawatu, Hawke's Bay and Canterbury.

Each site had a different crop rotation during the monitoring period. The rotations included vegetable crops of interest for this project such as onions, broccoli, pumpkin, potato, lettuce, carrots, cabbage, spinach, and peas.

All sites, except for one, had a permanent monitoring area of approximately 100 m in length with a width of 10-20 m, which was continually assessed for the duration of the project. It is important to note that the permanent monitoring area was designed to ensure that a location bias is not created (for example, by selecting different areas of the paddock for each of the crops within the rotation).

Standard management data such as sowing date and fertiliser management were recorded. Monthly sampling of soil to depths of 0–15 cm, 15–30 cm and 30–60 cm was made at each site, beginning at planting of the first crop in the rotation. These soil samples were collected along the permanent monitoring area within the field and consisted of a minimum of 10 samples at each sampling occasion. Samples were combined per field, stored in cool boxes and sent to commercial laboratories for analysis. These soil samples were sent to commercial labs for mineral analysis. Monthly samples were also collected for HWEON analysis to estimate mineralisation. Monthly biomass samples were collected and sent to PFR where samples were weighed, dried, ground and N content determined by an automated dry combustion method using a Leco TruMac CN analyser (Leco Corporation, MI, USA). Plant biomass samples were separated into residue and marketable components prior to weighing and N analysis.

3 Evaluation of N balances across Workstream 1

3.1 Soil nitrogen

3.1.1 Initial mineral N

The initial mineral N content was collected before any fertiliser applications were made to the fields. The results are shown in Figure 8 and Figure 9 for Rotation 1 and 2 based in Canterbury, and Figure 10 and Figure 11 for Rotation 3 and 4 based in Hawke's Bay.

For the soils in Canterbury, mineral N was higher in the top layers of the soil, and then reduced as depth increases. For example, in the potato crop for Rotation 1 (Figure 8), the amount of mineral N in the top 30 cm averaged 125 kg N/ha when no N was applied, and this reduced to just under 10 kg N/ha at 120–150 cm depth. This pattern is similar for the soil in Rotation 2 (Figure 9). In contrast, the pattern of soil mineral N change with depth was quite different for the soil in Rotation 3 and 4 (Figure 10 and 11). For instance, the mineral N for the starting onion crop in Rotation 3 averaged 50 kg N/ha for the top 15 cm of soil, and this increased to 100 kg N/ha at the 60–90 cm depth, before decreasing at further depths. In rotation 4 (Figure 11), this is seen at the depth of 90–120 cm for the starting pak choy crop but tended to be at the 30–60 cm depth for the other crops. Hence, the soil N patterns were quite different in the two different soils.

The mineral N at the start of the rotations did not differ due to N treatment at any depth within the profile, as would be expected as no fertiliser treatments had been applied as yet. Over time, the effect of N rate on soil mineral N content became more apparent, especially at the N3 and N4 treatment points. There was no consistent effect of irrigation on soil N in these data.

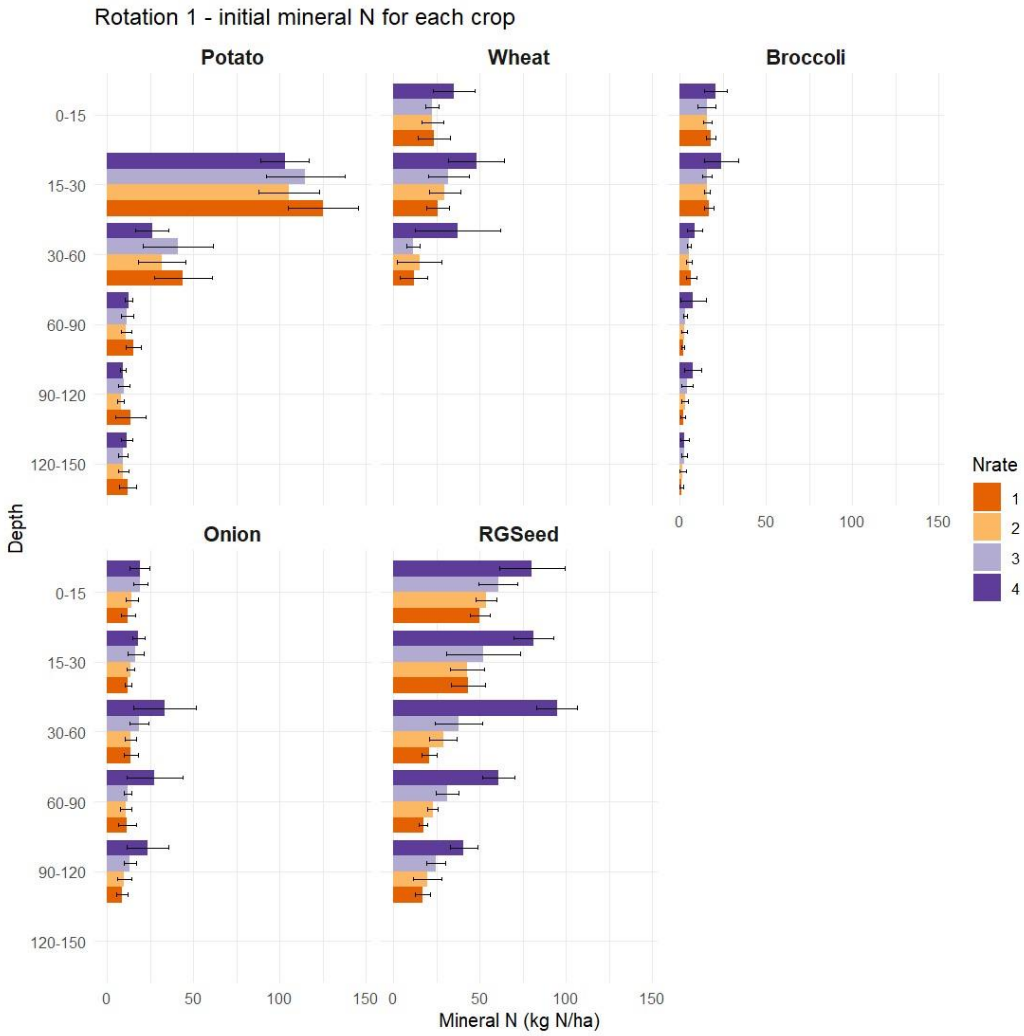

Figure 8. Soil mineral nitrogen (N) content at the start of each crop of Rotation 1, at different depths in the soil profile and four N treatments. Rotation 1 was grown at The New Zealand Institute for Plant and Food Research Limited, Lincoln research site, Canterbury. Error bars are 95% confidence intervals.

Key observations for Rotation 1:

- N treatment differences in soil N content appeared by the time the wheat crop was sown (Figure 8). Treatment N1, N2 and N3 had similar levels of mineral N in the soil, but the N4 treatment resulted in significantly higher soil mineral N levels at all depths. For instance, for the wheat crop soil mineral N ranged from 22 to 23 kg N/ha for treatments N1, N2 and N3, while for treatment N4, the soil mineral N was 35 kg N/ha, significantly higher ($p < 0.03$) than the other treatments.

- For the broccoli crop however, there was no difference between N treatments in soil N content across all depths. This suggests that conditions during the previous wheat crop (in this case wheat receiving the same level of 150 kg N/ha across all plots) can affect the starting position of the subsequent crop.

- However, in the ryegrass seed crop (RGSeed), there was significant difference in soil N content due to N treatment across all depths. For example, in the 0–15 cm depth, soil N increased non-significantly from 50 to 60 kg N/ha for treatment N1 and N3 respectively, but then increased significantly (*p* < 0.002) to 80 kg N/ha for the N4 treatments. This pattern was consistent across all depths for this crop.

Key observations for Rotation 2:

- There was a strong effect of N treatments on soil N content of the oats crop, with significant differences between N rates at the 0–15 cm depth, but then only significant effects caused by the N4 treatment at subsequent depths. The difference in soil N content was also only caused by the N4 treatment in the potato crop (Figure 9).
- However, there was a very strong N treatment effect on soil N content across all depths for the start of the rye grass seed crop across all depths.

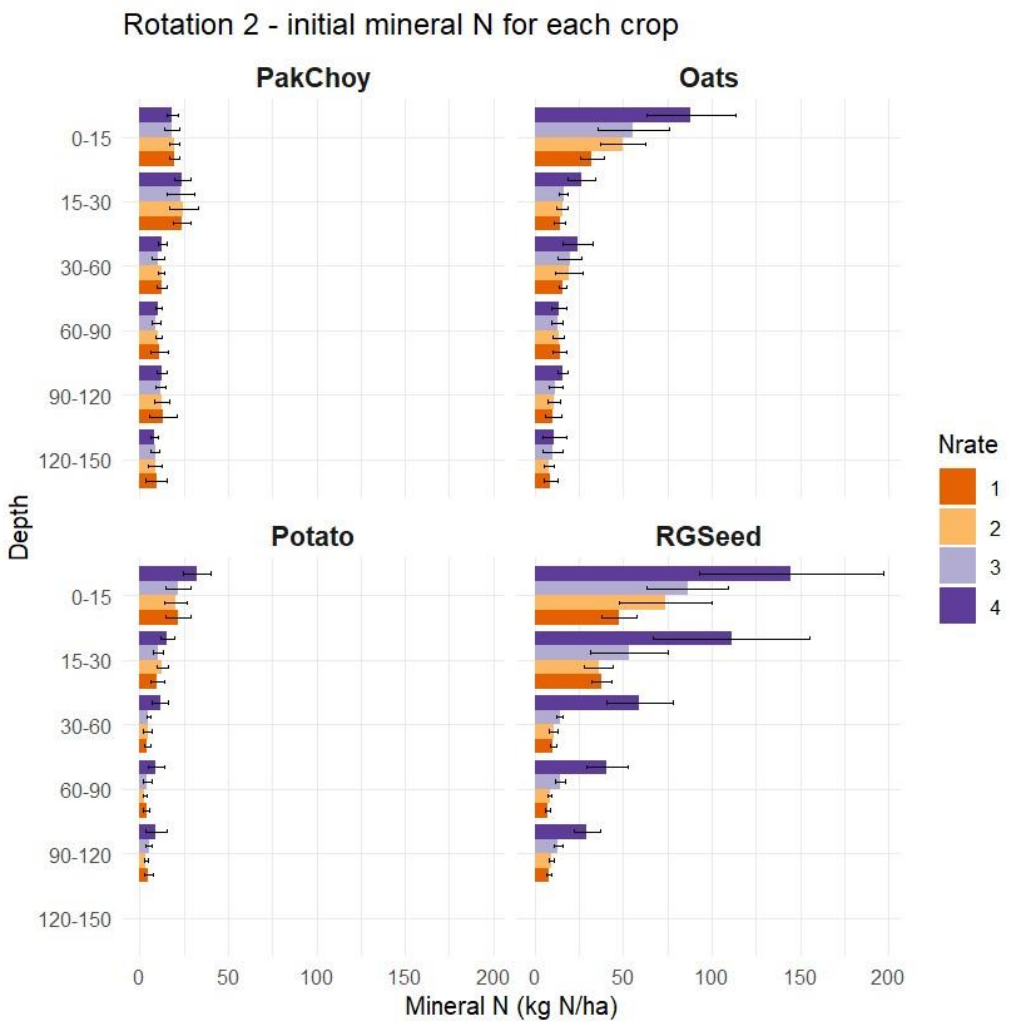

Figure 9. Soil mineral nitrogen (N) content at the start of each crop of Rotation 2, at different depths in the soil profile and four N treatments. Rotation 2 was grown at The New Zealand Institute for Plant and Food Research Limited, Lincoln research site, Canterbury. Error bars are 95% confidence intervals.

Key observations for Rotation 3:

- Soil N content was not affected by N treatment in the onion crop across all soil depths (Figure 10).
- In the ryegrass forage crop, there was no N effect on soil N content at the 0–15 and 15–30 cm depths. There was a significant effect ($p < 0.001$) of N treatment on the soil N content at the 30–60 cm depth; soil N content ranged from 80, 115, 130 and 168 kg N/ha for treatments N1, N2, N3 and N4 respectively.
- At lower depths, soil N contents of the N2 and N3 treatments were similar, and significantly (p- < 0.001) higher than the N1 soil N content, but lower than the N4 soil N content. For instance, N2 and N3 soil N contents were 120 and 118 kg N./ha at the 60–90 cm depth, higher than the 90 kg N/ha recorded for the N1 treatment, and lower than the kg N/ha recorded for the N4 treatment.

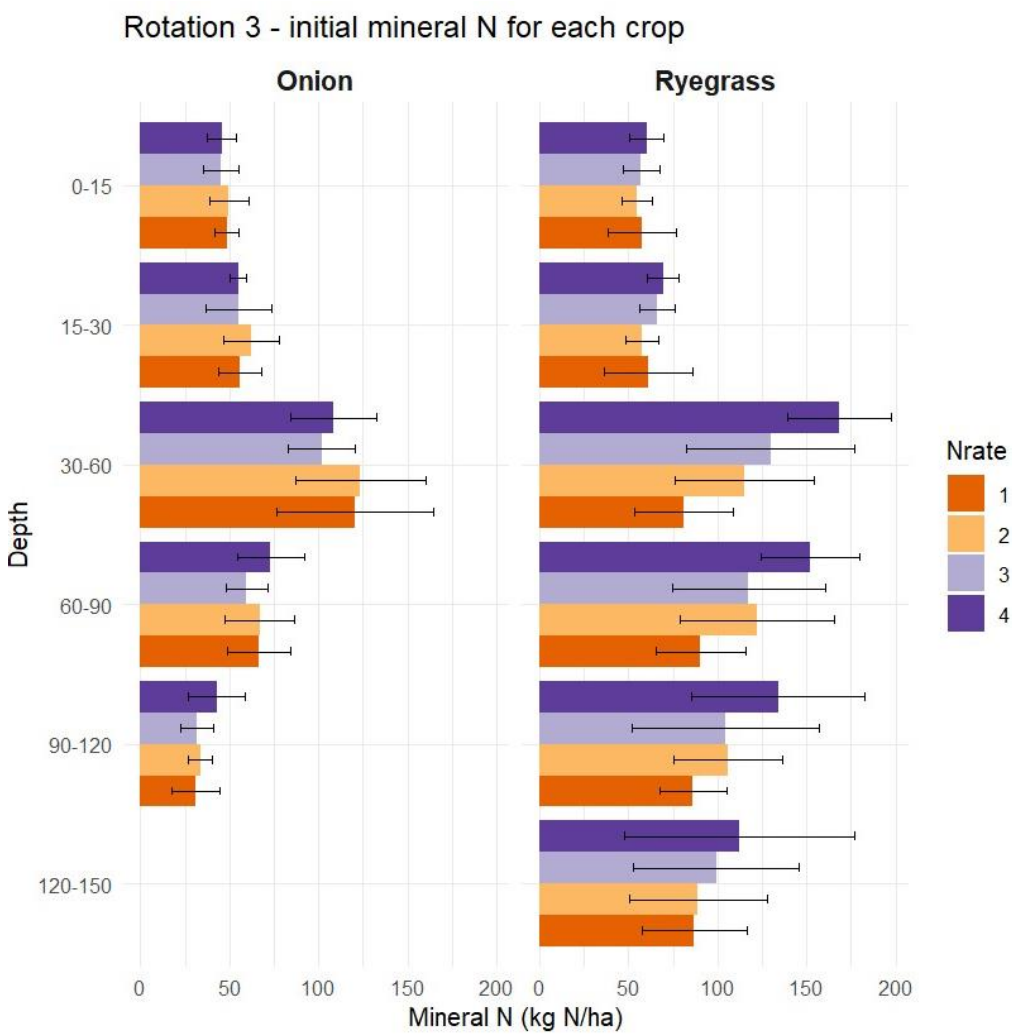

Figure 10. Soil mineral nitrogen (N) content at the start of each crop of Rotation 3, at different depths in the soil profile. Rotation 3 was grown at The New Zealand Institute for Plant and Food Research Limited, Havelock North research site, Hawke’s Bay. Error bars are 95% confidence intervals.

Key observations for Rotation 4

- Similar patterns to Rotation 3 were observed (Figure 11).
- Soil N content was not affected by N treatment in the pak choy crop in the 0–90 cm depth of soil. However, at the 90–120 cm depth there was significantly higher soil N in the N1 treatment plots compared to the N4 treatment plots, even though no fertiliser had yet been applied.
- There was also significant variability at this depth, with very large 95% confidence intervals. This suggests that there was some movement in soil N at this depth but was no longer apparent in the at the sowing-time of subsequent crops.
- There was significantly higher soil N content in the 30–60 cm depth for the lettuce and subsequent crops compared to the 0–15 and 15–30 cm depths. There was evidence of an elevated water table in Rotations 3 and 4 (see also Appendix 3), and this may be a cause of the higher N contents at depth in this soil.

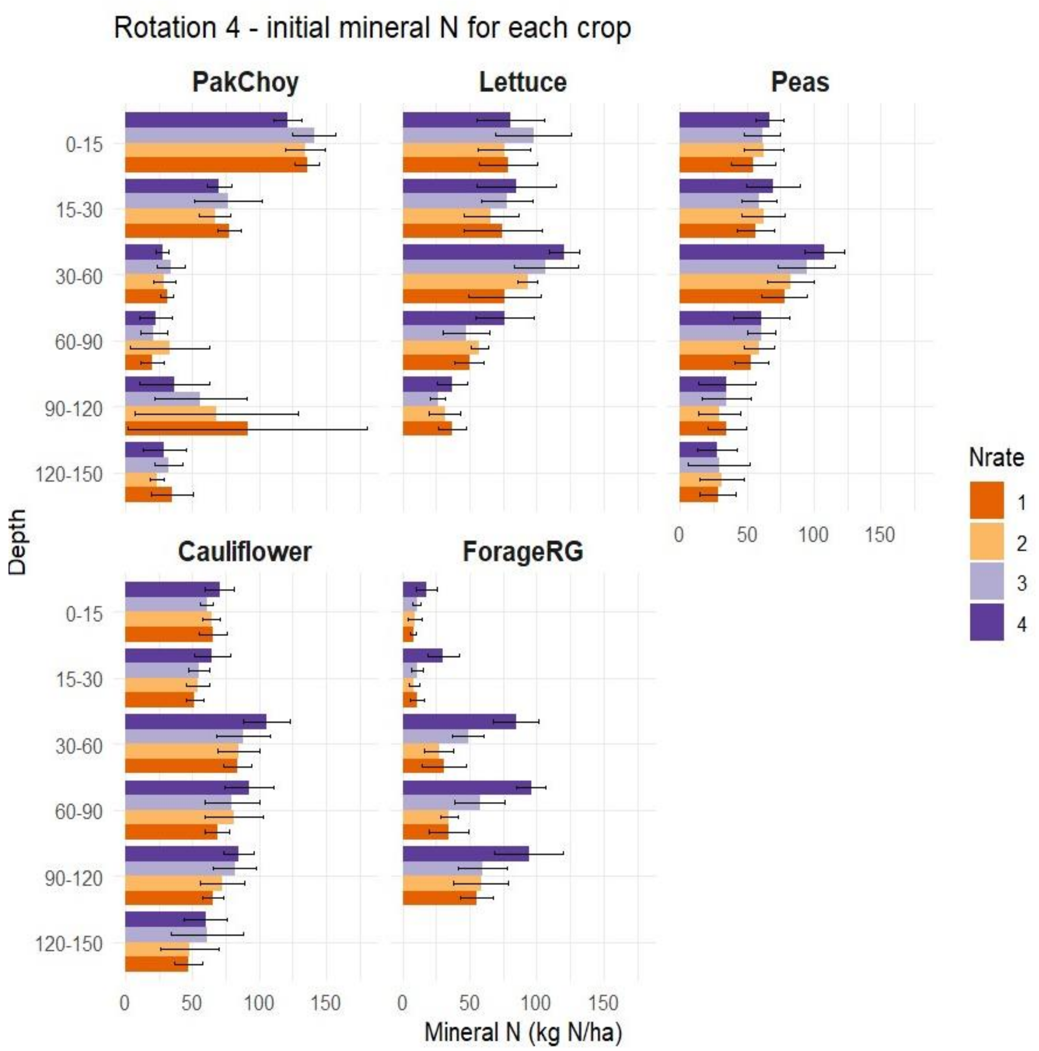

Figure 11. Soil mineral nitrogen (N) content at the start of each crop of Rotation 4, at different depths in the soil profile. Rotation 4 was grown at The New Zealand Institute for Plant and Food Research Limited, Havelock North research site, Hawke's Bay. Error bars are 95% confidence intervals.

3.1.2 Soil N dynamics

The soil N at the start of crop is a consequence of changes in soil N over time that reflects changes in supply through mineralisation, residue decomposition, fertiliser, uptake by the crop and movement through the profile due to drainage. These dynamics are shown in Figure 12, and Figure 13 for Rotation 1 and 2, and Figure 14 and Figure 15 for Rotation 3 and 4. Interpolations of soil N content through depth and time for N treatments in each Rotation are shown in Appendix 4. There are two key factors to note – residue decomposition, and different patterns of N movement between the two regions.

Sources of variation in mineral N

In general soil mineral N content tends to be similar between N1 and N2 (Figures 12–15), but increases are observed due to N3 and particularly the N4 treatments. The soil mineral N levels under the N4 treatment tend to accumulate more in the lower depths of the soil, indicating that there is an oversupply for uptake and some movement through the profile in drainage. The addition of fertiliser is not always apparent; it may have been that timing of soil samples did not always coincide with fertiliser additions, but can be seen in the top 0–30 cm soil for Rotation 2 (Figure 13) in the potato crop, where there are large increases apparent in the N4 treatment, with equally rapid decrease as the N is taken up by the crop. There is then increase in N likely associated with mineralisation of soil organic matter and this extra N in the top 15 cm can then be seen appearing at lower depths in the soil (Figure 13).

The increase in soil mineral N under the onion crop in Rotation 1 (Figures 12–15) is most likely associated with residue decomposition of previous broccoli crop (see also Appendix 4). This increase is strongly apparent in the 0–30 cm layer and starts to appear at lower depths of the soil, after the onion crop and the following ryegrass seed crop.

Estimates of changes in soil mineral N under the onion crop are shown in Table 2. From sowing of the onion crop to the peak of soil mineral N observed, there was an estimated supply via mineralisation of 33 kg N/ha based on HWEON values and calculations. Together with fertiliser and mineralisation there was a shortfall in the amount that soil mineral N increased from sowing of the onion crop to the maximum level observed of 49, 47, 66 and 64 kg N/ha for treatments N1, N2, N3 and N4 respectively (Table 2). This shortfall was most likely made up by decomposition of the broccoli residue, which had N contents higher than the shortfalls (Table 2).

The estimated percentage of supply from the broccoli decomposition shows that not all of the broccoli residues could be observed in the soil N content. It is likely though that most of it was decomposed and available for plants. However, improved modelling of residue decomposition and subsequent supply to crops would be a useful contribution to help manage fertiliser in crops. In this onion crop, it was decided to ignore the possible contribution of broccoli residue due to uncertainty in the knowledge of when that N would become available. Ignoring residues and their supply of N to subsequent crops raises the risk of oversupply of N to the crop. Hence, robust models of residue decomposition are key factors for further development.

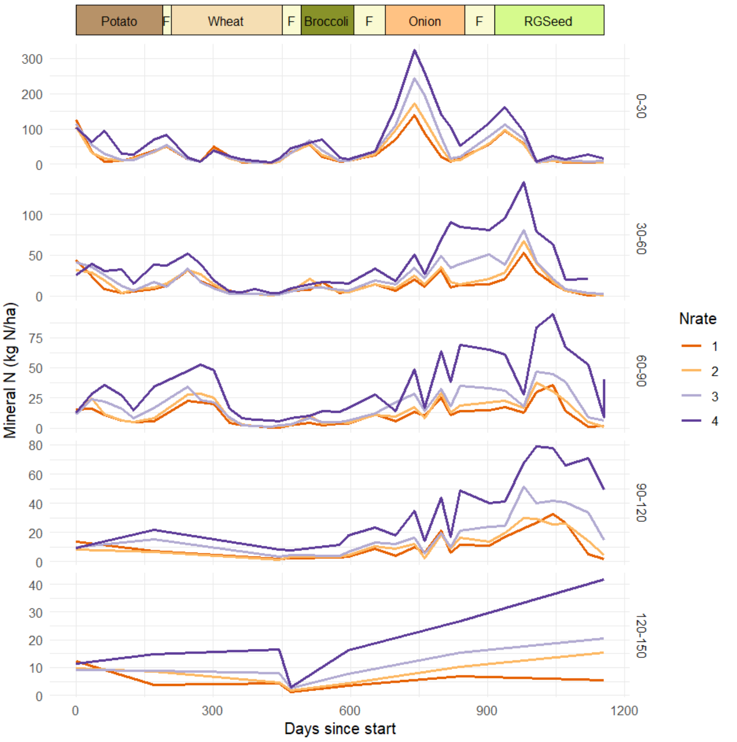

Figure 12. Effect of nitrogen (N) treatments on soil mineral N dynamics at depths of 0–30 cm, 30–60 cm, 60–90 cm, 90–120 cm and 120–150 cm, during Rotation 1 grown at The New Zealand Institute for Plant and Food Research Limited site in Lincoln, Canterbury. The different crops and timings are included in the plot.

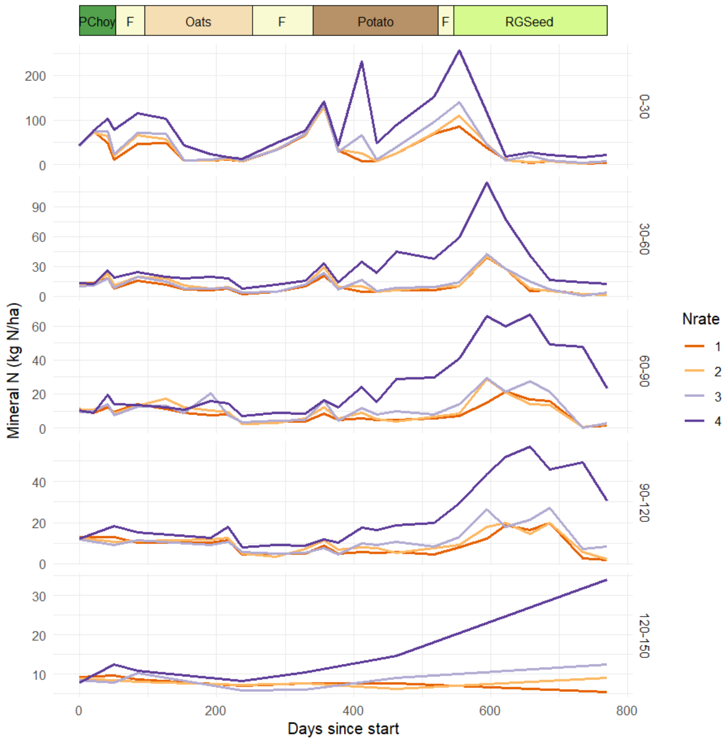

Figure 13. Effect of nitrogen (N) treatments on soil mineral N dynamics at depths of 0–30 cm, 30–60 cm, 60–90 cm, 90–120 cm and 120–150 cm, during Rotation 2 grown at The New Zealand Institute for Plant and Food Research Limited site in Lincoln, Canterbury. The different crops and timings are included in the plot.

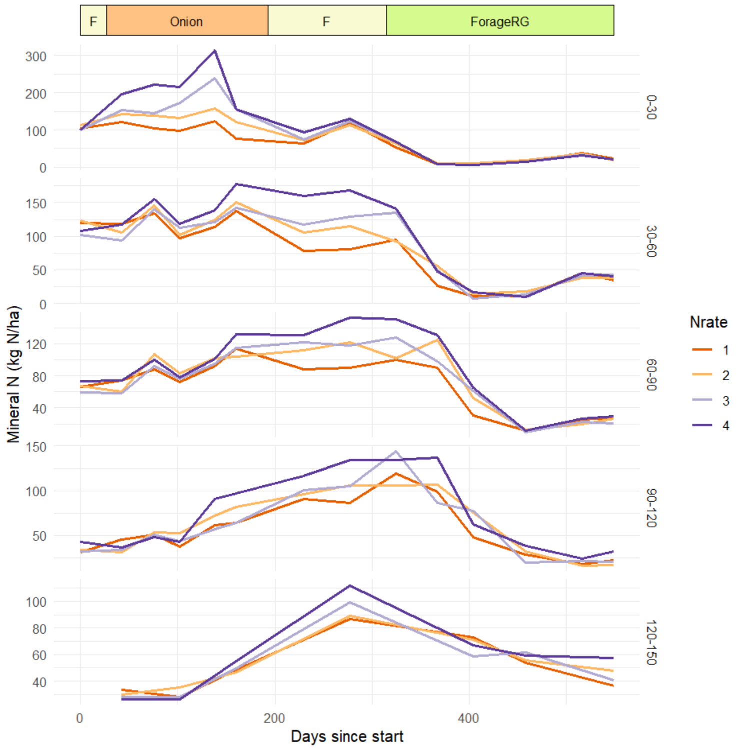

Figure 14. Effect of nitrogen (N) treatments on soil mineral N dynamics at depths of 0–30 cm, 30–60 cm, 60–90 cm, 90–120 cm and 120–150 cm, during Rotation 3 grown at The New Zealand Institute for Plant and Food Research Limited research site in Havelock North, Hawke's Bay. The different crops and timings are included in the plot.

Figure 15. Effect of nitrogen (N) treatments on soil mineral N dynamics at depths of 0–30 cm, 30–60 cm, 60–90 cm, 90–120 cm and 120–150 cm, during Rotation 4 grown at The New Zealand Institute for Plant and Food Research Limited research site in Havelock North, Hawke's Bay. The different crops and timings are included.

Table 2. Changes in soil nitrogen (N) under the onion crop in Rotation 1 and potential contribution of decomposition of previous broccoli crop residues to soil mineral N levels in onion. Rotation 1 was grown at The New Zealand Institute for Plant and Food Research Limited site in Lincoln, Canterbury. Observations are from the start of onion growth to the peak in soil mineral N observed (see Figures 12–15).

	N1	N2	N3	N4
Increase in soil mineral N (kg N/ha)	82	110	165	217
Mineralisation supply (kg N/ha)	33	33	33	33
Fertiliser supply (kg N/ha)	0	30	60	120
Required N (Increase – total input) (kg N/ha)	49	47	66	64
N content of broccoli residue (kg N/ha)	68	83	106	133
Estimated percent of N supplied from residue decomposition (%)	74	57	62	62

Required N = Increase in soil mineral N- (Mineralisation supply + Fertiliser supply)
Estimated percent of N supplied from residue decomposition = (Required N / N content of broccoli residue)*100
N1 (no fertiliser applied), N2 (half the recommended good management rate), N3 (good management rate), N4 (double the good management rate).

Patterns of soil N through the profile

The patterns of soil N at different depths are different between the two regions. In Canterbury (Figure 12 and Figure 13), soil mineral N in depths below the 30 cm layer tended to be lower than in the top 30 cm. Increases in mineral N content at these lower depths appeared somewhat after those in the top 30 cm.

In the Hawke's Bay soil (Figure 14 and Figure 15) there was a higher or similar concentration of mineral N in the 30–60 cm depth compared to the 0–30 cm depth, and this was maintained reasonably constantly for a large duration of the rotation. This relatively constant soil N content was also noted at the 60 to 90 cm depth. Similar trends were observed with the initial mineral N plots (Figure 10 and Figure 11), highlighting the regional variation in the pattern of N levels in the soils. Observations during soil sampling indicate a high-water table in Rotation 3 and 4, at times observable at 30–60 cm depths, and this may contribute to the higher soil N contents visible at the 30–60 cm and 60–90 cm depths. The effect on crop N use in these types of soils with high water tables should be further explored.

3.1.3 Mineralisable N

Measurements of Hot Water Extractable Organic Nitrogen (HWEON) were used to estimate the amount of N mineralised during growth of a crop, using estimated soil temperature and soil water status during growth (Beare et al. 2023). HWEON values are shown in Figure 16.

The HWEON in the top 0–15 cm of soil varied between the two rotations in Canterbury and Hawke's Bay (Figure 16). In Canterbury, HWEON averaged 83 and 81 mg/kg soil in Rotations 1 and 2 respectively, significantly lower ($p < 0.001$) than the average of 116 and 102 mg /kg of HWEON for Rotations 3 and 4, respectively, in Hawke's Bay. For the 15–30 cm depth, HWEON were similar between the two regions, averaging 66 and 64 mg/kg soil for Rotations 1 and 2 respectively, and 79 and 63 for Rotations 3 and 4 (Figure 16). Across the 0–30 cm depth, the total amount of HWEON is significantly ($p < 0.001$) higher in Rotation 3 and 4 from the Hawke's Bay soil with an overall average of 178 mg /kg of soil compared to 148 mg /kg of soil Rotation 1 and 2 in the Canterbury soil (Figure 16). Within the Hawke's Bay region, Rotation 3 had a significantly higher HWEON at 195 mg /kg compared to 165 mg /kg in Rotation 4.

There was no significant effect of N application on HWEON values for any rotation. Overall, HWEON values in the top 30 cm of the soil profile were quite consistent within sampling times and across the duration of the rotations. There were some significant changes in HWEON, but only in Rotation 4 (Figure 16) during the pea crop. HWEON decreased between the second and third sampling point (21 February 2022 and 21 April 2022) from 112 to 102 mg/kg soil (a decrease of 10 units). At the same time, HWEON increased significantly ($p < 0.01$) in the 15–30 cm soil profile from 56 to 68 mg//kg soil (an increase of 12 units), but across the 0–30 cm depth there was no significant change. This consistency in HWEON agrees with findings in other work (Beare et al. 2023).

The data for WS2 provide measurements across different regions (Appendix 5). Replicated samples were not collected at each sample time so confidence intervals could not be determined for these data. Outliers were determined and removed from analysis; there were 20 outliers (7.5% of samples). This compares to just under 2% of samples being outliers in the WS1 data and highlights the importance of care in sample collection and management. There were fluctuations in values collected over time in WS2, but no indication of a continued decrease or increase over time. There was also greater variability in HWEON values in WS2 (Appendix 5) compared to WS1.

For current practice, growers should take HWEON samples as determined by a sowing schedule: a spring sample for spring sown crops, and an autumn sample for autumn sown crops.

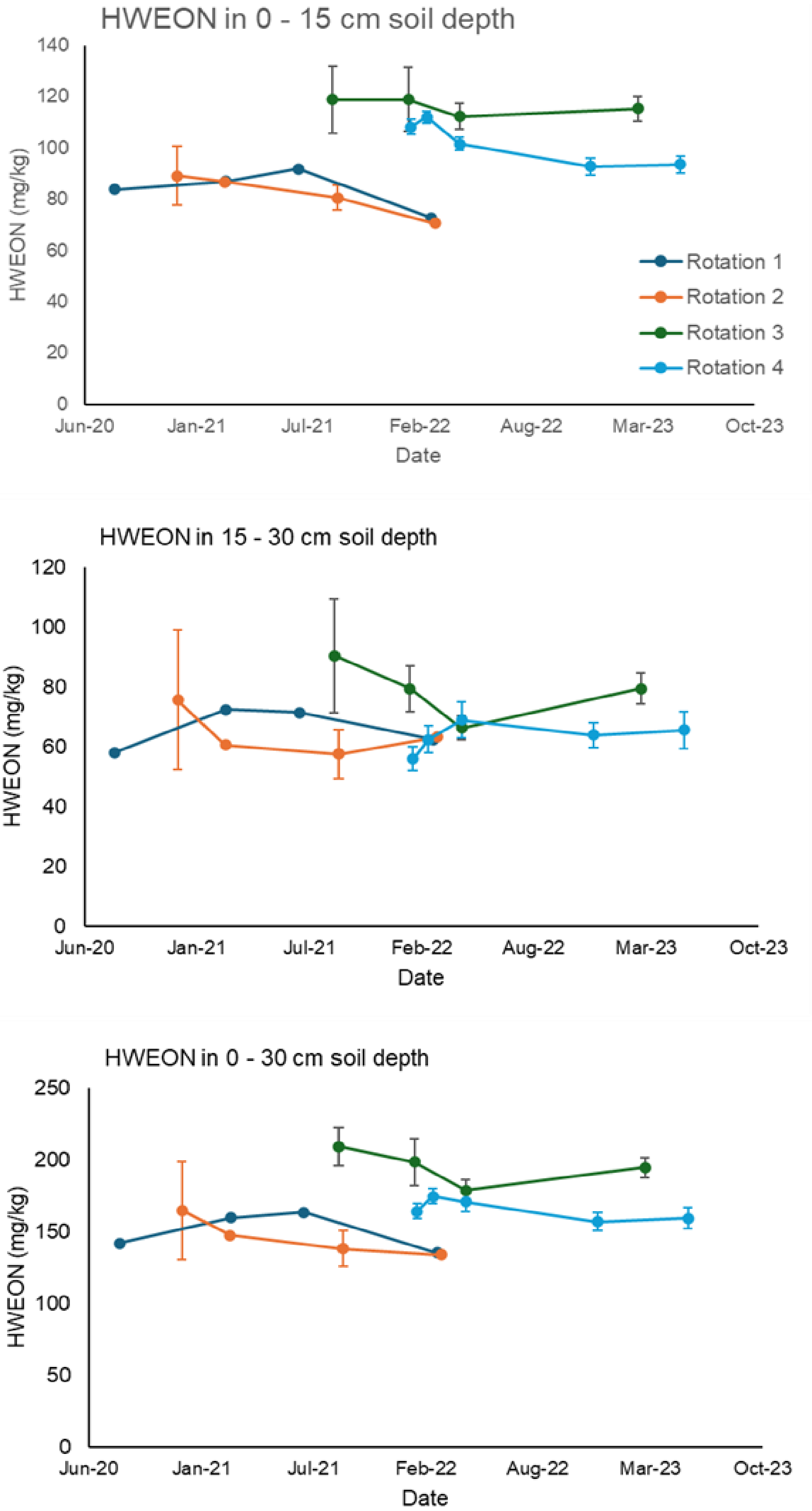

Figure 16. HWEON (Hot Water Extractable Organic Nitrogen) in the 0–15 and 15–30 cm soil layers of Rotation 1 and 2 grown at The New Zealand Institute for Plant and Food Research Limited site Lincoln, Canterbury, and Rotations 3 and 4 grown in the research site in Havelock North, Hastings. Error bars are 95% confidence intervals.

3.2 N effects on crop yield and crop N uptake

3.2.1 Yield response

Marketable yield determines economic returns, and any N balance must be applied in situations where N rates provide positive returns to yields. The response of marketable yield to applied N rates for the different crops in Rotation 1 and 2 are shown in Figure 17 and for Rotations 3 and 4 in Figure 18. In these figures the highest significant yield in response to applied N is marked with a red point. For example, the potato yield in Rotation 1 (Figure 17) is highlighted in red as the highest yield achieved of 77.4 t/ha (± a 95% confidence interval of 5.8 t/ha) was at the N3 treatment. While the N4 treatment yield was higher at 77.4 t/ha than the N3 treatment yield of 72.0 t/ha, but not significantly higher. The N3 treatment yield was significantly higher ($p < 0.01$) than the yields at the N1 (56.2 t/ha) and N2 (63.8 t/ha) treatment levels. If there is no red point, there is no significant N treatment effect on marketable yield.

Similarly, the potato crop in Rotation 2 (Figure 17) had the highest yield of 91.8 t/ha at the N4 treatment, and this was significantly higher than the yield of 81 t/ha at the N3 treatment. Ryegrass seed yield increased with applied N and was a maximum of 2.25 t/ha at the N2 treatment in Rotation 1, but it was not significantly higher from the yield in N1. Since there was no real effect of N in this crop, there was no marked points of maximum yield. In Rotation 2, the highest ryegrass seed yield occurred at N3 but was not significantly different to the N2 yield, but this was significantly different to the N1 yield. The onion crop in Rotation 1 also showed a significant increase in response to applied N, with the highest yield of 91 t/ha occurring in the N2 treatment, and then declining with additional N applications. Marketable yield of wheat, pak choy, oats and broccoli did not increase significantly with applied N.

In Rotation 3, onion yield did not increase from the level with no fertiliser to the N3 rate, but then decreased significantly to 34.5 t/ha at the N4 rate (Figure 18). This suggests that there was sufficient N supply in the soil as the yield with no applied fertiliser was similar to yields obtained with 60 and 120 kg N/ha (N2 and N3 treatments respectively). The addition of 240 kg N/ha (N4 treatment rate) resulted in an oversupply of N and seemed to reduce onion yield.

The forage ryegrass crop was treated as a grazing crop by cutting and removing biomass. There was some effect of N rate on ryegrass forage yield, but it was not consistent across harvest times, or rotation (Figure 18).

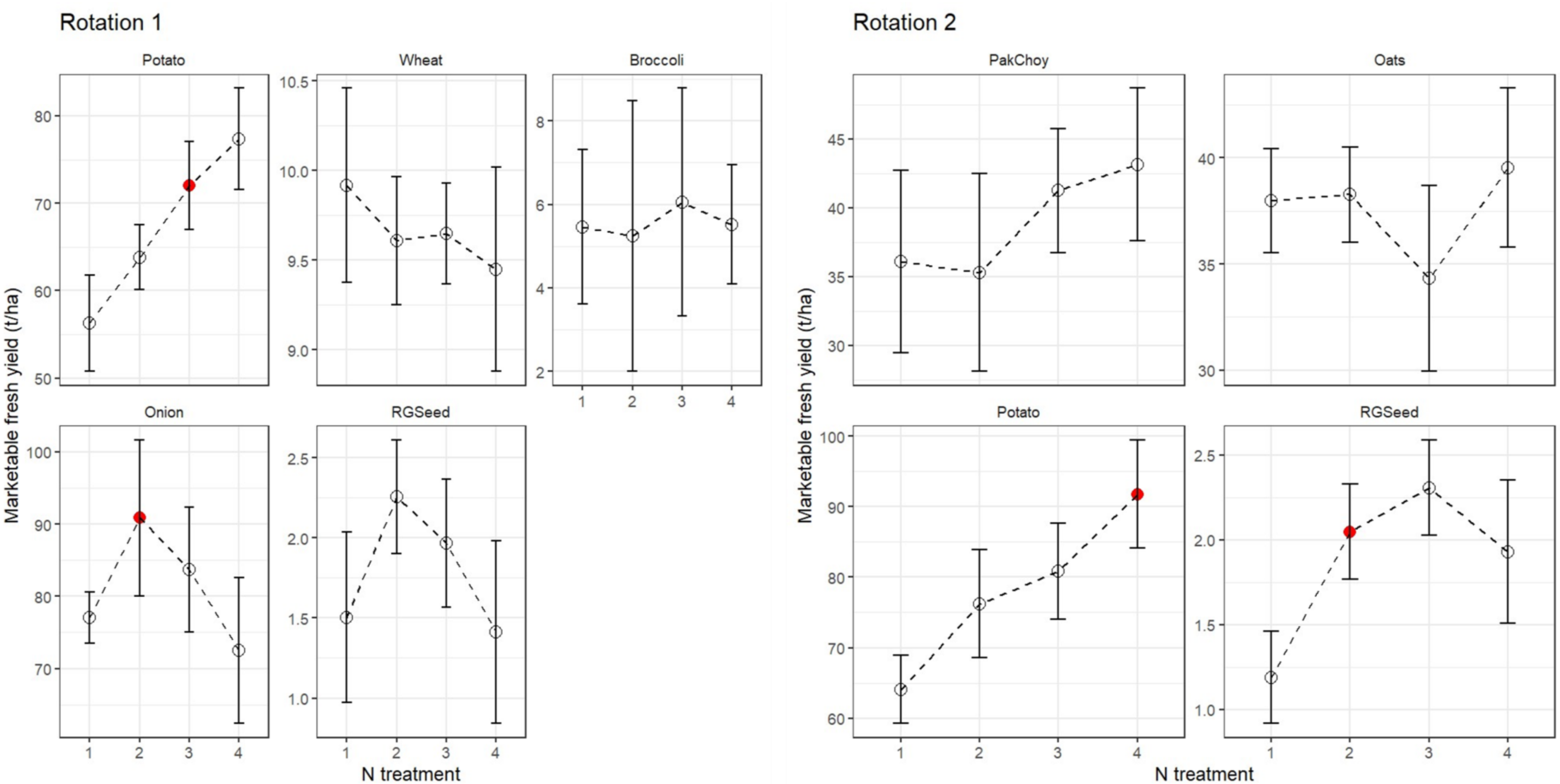

Figure 17. Change in marketable yield with nitrogen (N) treatment for crops grown in a) Rotation 1 and b) Rotation 2 at The New Zealand Institute for Plant and Food Research Limited Lincoln site, Canterbury. Red points mark the N treatment that had the significantly highest marketable yield. Where there are no red points, there was no significant effect of N on yield. Error bars are 95% confidence intervals.

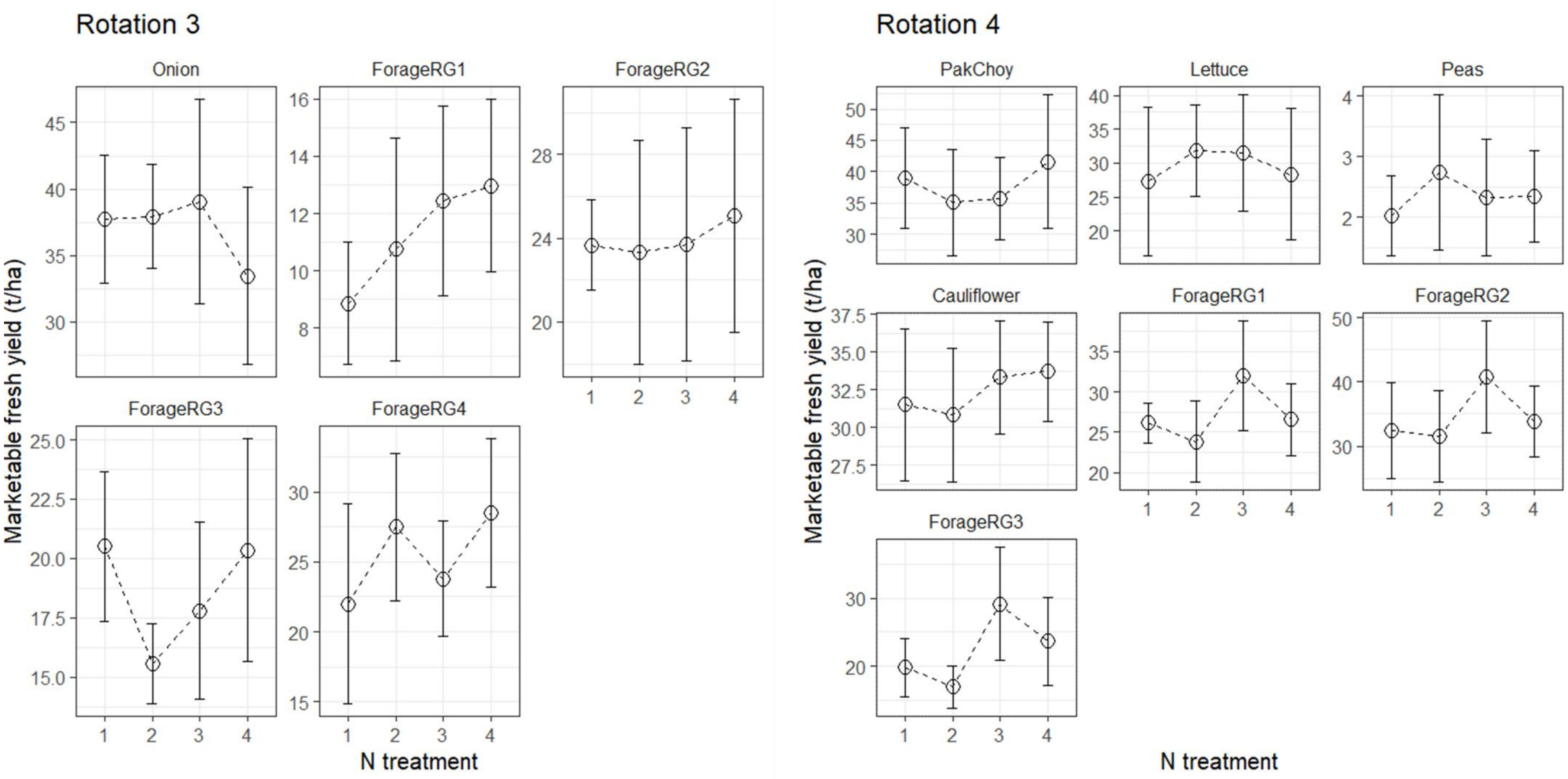

Figure 18. Change in marketable yield with nitrogen (N) treatment for crops grown in a) Rotation 3 and b) Rotation 4 at The New Zealand Institute for Plant and Food Research Limited, Havelock North research site, Hawke's Bay. Red points mark the N treatment that had the significantly highest marketable yield. Where there are no red points, there was no significant effect of N on yield. The sequential harvests that simulate grazing in the forage ryegrass are included as separate crops. Error bars are 95% confidence intervals.

3.2.2 Crop total biomass, marketable and stover dry weight yields

Dry weight of the crop provides a precise estimate of biomass that can be directly related to plant response to nutrients. In addition, dry weight is needed to calculate N uptake, when multiplying it by the N% of the biomass.

The changes in dry weight total, marketable and stover biomass with applied N are shown for the different crops of Rotation 1 and 2 in Figure 19 and the crops grown in Rotation 3 and 4 in Figure 20. In these figures, the N treatment that had the highest significant yield is highlighted in red. An example is the potato biomass yields in Rotation 1 (Figure 19) where the yield at the N3 treatment was statistically higher than treatments N1 and N2, but not statistically different to the N4 level.

Some observations from these figures were:

- Not all crops had a significant response to applied N. This is particularly evident in Rotation 3 and 4 (Figure 20), and also wheat, pak choy and oats in Rotation 1 and 2 (Figure 19). For these crops there was sufficient N supplied by the soil that there was no benefit of additional N.
- The onion crop in Rotation 1 had the highest statistically significant yield occur at the N2 treatment (Figure 19), and then yield decreased with additional N. In Rotation 3, the onion crop was oversupplied with N as there was no significant increase in yield with applied N; yield was similar for treatments N1 to N3, and then decreased significantly at the N4 treatment rate.
- Whilst broccoli marketable yield did not increase with applied N (Figure 17), the total biomass dry weight did (Figure 19). The highest dry weight obtained of 4.1 t/ha was at the N4 treatment (Figure 19). The marketable yield was taken as a single cut, rather than sequential harvest over time. The dry weight yield suggests that the marketable yield would have increased with N rate if sequential harvesting had proceeded.

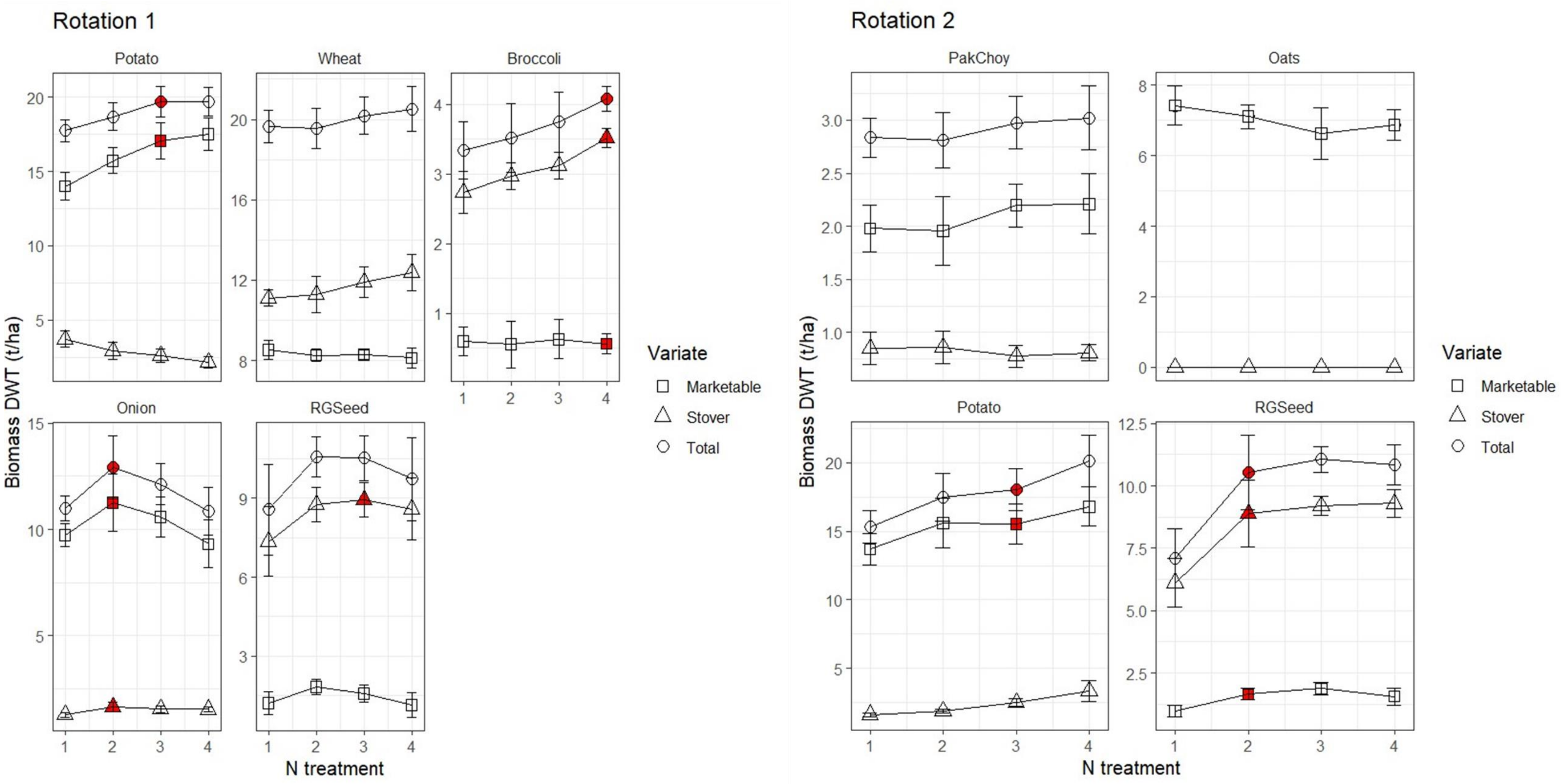

Figure 19. Effect of nitrogen (N) treatment on total, marketable and stover dry weight biomass for crops grown in a) Rotation 1 and b) Rotation 2 at The New Zealand Institute for Plant and Food Research Limited Lincoln site, Canterbury. Red points mark the N treatment that had the significantly highest total, marketable, stover or total dry weight biomass. Error bars are 95% confidence intervals.

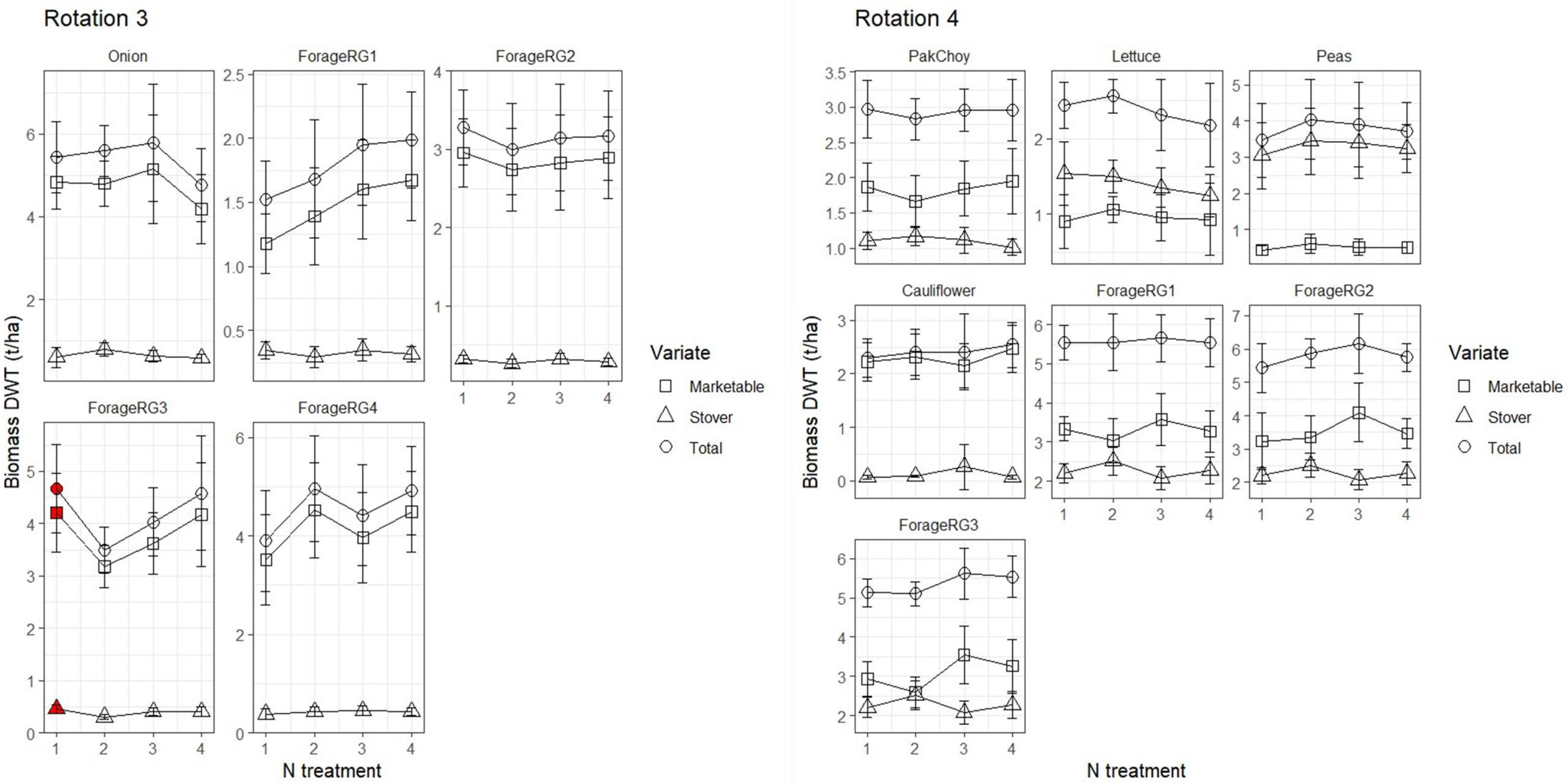

Figure 20. Effect of nitrogen (N) treatment on Total, marketable and stover dry weight biomass for crops grown in a) Rotation 3 and b) Rotation 4 at The New Zealand Institute for Plant and Food Research Limited Havelock North site, Hawke's Bay. Red points mark the N treatment that had the significantly highest total, marketable, stover or total dry weight biomass. Error bars are 95% confidence intervals.

3.2.3 Crop N uptake

An important aspect for developing the model and tool was determining the key crop coefficients important in the calculation of the crop N uptake. These key coefficients include: the critical crop N content for total, marketable and stover biomass, a marketable yield, the dry matter percent of the marketable component of the crop (DM%); the partitioning of dry matter between the marketable and non-marketable components of the crop (HI); and the partitioning of N between marketable and residue component of the crop, the N content of the residue and the dry matter content of the residue.

To determine the coefficient values, we used ANOVA to compare treatment effects on the parameter values. The analysis used a split-plot approach, with irrigation as the main plot and N rate as the sub-plot, and this was evaluated for each crop used in each of the four rotations. Where residual checks indicated non-normality, the data were log transformed.

Analysis showed that there were differences in dry weight total and marketable yield due to treatments. There were no irrigation effects, so focus was on N treatment, and linear contrasts were used to determine which N treatment had significantly higher yields than the other treatments. Specifically, we evaluated the hypothesis that the N3 treatment (the estimated best practice rate) had significantly higher yields that N1 (no applied N fertiliser), N2 (half best practice rate), and N4 treatments (twice the best practice rate). Where different N treatments had a statistically similar yield, the lower N treatment was considered as the optimum rate.

We then determined the N content in the marketable crop (Nc%) by identifying the highest attained yield with the lowest N input; this is the treatment combination that determines the Nc%. This is a well-recognised approach for determining N% of crops and is referred to as the critical N dilution curve (Greenwood et al. 1980; Justes et al. 1994). The approach is behind many N response models, e.g. EuRotate, N-Able (Greenwood 2001; Rahn et al. 2010). This same approach was used to determine the different crop coefficient values. These crop coefficients were then used in model development and validation and used to develop coefficients for best model fit: the developed coefficients are shown in Appendix 6.

From experimental inputs we estimated N uptake. Examples for the potato and onion crops are given in Table 3 and Table 4, where different coefficient values vary with N applications and between crops. For potatoes the N treatment with highest marketable dry weight was N3 – at this N rate, the N% was 1.38 for the potato crop in Rotation 1 and 1.80 for the potato crop in Rotation 2. These could be varietal issues (Russet Burbank grown in Rotation 1 and ‘Agria’ grown in Rotation 2) though model fitting does not find a significant difference in these coefficients (Appendix 6).

The onion crop in Rotation 1 had highest marketable dry weight yield at the N2 treatment (Figure 19) with a N% of 1.38 (Table 4). In contrast, the N% of onions in Rotation 3 were higher than those observed in Rotation 1, and together with the lack of yield response in Rotation 3 (Figure 20) indicate that these N% for onion in Rotation 3 are due to luxury uptake that has no benefit to yield.

Table 3. Key parameters for estimation of nitrogen (N) uptake of marketable component of potato crops in Rotation 1 and 2, grown at the New Zealand Institute for Plant and Food Research Limited site in Lincoln, Canterbury. Treatment contrasts against the N3 treatment are shown.

Rotation/Crop	N rate	DW Yield (t/ha)	N%	DM%	Uptake (kg N/ha)	Harvest index (Marketable yield/ Total biomass)
Rotation 1/Potato						
	1	14.01	0.95	24.98	132.88	0.79
	2	15.72	1.15	24.65	180.01	0.84
	3	17.06	1.38	23.69	236.06	0.87
	4	17.49	1.68	22.65	293.67	0.89
Significance of contrast						
	N1 vs N3	<0.001	<0.001	0.002	<0.001	<0.001
	N2 vs N3	0.06	0.003	0.01	0.005	0.132
	N4 vs N3	0.516	<0.001	0.006	0.005	0.133
Rotation 2/Potato						
	1	13.69	0.97	21.35	133.18	0.89
	2	15.62	1.32	20.45	205.92	0.89
	3	15.53	1.8	19.19	278.83	0.86
	4	16.8	2.18	18.32	366.26	0.84
Significance of contrast						
	N1 vs N3	0.012	<0.001	<0.001	<0.001	0.013
	N2 vs N3	0.89	<0.001	0.007	<0.001	0.02
	N4 vs N3	0.07	<0.001	0.05	<0.001	0.058

Table 4. Key parameters for estimation of nitrogen (N) uptake of marketable component of onion crops in Rotation 1, grown at The New Zealand Institute for Plant and Food Research Limited site in Lincoln, Canterbury and Rotation 3 grown Havelock North research site in Hawke's Bay. Treatment contrasts against the N3 treatment are shown.

Rotation/Crop	N rate	DW Yield (t/ha)	N%	DM%	Uptake (kg N/ha)	Harvest inde (Marketable yield/ Total biomass)x
Rotation 1/Onion						
	1	9.74	1.34	12.64	130.57	0.88
	2	11.26	1.38	12.4	155.34	0.87
	3	10.59	1.47	12.67	154.88	0.87
	4	9.31	1.59	12.91	147.63	0.86
Significance of contrast						
	N1 vs N3	0.124	0.048	0.85	0.052	0.044
	N2 vs N3	0.215	0.161	0.157	0.096	0.883
	N4 vs N3	0.026	0.055	0.205	0.464	0.02
Rotation 3/Onion						
	1	4.83	1.69	12.79	81.35	0.89
	2	4.80	1.75	12.64	83.62	0.86
	3	5.15	1.78	13.06	91.12	0.89
	4	4.18	1.87	12.52	77.84	0.87
Significance of contrast						
	N1 vs N3	0.69	0.8	0.56	0.38	0.05
	N2 vs N3	0.66	0.49	0.37	0.45	0.24
	N4 vs N3	0.84	0.07	0.24	0.86	0.005

The total uptake by the crop over time is plotted together with the total supply of N which includes a starting point of the initial mineral N in the soil and increase over time due to mineralisation as well as fertiliser N application in Figures 21–24. Ideally, the closer matched soil N supply is to crop N uptake, the less likely there is to be 'uncharacterised' N in the system, leading to better environmental outcomes.

In some of the crops there are large mismatches between total N supply and N uptake – these are most evident in Rotation 3 (Figure 22) and 4 (Figure 24) and therefore likely to have relatively large uncharacterised portions of the N balance. Crops with very close matches are potato in Rotation 2 Figure 22 and the forage ryegrass crops in Rotation 3 and 4 (Figure 23 and Figure 24).

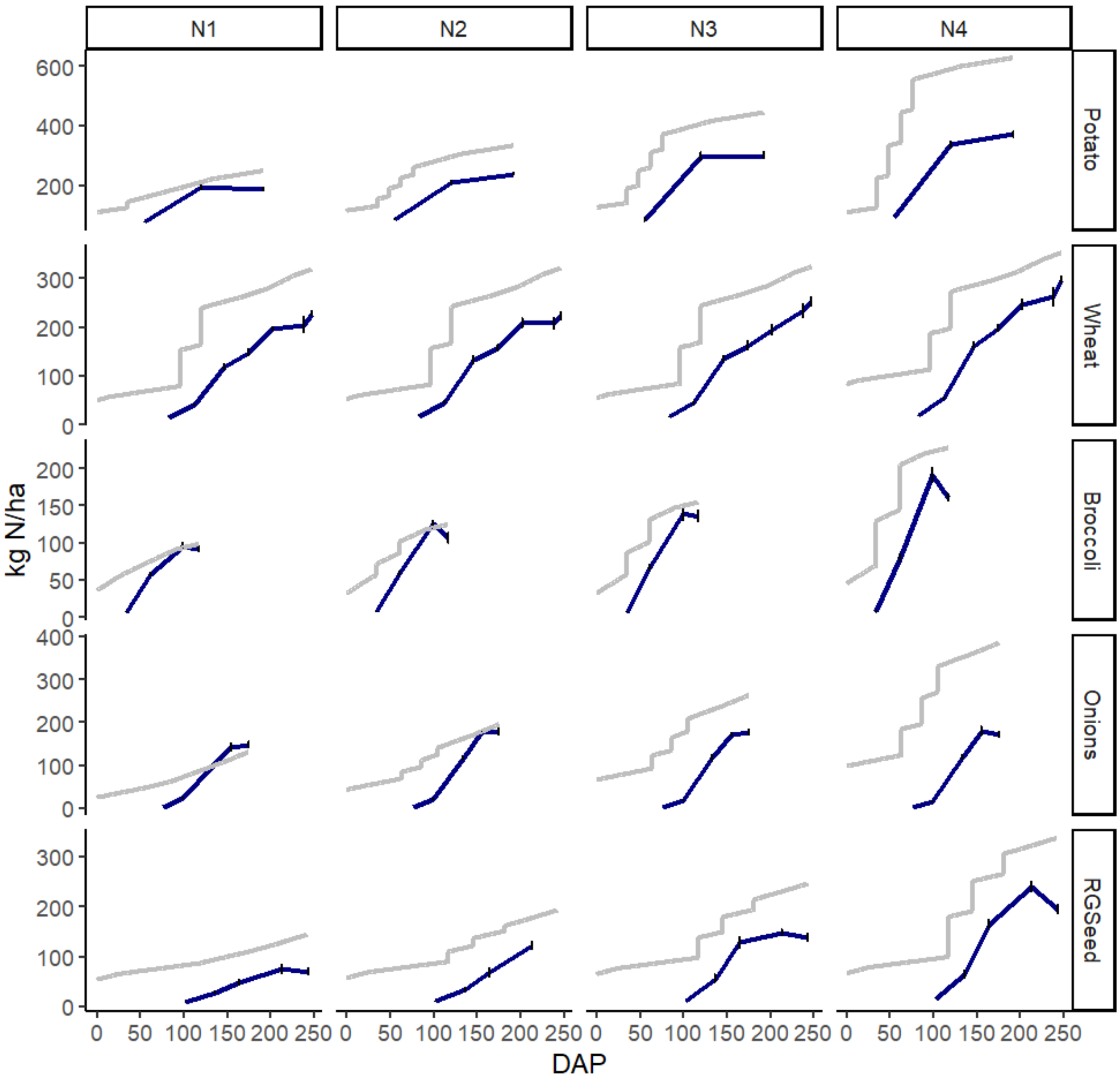

Figure 21. Crop nitrogen (N) uptake of total biomass (blue line) and supply of soil N via initial mineral N content, mineralisation during crop growth and fertiliser applications (grey line) for crops' growth with different N treatments in Rotation 1, at The New Zealand Institute for Plant and Food Research Limited site in Lincoln, Canterbury. DAP is days after planting. Error bars are 95% confidence intervals.

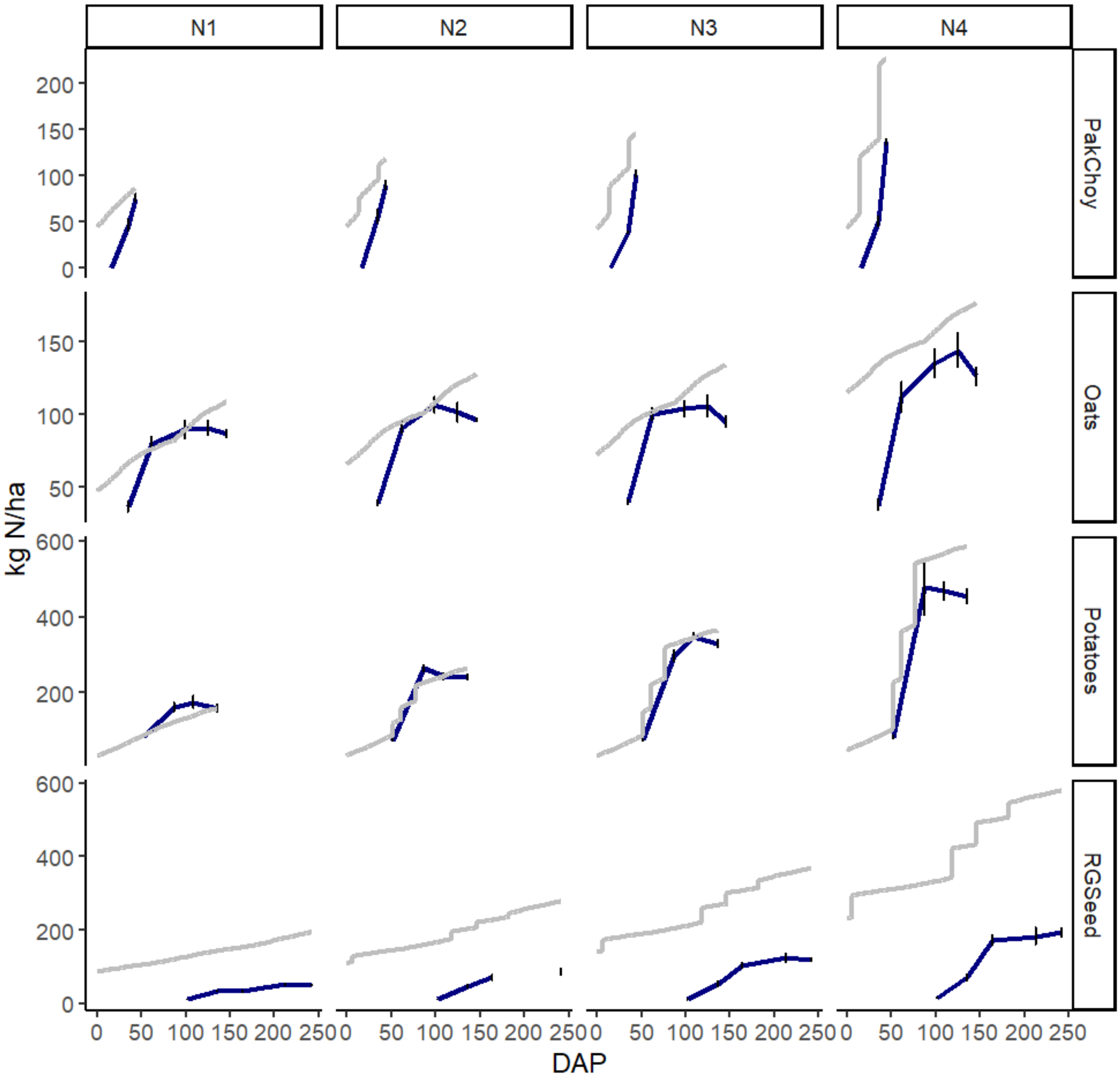

Figure 22. Crop- nitrogen (N) uptake of total biomass (blue line) and supply of soil N via initial mineral N content, mineralisation during crop growth and fertiliser applications (grey line) for crops' growth with different N treatments in Rotation 2, at The New Zealand Institute for Plant and Food Research Limited site in Lincoln, Canterbury. DAP is days after planting. Error bars are 95% confidence intervals.

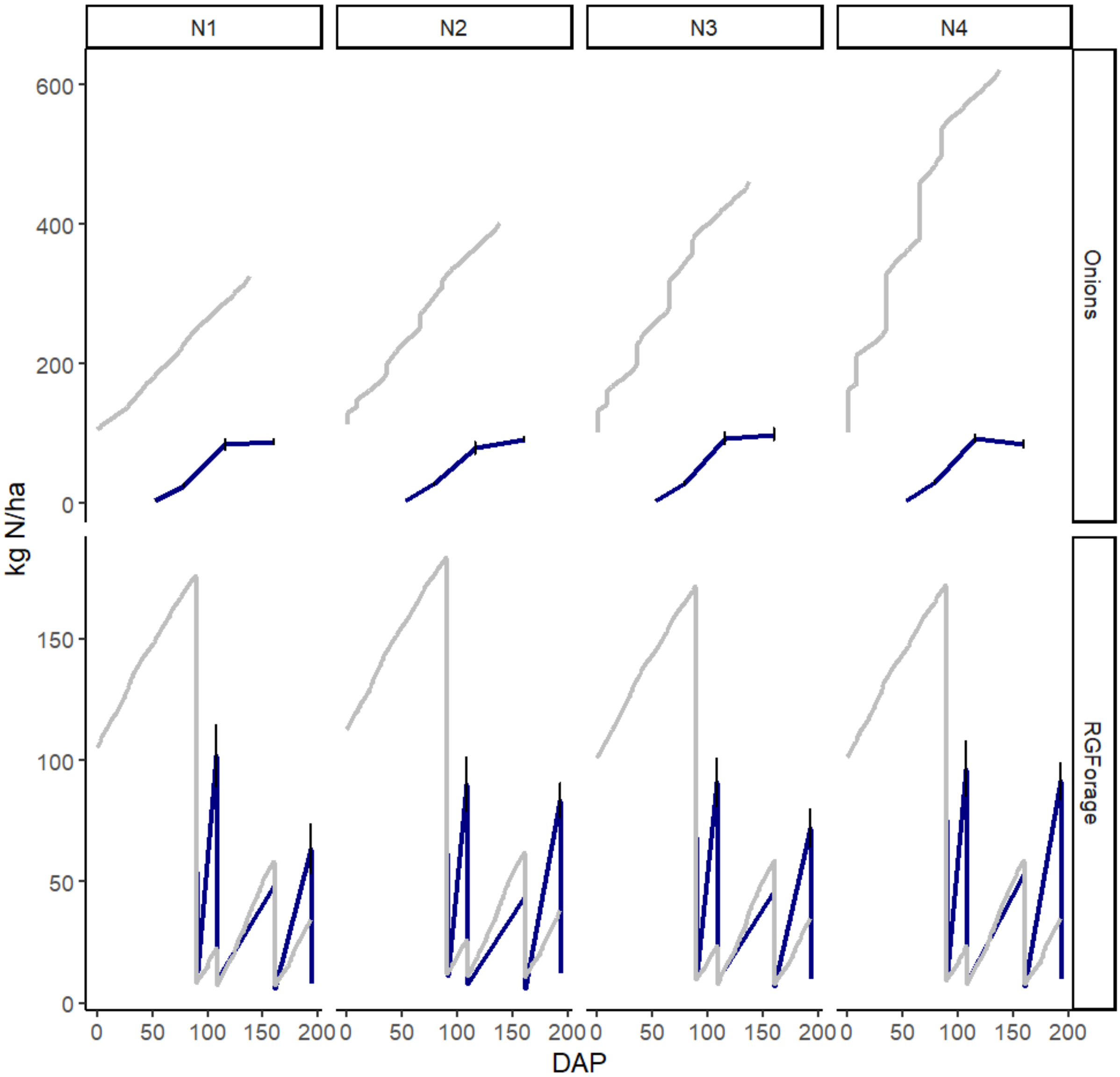

Figure 23. Crop nitrogen (N) uptake of total biomass (blue line) and supply of soil N via initial mineral N content, mineralisation during crop growth and fertiliser applications (grey line) for crops' growth with different N treatments in Rotation 3, at The New Zealand Institute for Plant and Food Research Limited site in Havelock North, Hawke's Bay. DAP is days after planting. Error bars are 95% confidence intervals.

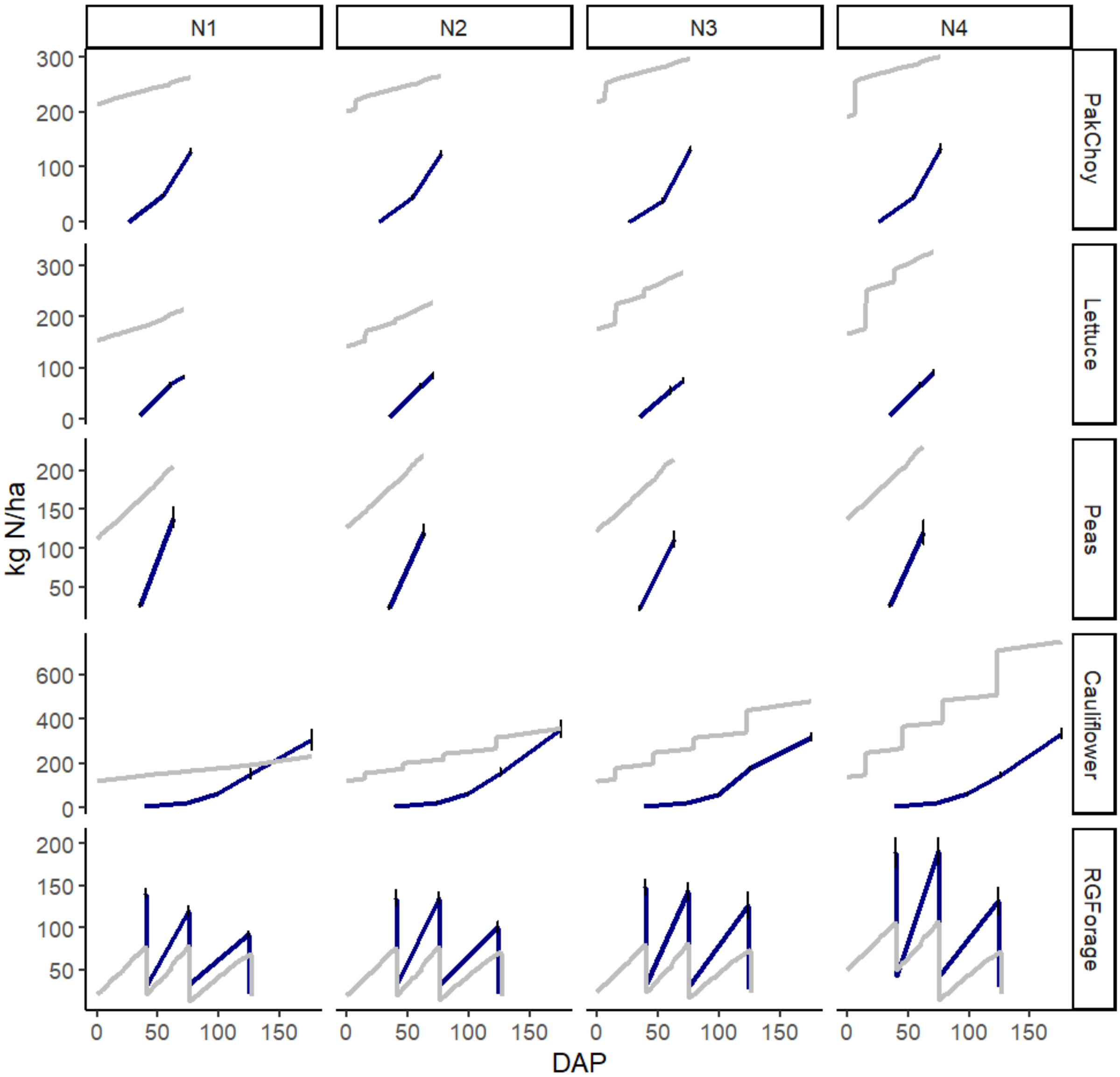

Figure 24. Crop nitrogen (N) uptake of total biomass (blue line) and supply of soil N via initial mineral N content, mineralisation during crop growth and fertiliser applications (grey line) for crops' growth with different N treatments in Rotation 4, at The New Zealand Institute for Plant and Food Research Limited site in in Havelock North, Hawke's Bay. DAP is days after planting. Error bars are 95% confidence intervals.

3.3 Effects on crop N balance

The Uncharacterised portion of the N balance is shown in Figures 25–28 and reflects N in the system that cannot be explained by crop N uptake, or by N that remains in the residue or the soil after harvest. Higher values of Uncharacterised N suggest more likely movement of N below the 30 cm depth, or perhaps N volatilised to the atmosphere. The N balances for each crop are shown in Appendix 7.

In general, the Uncharacterised portion increases significantly with N rate. There are also some crops with negative Uncharacterised values – this indicates that crops have not had sufficient N supplied from the 0–30 cm depth of soil, and have used soil N from depths below 30 cm. This is particularly the case for the forage ryegrass crops in Rotation 3 and 4 (Figure 27 and Figure 28). The supply of N in the top 30 cm often did not match the uptake (Figure 23 and Figure 24) and this crop was able to obtain N from lower depths, which may not be the case for all crops. Rooting depth is a consideration (see Appendix 6) in further calculations of Uncharacterised N, but for most crops the roots that functionally absorb nutrients are in the top 30 cm (Greenwood et al. 1982; Jackson & Stivers 1993; Kristensen & Thorup-Kristensen 2007; Thorup-Kristensen & Kirkegaard 2016) .

In Rotation 3 and 4 most crops, except the onion crop, showed no significant change in Uncharacterised N with applied N fertiliser, and this is largely due to very high soil mineral N values remaining in the soil after harvest (Appendix 7). Whether this is an artefact of rising and falling water tables in this soil during the rotations needs to be further determined.

Some observations of changes in Uncharacterised N for the different rotation and crops are:

- The pattern of increase in Uncharacterised N with applied N was the same in the two onion crops grown in Rotation 1 and 3. In Rotation 1, Uncharacterised was 230 kg N/ha, 200 kg N/ha greater than the level with no applied N. In Rotation 3, Uncharacterised N was 375 kg, also 200 kg N/ha above the level observed with no applied N fertiliser. There was an oversupply in N to onion crops in both Rotation 1 and 3 (see Sections 3.1 and 3.2), and while this has resulted in an increased level of Uncharacterised for the onion crop in this Rotation, the starting level of soil N also contributed to this. In Rotation 3, the starting level of soil N did not significantly reduce the rates of applied N; this highlights the importance of adapting N application based on soil supply.

- The pak choy in Rotation 2 had Uncharacterised N levels less than 50 kg N/ha (Figure 26), whereas in Rotation 4, the Uncharacterised was greater than 100 kg N/ha (Figure 28). This is another case where oversupply of N results in a much larger Uncharacterised portion of the N balance.

- The potato crops also had similar trends of an increase in Uncharacterised N with applied N. However, the ranges were quite different, with Uncharacterised N increasing from 0 to 225 kg N/ha with applied N in Rotation 1 (see Figures 25–28). In comparison, the Uncharacterised N of the potato crop in Rotation 2 increased from -20 to 8 kg N/ha (Figure 26). There was no limitation of N to yields in these crops (See Section 3.1 and 3.2), and N supply better matched uptake by the potato crop in Rotation 2 (Figure 22). This result highlights that a low Uncharacterised N can be obtained from appropriate use of N fertiliser that optimises yield but reduces the Uncharacterised portion of the N balance.

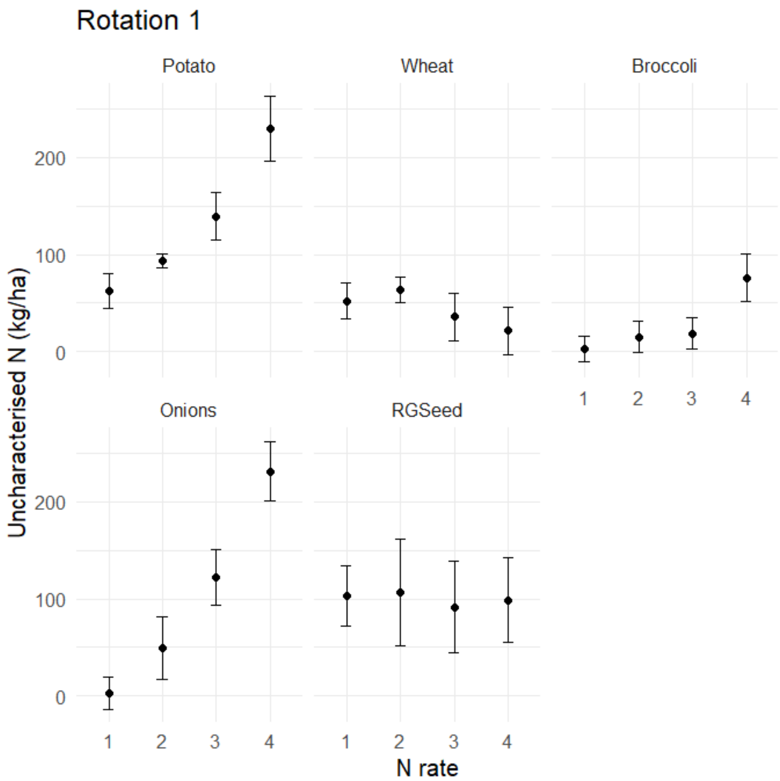

Figure 25. Amount of Uncharacterised nitrogen (N) of the N balance in response to N treatment for different crops grown in Rotation 1 at The New Zealand Institute for Plant and Food Research Limited site in Lincoln, Canterbury. Error bars represent 95% confidence intervals.

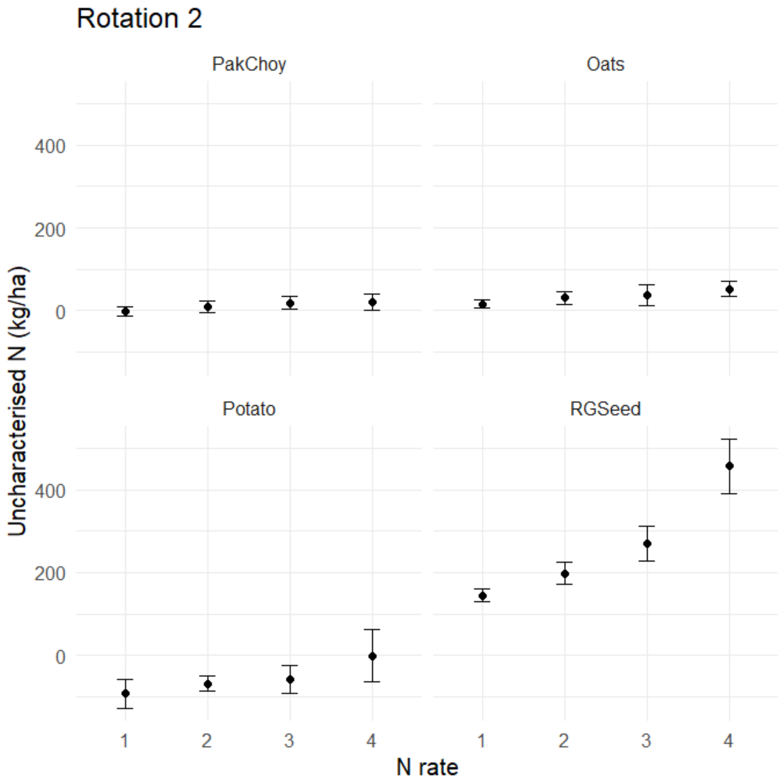

Figure 26. Amount of Uncharacterised nitrogen (N) of the N balance in response to N treatment for different crops grown in Rotation 2 at The New Zealand Institute for Plant and Food Research site in Lincoln, Canterbury. Error bars represent 95% confidence intervals.

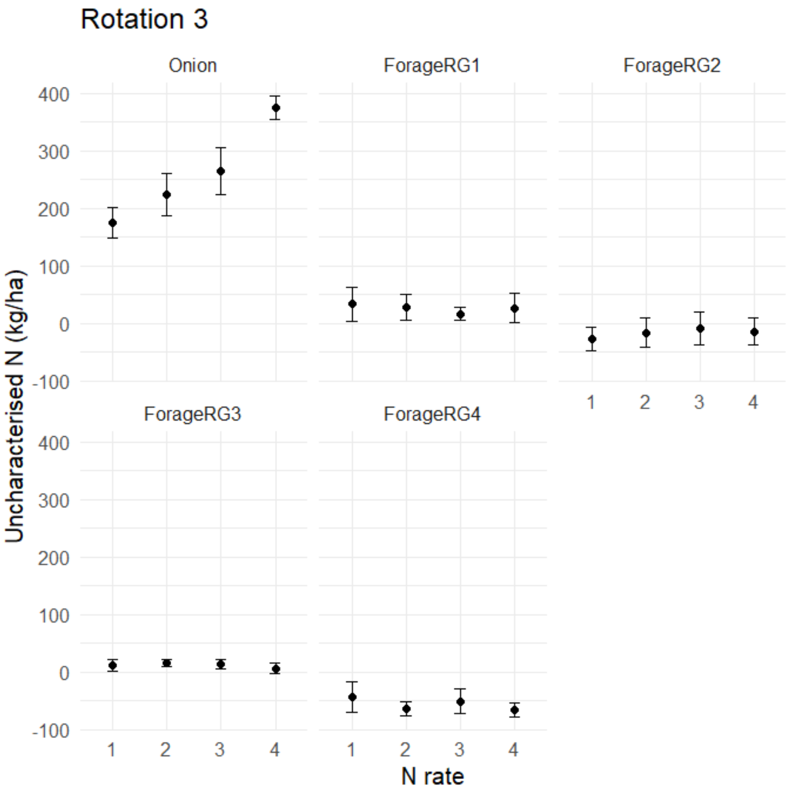

Figure 27. Amount of Uncharacterised nitrogen (N) of the N balance in response to N treatment for different crops grown in Rotation 3 at The New Zealand Institute for Plant and Food Research Limited site in Havelock North, Hawke's Bay. Error bars represent 95% confidence intervals.

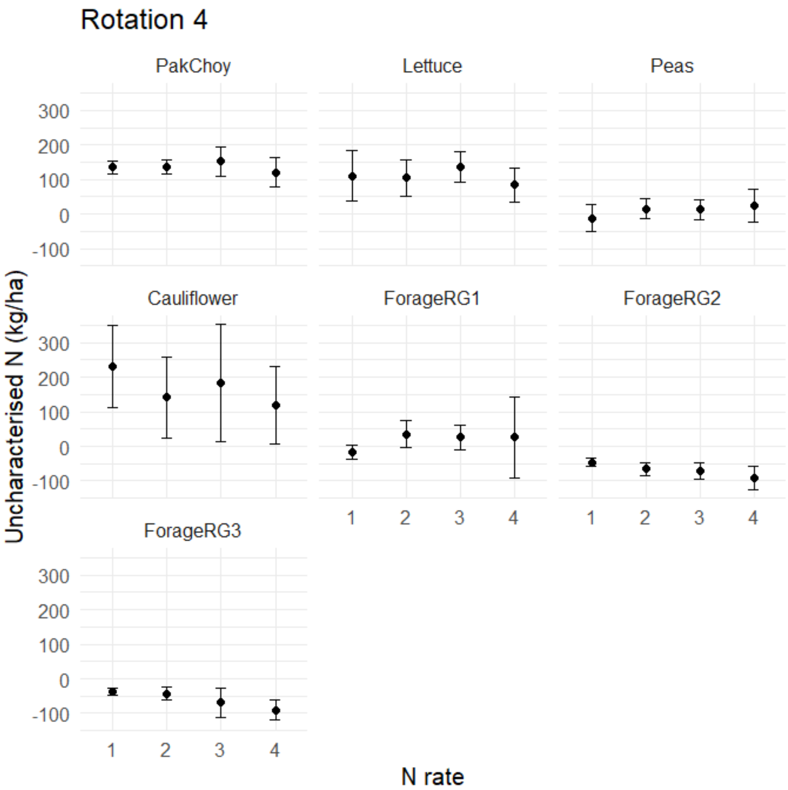

Figure 28. Amount of Uncharacterised nitrogen (N) of the N balance in response to N treatment for different crops grown in Rotation 4 The New Zealand Institute for Plant and Food Research Limited site in Havelock North, Hawke's Bay. Error bars represent 95% confidence intervals.

Since exported N is a key component of the balance, a partial N balance estimated using Fertiliser N – Export N has been related to Uncharacterised N in cereal and maize crops (Rozas et al. 2004; Rocha et al. 2020; Tamagno et al. 2022). This shows that for each of the crops, as there is a greater input of Fertiliser N compared Export N, i.e. a greater surplus of N supplied, there is an increase in Uncharacterised N. When this surplus estimated as Fertiliser N – Export N was plotted for the crops in Rotation 1–4, there was significant variability. A more consistent outcome was obtained when plotting the surplus estimated as Total Input (initial soil mineral N + mineralizable N + residue N + Fertiliser N) minus Export N against the Uncharacterised N (Figure 29).

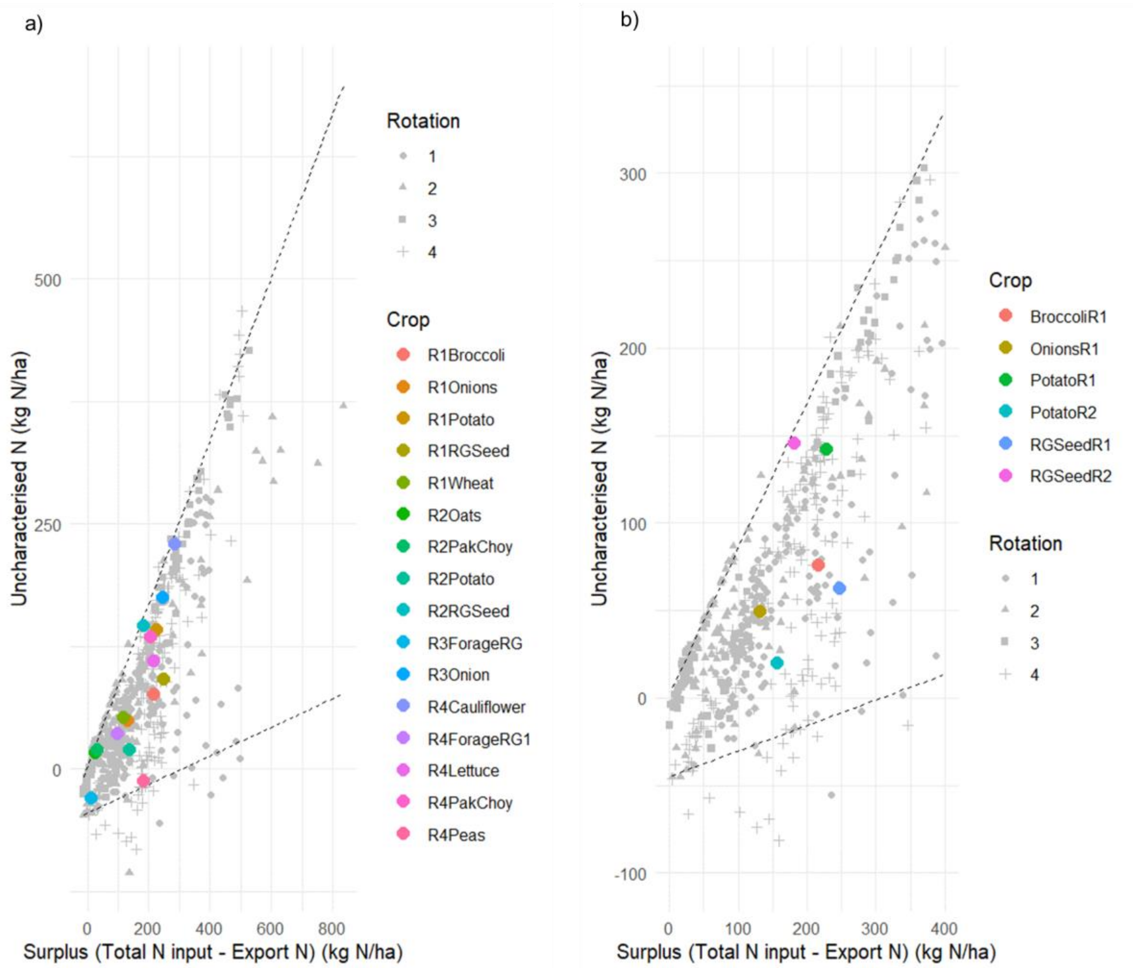

Figure 29. Relationship between Uncharacterised nitrogen (N) and Nitrogen Surplus (Total N input – Export N) for the crops grown in different Rotations grown at The New Zealand Institute for Plant and Food Research Limited. Dotted lines indicate 5% and 95% quantiles. Grey dots indicate all data points. Figure a) shows all the points where crop yields were highest, including crops where there was no yield response to applied N. Figure b) only includes the crops that had a significant response to applied N, and the points indicate where the highest significant yield occurred. Total N input is the sum of all N inputs, Export N is the N in marketable material.

As the Surplus increases then the Uncharacterised N amount increases. The coloured points in Figure 29a shows the Surplus and Uncharacterised N obtained for the highest significant yield recorded. This includes crops where there was no significant response to applied N, so for these crops, the Surplus and Uncharacterised N reflects the results when no fertiliser was applied and, in these situations, it is unknown if nitrogen was oversupplied. Figure 29b highlights data for crops where there was a yield response to applied N. The points in Figure 29b are the highest statistically significant yield and show that there are significant variations depending on crop. It is worth noting the difference in the two potato crops (Figure 29b) and this is explored in Section 3.4.

There are a large number of Uncharacterised N values that are negative (Figure 29 a,b). In these situations, insufficient N has been provided to the crop, and N is being used from below the 30 cm depth (see also Appendix 7). This is most obvious in the potato crop (Rotation 2), and the ryegrass crops in all rotations. Obtaining N from lower depths is not a viable option for many crops where the bulk of functional roots in in the top 30 cm of soil (Greenwood et al. 1982; Jackson & Stivers 1993; Kristensen & Thorup-Kristensen 2007; Thorup-Kristensen & Kirkegaard 2016) which is why the N balance is based on soil N supply from the top 30 cm of soil.

It is necessary to know if with oversupply of N, the Uncharacterised N is consistently higher than if optimum N is supplied to the crop. This helps confirm the value of providing an optimum N to the crop as a management tool for optimum production and sustainability outcomes. Given the variability shown in Figure 29, we estimated the relative levels of Uncharacterised N to compare across crops. For crops where there was a yield response to applied N, Uncharacterised N was estimated relative to that of the highest significant yield.

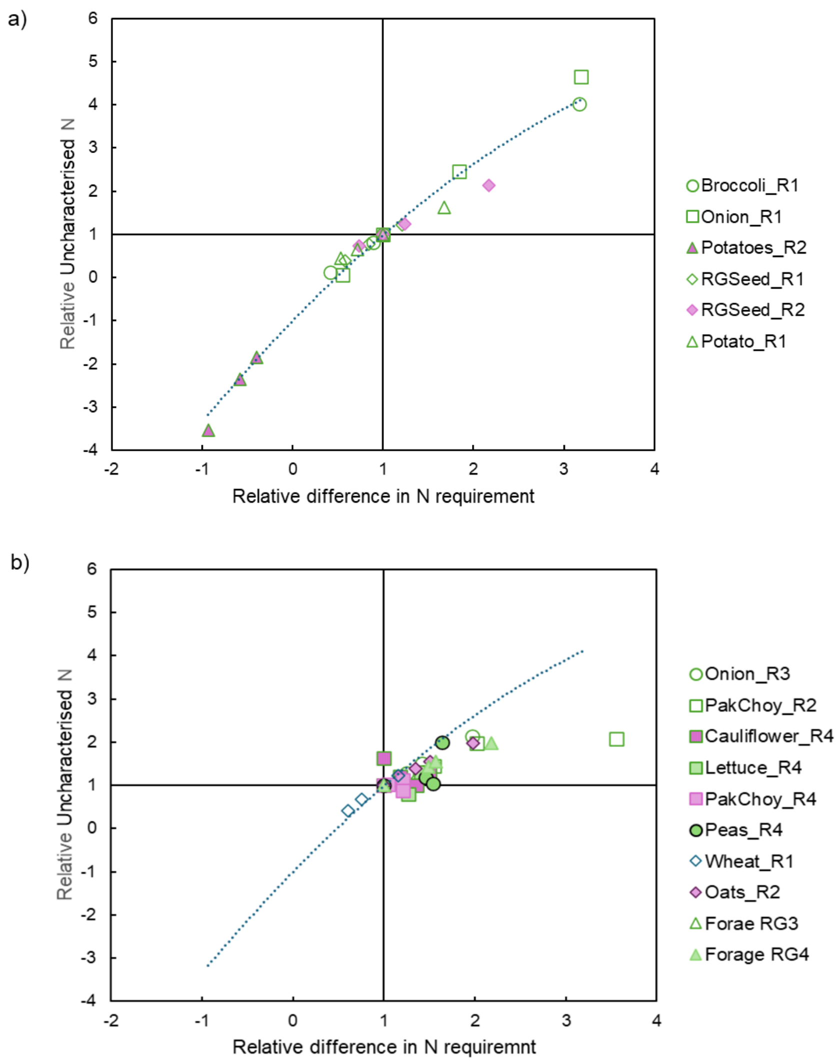

Figure 30. Changes in relative Uncharacterised nitrogen (N) with relative differences in N requirement (Total N Input – Export N) estimated for a) crops where there was a yield response to applied N and b: crops where there was no yield response to applied N. The dotted line indicates a regression across all data ($p < 0.001$, $R^2 = 0.98$, y= 0.1759x2 + 2.166x - 1.004).

For crops where there was no yield response to N, Uncharacterised was estimated it was relative to the Uncharacterised N of the 0 kg N/ha treatment (no applied N). Results are shown in Figure 30. We also estimated the relative oversupply of N (Total Input N – Total uptake N) on the same basis.

The results for crops where there was yield response to applied N are shown in Figure 30a. In this plot, relative values of 1 indicate the outcomes for the highest significant yield; relative values greater than 1 indicate an oversupply of N, values less than 1 an undersupply of N. The relative Uncharacterised N increases with an oversupply of N and decreases when insufficient N is applied. The results follow the general trend indicated by the regression line.

In Figure 30 b, results are shown for crops where there was no yield response to applied N, and in this case the 0 kg N/ha treatment (N1 treatment) has a relative value of 1. The crops where no N was applied across treatments (oats, forage ryegrass in Rotation 3 and 4) or the same across all treatments (150 kg N/ha to Wheat) are included. Increasing N above 0 kg N/ha increases the relative level of Uncharacterised N. It is not possible to determine if the N1 treatment was at an oversupply level already, but the data indicate that increasing N supply above this does increase Uncharacterised N.

Overall, supplying less N than that needed for optimum yield leads to a reduction of relative Uncharacterised N. Over supply of N leads to an increase in relative Uncharacterised N. Good management of N, as indicated by experimental results, manages the N balance and ensures adequate input for yield while managing environmental outcomes.

3.4 Applying the N balance for management –comparison of potato crops in Rotations 1 and 2

Of particular interest is the difference in Uncharacterised and nitrogen use efficiency (NUE) between the two different potato crops when using different management options, including the SVS tool and in season Quick-N test strips (Table 5). 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, and the Uncharacterised N each produced (Table 5, Figure 29).

Table 5. Comparison of potato crops in Rotations 1 and 2 with management, yield and Uncharacterised nitrogen (N) of N3 treatment that achieved highest yield.

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

SVS prototype is the tool developed in the Sustainable Vegetable Systems project.

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 (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. In terms of 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 (compare N supply for potatoes in Rotation 2 shown in Figure 22, to that for potatoes in Rotation 1 shown in Figure 21). While estimating 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.

3.5 Principal component analyses

A Principal Component Analysis (PCA) evaluates all data to identify key drivers of N balance for more sustainable outcomes. PCA was used to reduce key variables into two dimensions. In this process PCA scores were obtained for each crop under each treatment. In this model the effects of irrigation, crop rotation, crop type and nitrogen level were considered to be fixed effects. To allow for the split plot design where blocks were split up into irrigation levels a random effect of irrigation within block was included. PCA is a robust method for reducing dimensionality and exploring the structure of multivariate and complex data. The variates evaluated were fresh marketable yield, dry weight marketable yield, export N uptake (N in the marketable yield component) and total N uptake and residue N uptake. N balance variates included where the Uncharacterised N, the N surplus to the crop need, the partial N balance (Fertiliser N – Export N) and a measure of nitrogen use efficiency (NUE = total N uptake/Total N input).

Figure 31 shows the PCA biplot with the two principal components that explain most of the variance in the data (combined explanation of 74.5 %). Variates located in the same quadrant of the biplot are strongly correlated. Thus, marketable fresh yield, dry weight yield, marketable N uptake and total N uptake are in the same quadrant and are highly correlated with each other as expected. These variates reflect growth due to management and environmental conditions.

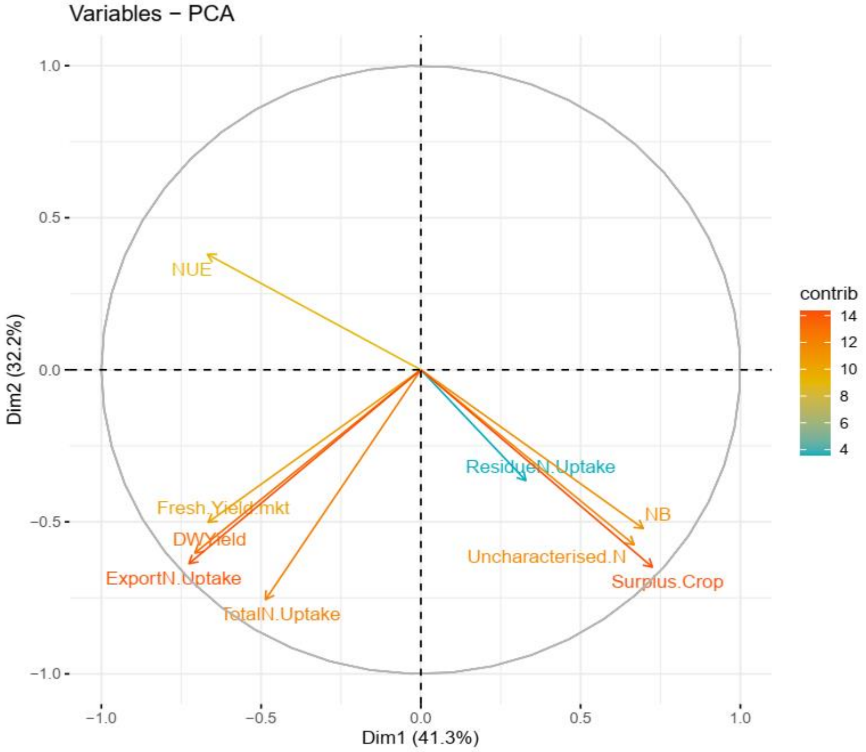

Figure 31. Biplot of Principal Component Analysis (PCA) for data from Workstream 1. Variates evaluated were Fresh marketable yield, dry weight marketable yield, export nitrogen (N) uptake (N in the marketable yield component) and total N uptake and residue N uptake. N balance variates included where the Uncharacterised N, the N surplus to the crop need, the partial N balance (NB = Fertiliser N – Export N) and a measure of nitrogen use efficiency (NUE = total N uptake/ Total N input).

Key observations form the biplot are:

- The growth variates (marketable yield, dry weight yield, marketable N uptake, total N uptake) are not correlated with the variates more strongly associated with the N balance, such as Uncharacterised N, surplus N, the N balance, (Fertiliser N – Export N) which occur in the adjacent quadrant
- There will be some indirect effect of growth variates on the N balance variates (for example marketable yield effects on surplus to crop, N balance and Uncharacterised N). However, the analysis suggests that the N balance variates are therefore more related to management considerations than growth considerations
- The NUE is correlated with the N balance variates but not the yield variates
- These data strongly suggest that the N balance components – and outcomes from a production system – are highly dependent on management during the growth of the crop.

Management practices seek to address any issues affecting production that arise from historical events, and within season events. Historical issues include weather events prior to the crop that may affect soil characteristics (quality and soil water contents are examples) as well as previous management events (that affect soil function and resource supply of water and nutrients). Within season events are weather factors driving growth, but also importantly soil functioning (mineralisation) and therefore supply of N to the crop. With this complexity, no one field can be the same as another, or expect a similar outcome in terms of a N balance as another. This variability in N balance is reflected in Figures 25–29. This highlights that a demonstrable management approach, where N supply is targeted to better match the N demand, provides a more relevant indicator of best practice management that both allows growers to be profitable in terms of yield, but obtain good environmental outcomes.

4 Model validation: Comparison of measured data with SCRUM-APSIM predictions

4.1 Workstream 3 objective/methodology

Workstream 3 used the Simple Crop Resource Uptake Model operating in the Agricultural Production Systems sIMulator (SCRUM-APSIM) to simulate WS1 experiments. This process developed the algorithms and coefficients used for the SVS tool.

The simulations were set-up in SCRUM-APSIM using soil, crop, and management details of each experiment. Weather data for the Lincoln and Hawke's Bay sites were obtained from the Lincoln and Whakatu NIWA stations, respectively. For each crop, the highest measured final yield was used as input in the model with the expectation that the crop would respond to water and N supply limitations imposed by the treatments. Measurements of crop yield, N uptake, soil mineral N, soil water content, and soil solution N concentration were made at different times during the trial period. Measurements of soil water in the top layer (0-30 cm) were made using the Time domain reflectometry (TDR) while a neutron probe (with tubes installed to a depth of 120 cm) was used in other layers.

In WS3, the SCRUM-APSIM model was continuously updated with data as it became available from field experiments in WS1. Changing tissue N content from a fixed coefficient to a dynamic exponential reduction during crop development was identified as an important area of improvement to the SCRUM model. This was implemented and applied to all simulations.

Analysis of model performance

Model outputs were compared against measured data for evaluated parameters. The prediction accuracy of the model was evaluated by four indices: the coefficient of determination (R^2), the root mean squared error (RMSE, Equation 1), the RMSE-observations standard deviation ratio (RSR, Equation 2), and the Nash – Sutcliffe efficiency (NSE, Equation 3).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(o_i - p_i)^2}{n}} \qquad \text{Equation 1}$$

$$RSR = \frac{\sum_{i=1}^{n}(o_i - p_i)^2}{\sqrt{\sum_{i=1}^{n}(o_i - \bar{o}_i)^2}} \qquad \text{Equation 2}$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(o_i - p_i)^2}{\sum_{i=1}^{n}(o_i - \bar{o}_i)^2} \qquad \text{Equation 3}$$

Where n is the number of observations under consideration, oi and pi are the observed and model predicted values, respectively, and $\overline{o}$ is the mean of the observed data.

The coefficient of determination (R^2) describes the change in data as a degree of fit, or the share of total variability explained by the model. The RMSE is the square root of the ratio of the square of the deviation between the measured value and the true value of the number of observations *n*. The RMSE has a value equal or greater than zero, with zero describing a perfect fit for the observed data. The RSR is the ratio of the RMSE and the standard deviation of measured data. The RSR varies from the optimal value of 0 to a large positive value. Classifications of 0 < RSR ≤ 0.5, 0.5 < RSR ≤ 0.6, 0.6 < RSR ≤ 0.7, RSR > 0.7 are considered are describe very good, good, satisfactory and unsatisfactory model prediction accuracy, respectively. The NSE (ranging from minus infinity to 1) is a normalised statistic that determines the relative magnitude of the residual variance compared to the measured variance. A perfect fit is represented by an NSE of 1. A very good, good, satisfactory, and unsatisfactory performance rating are represented by 0.75 < NSE ≤ 1, 0.65 < NSE ≤ 0.75, 0.5 < NSE ≤ 0.65, NSE ≤ 0.5, respectively.

4.2 Results and discussion

Graphical representation indicates that the SCRUM-APSIM model adequately captured the dynamics of plant growth and N uptake (Figure 32). Yield is an input in SCRUM-APSIM, and the highest measured yield was used for each crop. The accurate estimation of plant biomass and other plant-related variables demonstrates the model captured the effect of water and N supply. Accurate prediction of plant-related variables was supported by model performance indicators, which showed good to very good prediction rating (R^2=0.75–0.91, RSR=0.30–0.53, NSE=0.71–0.91; Table 1).

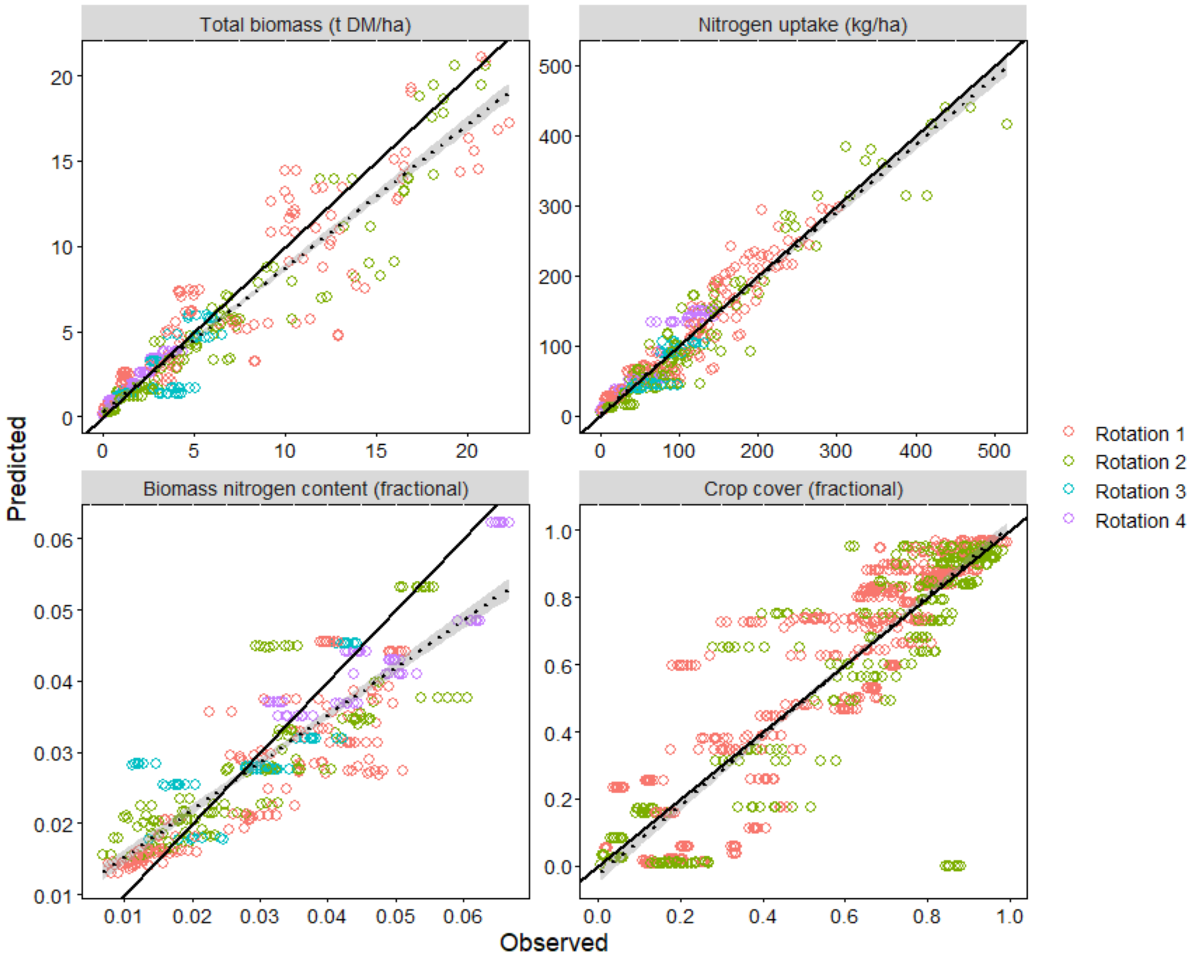

Figure 32. Predicted versus measured values of aboveground biomass and nitrogen (N) uptake four Sustainable Vegetables Systems Project crop rotations evaluated at Lincoln and Hawke's Bay under irrigation and fertiliser N managements. The solid line is a 1:1 relationship and the dotted line is the linear relationship between observed and predicted with a 95% confidence.

Performance indices indicated the model captured the general trends of water content in different layers of the soil profile with the exception of the surface layer (0–20 cm; Table 6). The exposure of the top layer of the soil profile to management practices such as cultivation and hilling of potatoes creates variability and uncertainty in soil moisture measurements. Figures 4–6 demonstrate that the model reproduced the dynamics of soil moisture in the top 60 cm during the duration of each experiment.

Soil mineral N was accurately predicted except for the deepest evaluated layer (120–150 cm). There was substantial variability in measurements consistent with the association of spatial heterogeneity with soil measurements. There was less noise when soil mineral N data were combined from the surface to specific depths. For the top 60 and 120 cm of the soil profile, the model accurately predicted soil mineral N (Table 6). This is important because leachate concentration was quantified at 60 and 120 cm depths. While there was noticeably high variability among replicates in measured data, comparison of soil mineral N to 60 and 120 m depth indicated greater under-prediction at the Hawke's Bay sites (Figures 7–10). This can be partly explained by the high water table at these sites. Four samples taken between June and October 2022 indicated 32–70.4 kg/ha of N in ground water.

Table 6. Statistics of comparison between simulated and observed data measured in the Sustainable Vegetable Systems project. R^2 is the coefficient of determination, RMSE is the root mean square error, RSR is the ratio of the RMSE to the standard deviation of measured data, NSE is the Nash-Sutcliffe model efficiency coefficient.

Variable	n	R^2 (%)	RMSE	RSR	NSE
Above-ground biomass (t DM/ha)	440	89	1.76	0.34	0.88
Above-ground N (kg/ha)	416	91	24.9	0.30	0.91
Nitrogen concentration (%)	392	75	0.01	0.53	0.72
Crop cover	937	79	0.15	0.54	0.71
Soil water content (mm/mm; 0–20 cm depth)	1790	55	0.06	0.87	0.25
Soil water content (mm/mm; 20–40 cm depth)	1837	70	0.03	0.66	0.56
Soil water content (mm/mm; 40–60 cm depth)	1836	85	0.02	0.42	0.82
Soil water content (mm/mm; 60–80 cm depth)	1836	78	0.03	0.51	0.74
Soil water content (mm/mm; 80–100 cm depth)	1837	83	0.03	0.42	0.83
Soil water content (mm/mm; 100–120 cm depth)	1837	78	0.04	0.51	0.74
Soil water content (mm/mm; 120–140 cm depth)	1837	85	0.05	0.46	0.79
Soil water content (mm/mm; 140–160 cm depth)	1827	88	0.06	0.60	0.64
Soil water content (mm; 0–60 cm depth)	1782	80	15.2	0.54	0.71
Soil mineral N (kg/ha; 0–30 cm depth)	675	69	44.3	0.60	0.63
Soil mineral N (kg/ha; 30–60 cm depth)	669	70	26.2	0.58	0.66
Soil mineral N (kg/ha; 60–90 cm depth)	659	72	21.0	0.57	0.67
Soil mineral N (kg/ha; 90–120 cm depth)	547	63	22.5	0.68	0.54
Soil mineral N (kg/ha; 120–150 cm depth)	218	47	19.8	0.76	0.42
Soil mineral N (kg/ha; 0–60 cm depth)	675	71	61.8	0.59	0.65
Soil mineral N (kg/ha; 0–90 cm depth)	659	74	75.3	0.57	0.67
Soil mineral N (kg/ha; 0–120 cm depth)	541	74	95.6	0.61	0.63
Soil mineral N (kg/ha; 0–150 cm depth)	217	71	104.8	0.57	0.68
Leachate concentration (kg N/ha; at 60 cm depth)	710	46	26.3	0.79	0.37
Leachate concentration (kg N/ha; at 120 cm depth)	710	23	25.9	0.99	0.01

Classifications of 0 < RSR ≤ 0.5, 0.5 < RSR ≤ 0.6, 0.6 < RSR ≤ 0.7, RSR > 0.7 and 0.75 < NSE ≤ 1, 0.65 < NSE ≤ 0.75, 0.5 < NSE ≤ 0.65, NSE ≤ 0.5, are considered to describe very good, good, satisfactory, and unsatisfactory model prediction accuracy, respectively.

Comparison of leachate N concentration at 60 and 120 cm depth are shown in Figures 11–14 and Figures 15–18, respectively. While most of measurements were associated with high variability, the model accurately reproduced the trends of leachate N concentration. Like soil mineral N, leachate concentration was under-estimated at the Hawke's Bay sites. The high water table and N in the ground water may be partly responsible.

Overall, the accurate prediction of soil N uptake, soil mineral N and soil moisture provides confidence in the ability of SCRUM-APSIM to simulation N leaching from crop rotations. A high water table is likely to introduce uncertainty in predictions.

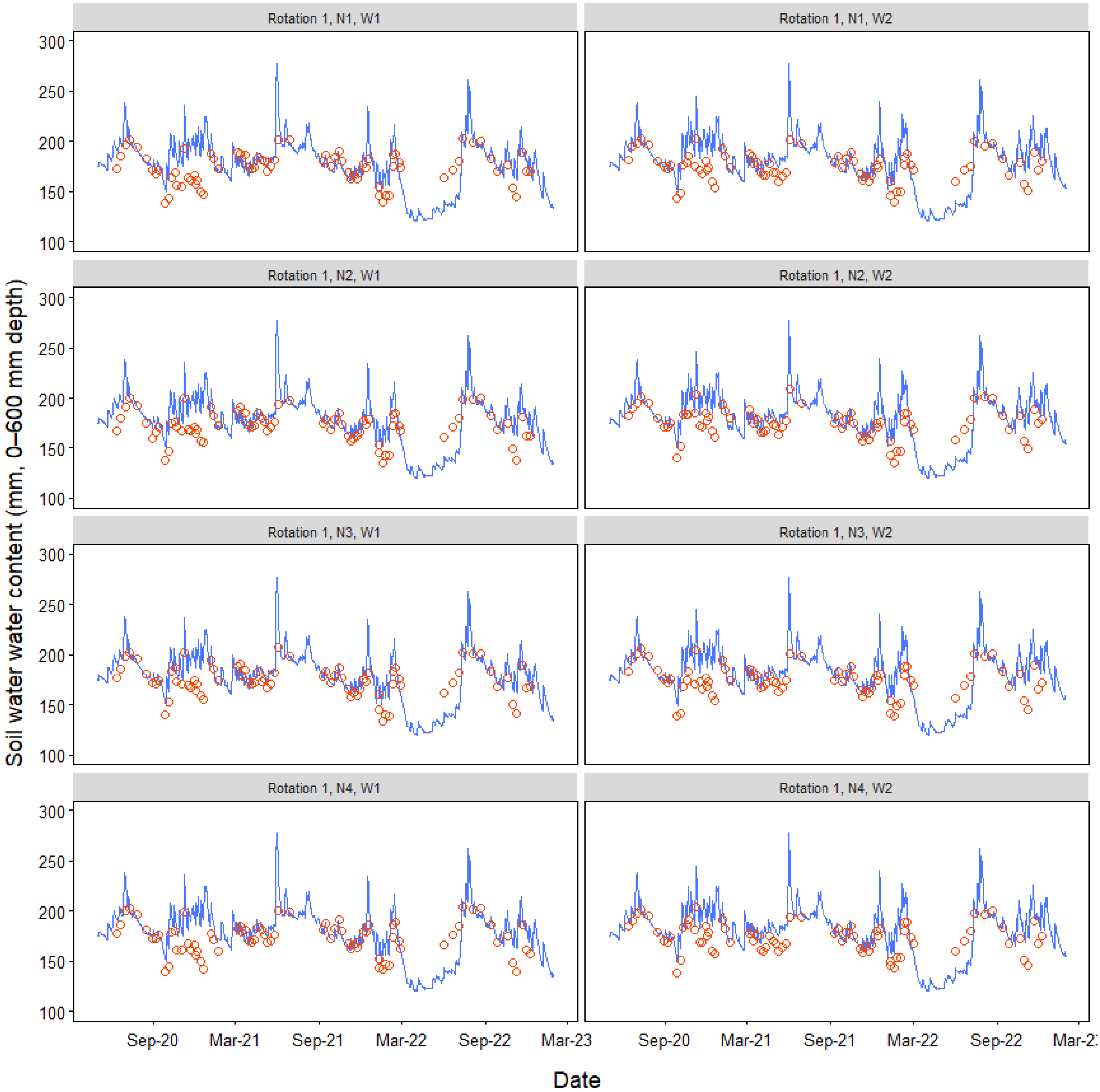

Figure 33. Measured (symbols) and predicted (lines) soil water content from a wheat-broccoli- onion-ryegrass rotation established at Lincoln under irrigation and fertiliser nitrogen (N) managements. N1=no added fertiliser N, N3=recommended fertiliser N, N2=0.5*N3 and N4=2*N3. Irrigation 1 and Irrigation 2 represent recommended and excessive rates, respectively.

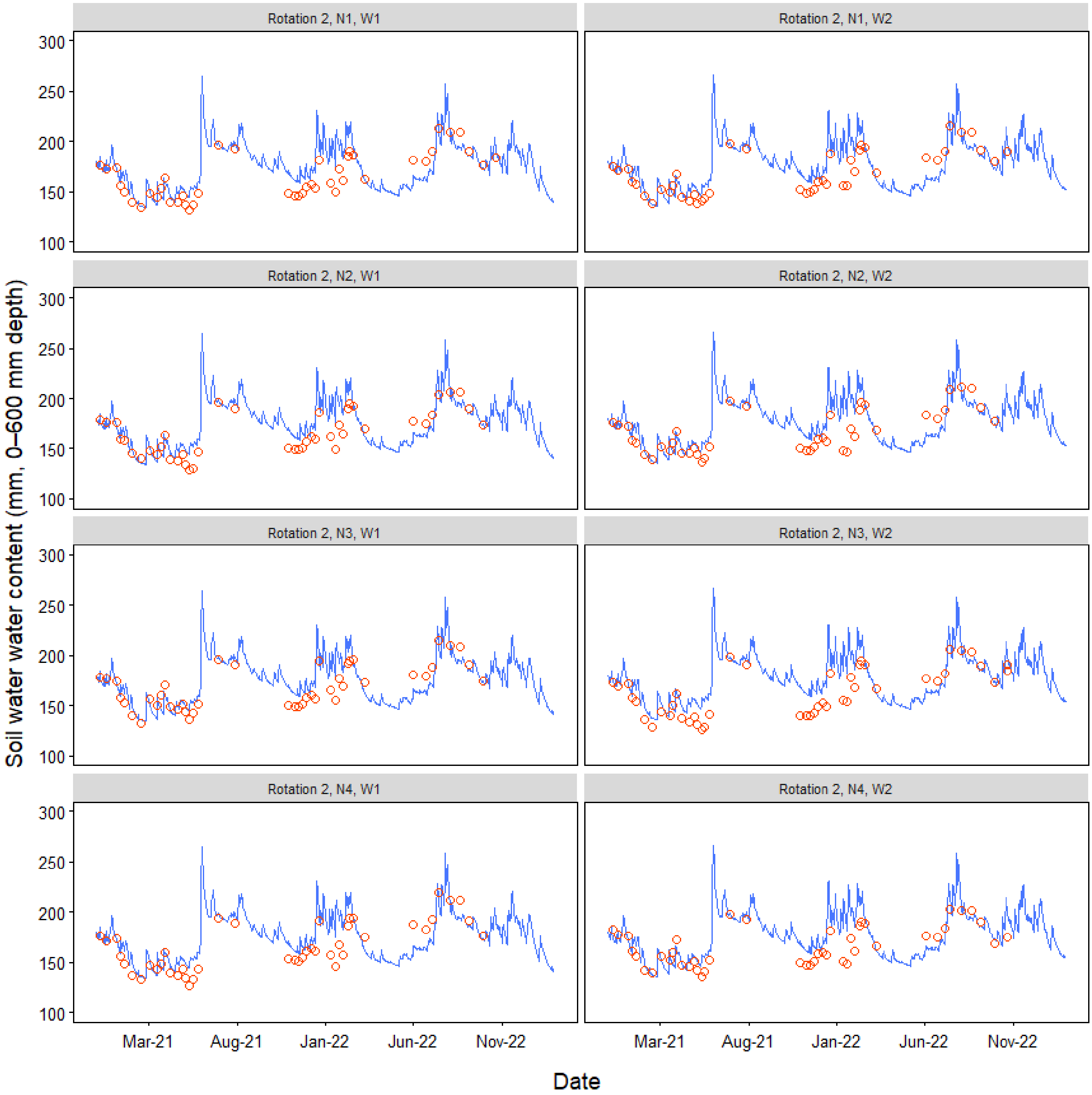

Figure 34. Measured (symbols) and predicted (lines) soil water content from a pak choi-oats-potatoes-ryegrass rotation established at Lincoln under irrigation and fertiliser nitrogen (N) managements. N1=no added fertiliser N, N3=recommended fertiliser N, N2=0.5*N3 and N4=2*N3. Irrigation 1 and Irrigation 2 represent recommended and excessive rates, respectively.

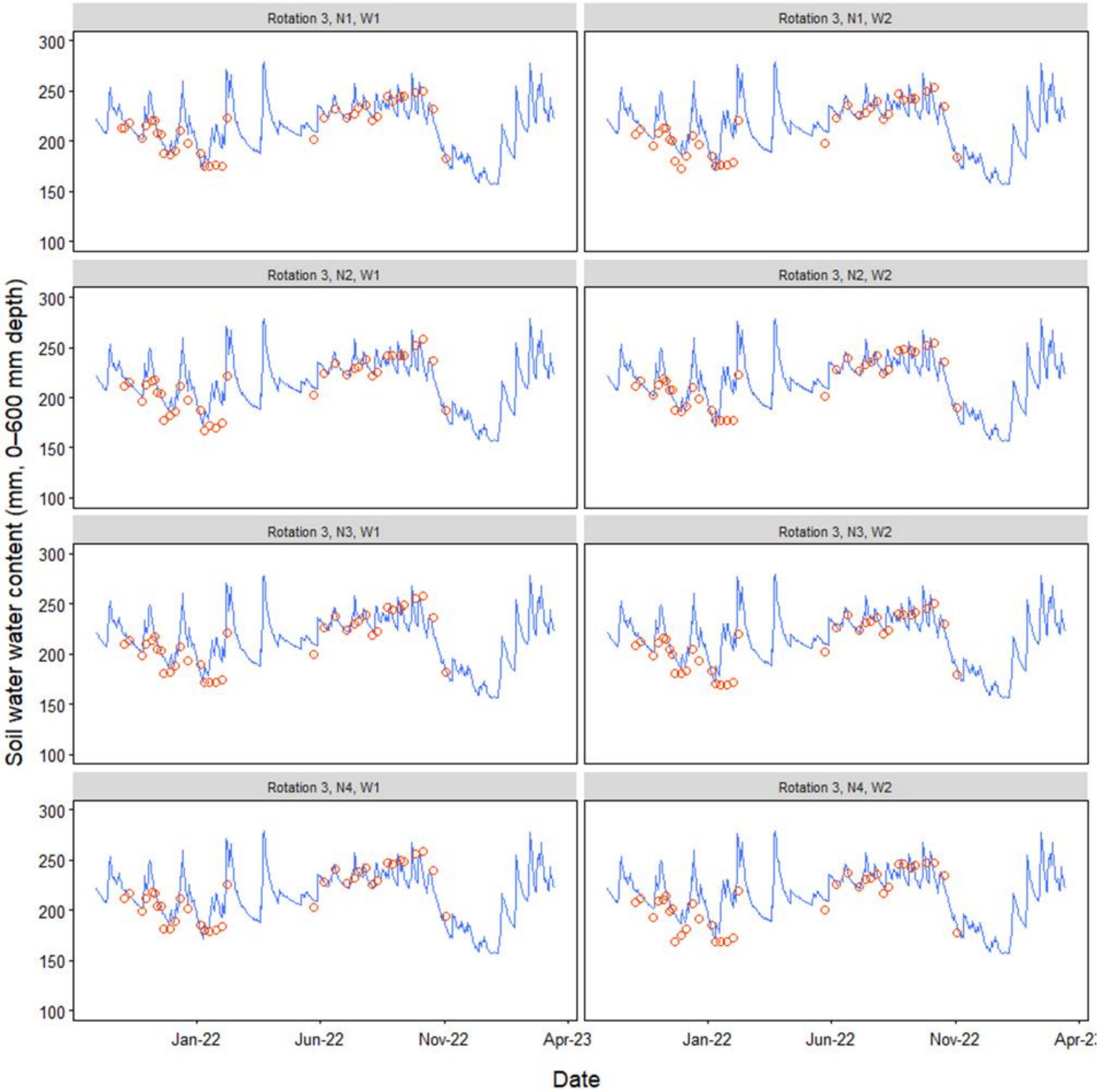

Figure 35. Measured (symbols) and predicted (lines) soil water content from an onion-ryegrass rotation established at Hawke's Bay under irrigation and fertiliser nitrogen (N) managements. N1=no added fertiliser N, N3=recommended fertiliser N, N2=0.5*N3 and N4=2*N3. Irrigation 1 and Irrigation 2 represent recommended and excessive rates, respectively.

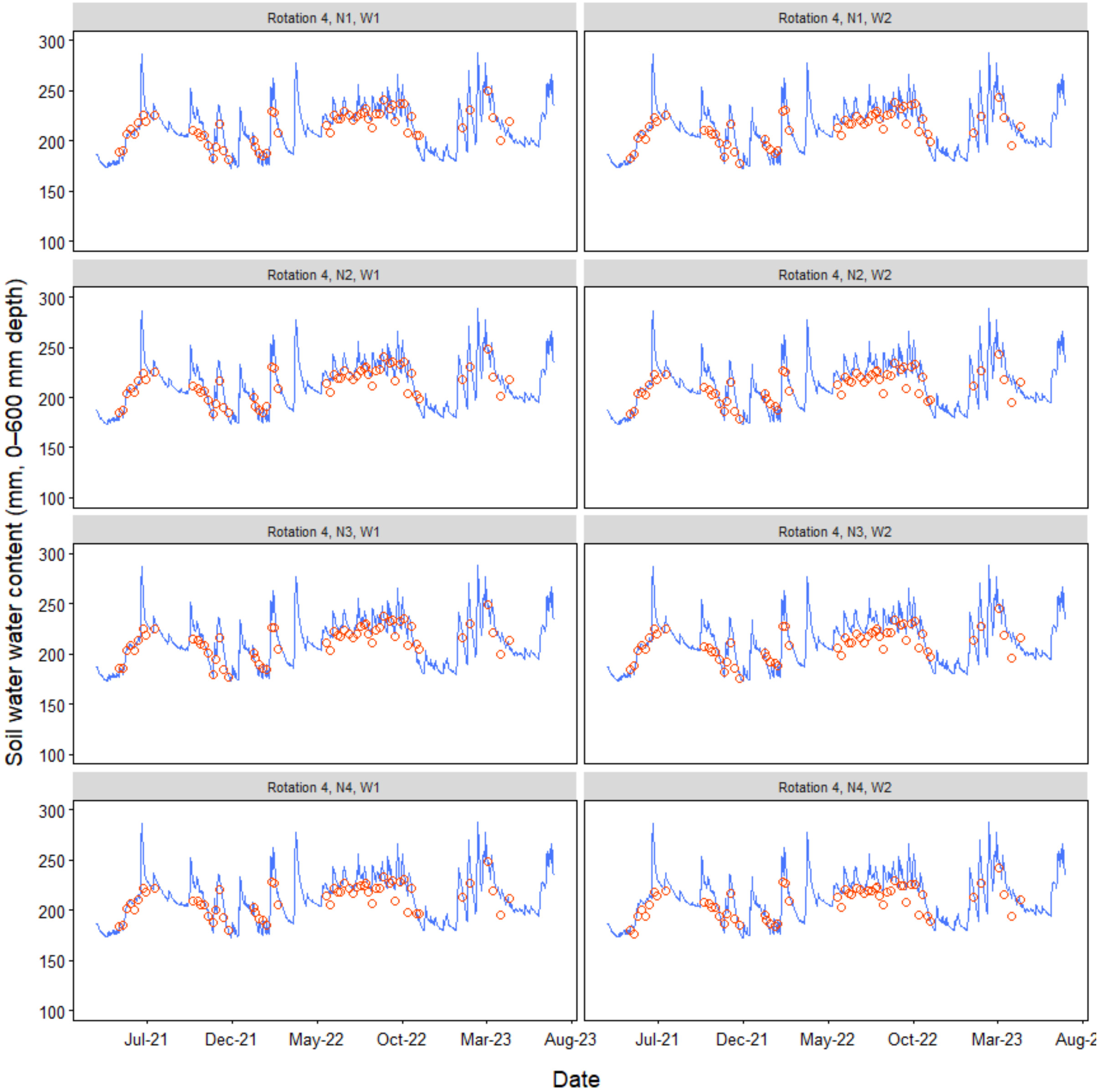

Figure 36. Measured (symbols) and predicted (lines) soil water content from a pak choi-lettuce-peas-cauliflower-ryegrass rotation established at Hawke's Bay under irrigation and fertiliser nitrogen (N) managements. N1=no added fertiliser N, N3=recommended fertiliser N, N2=0.5*N3 and N4=2*N3. Irrigation 1 and Irrigation 2 represent recommended and excessive rates, respectively.

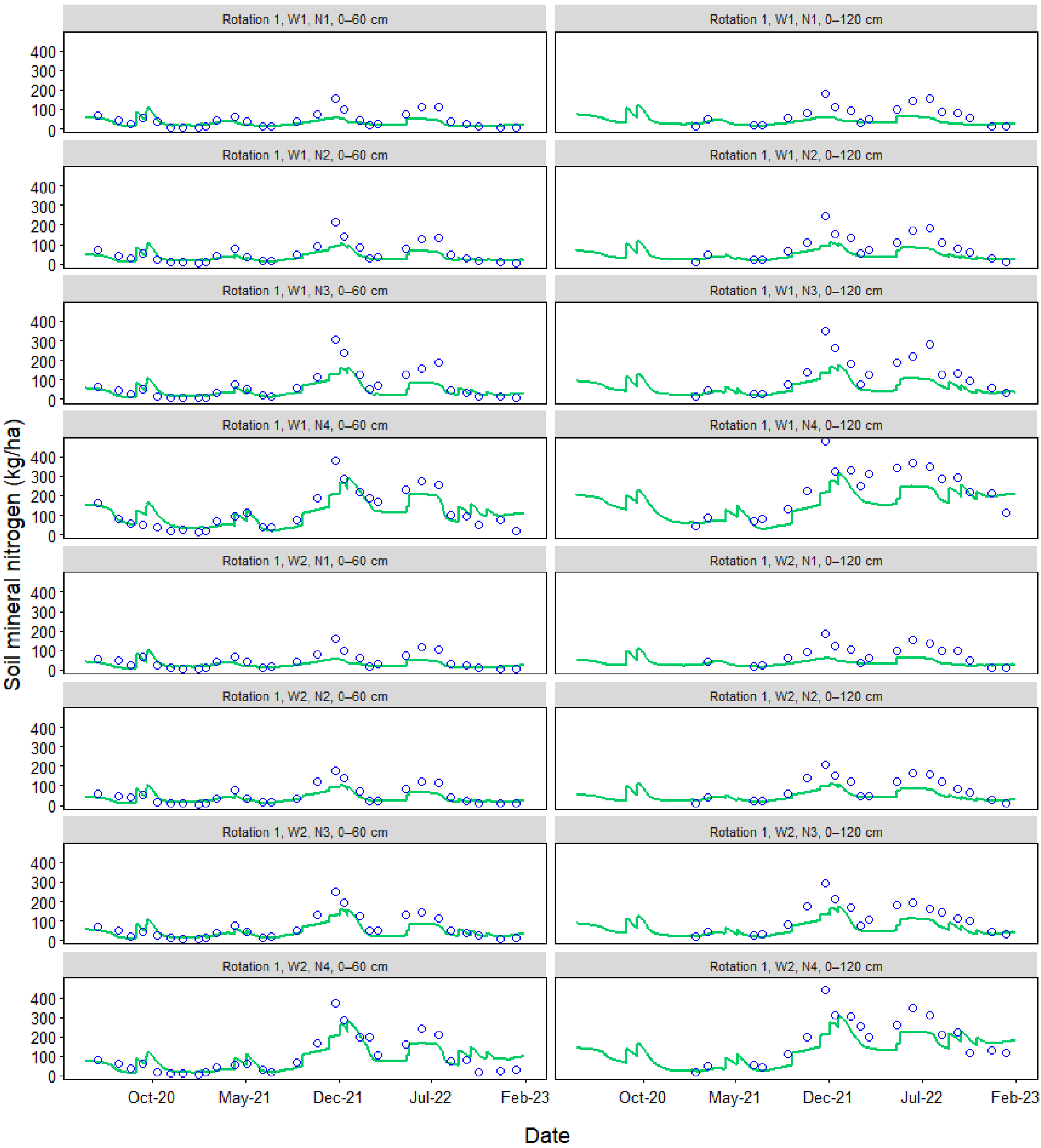

Figure 37. Measured (symbols) and predicted (lines) mineral nitrogen (N) in 0–60 cm and 0–120 cm layers of the soil profile from a wheat-broccoli- onion-ryegrass rotation established at Lincoln under irrigation and fertiliser N managements. N1=no added fertiliser N, N3=recommended fertiliser N, N2=0.5*N3 and N4=2*N3. Irrigation 1 and Irrigation 2 represent recommended and excessive rates, respectively.

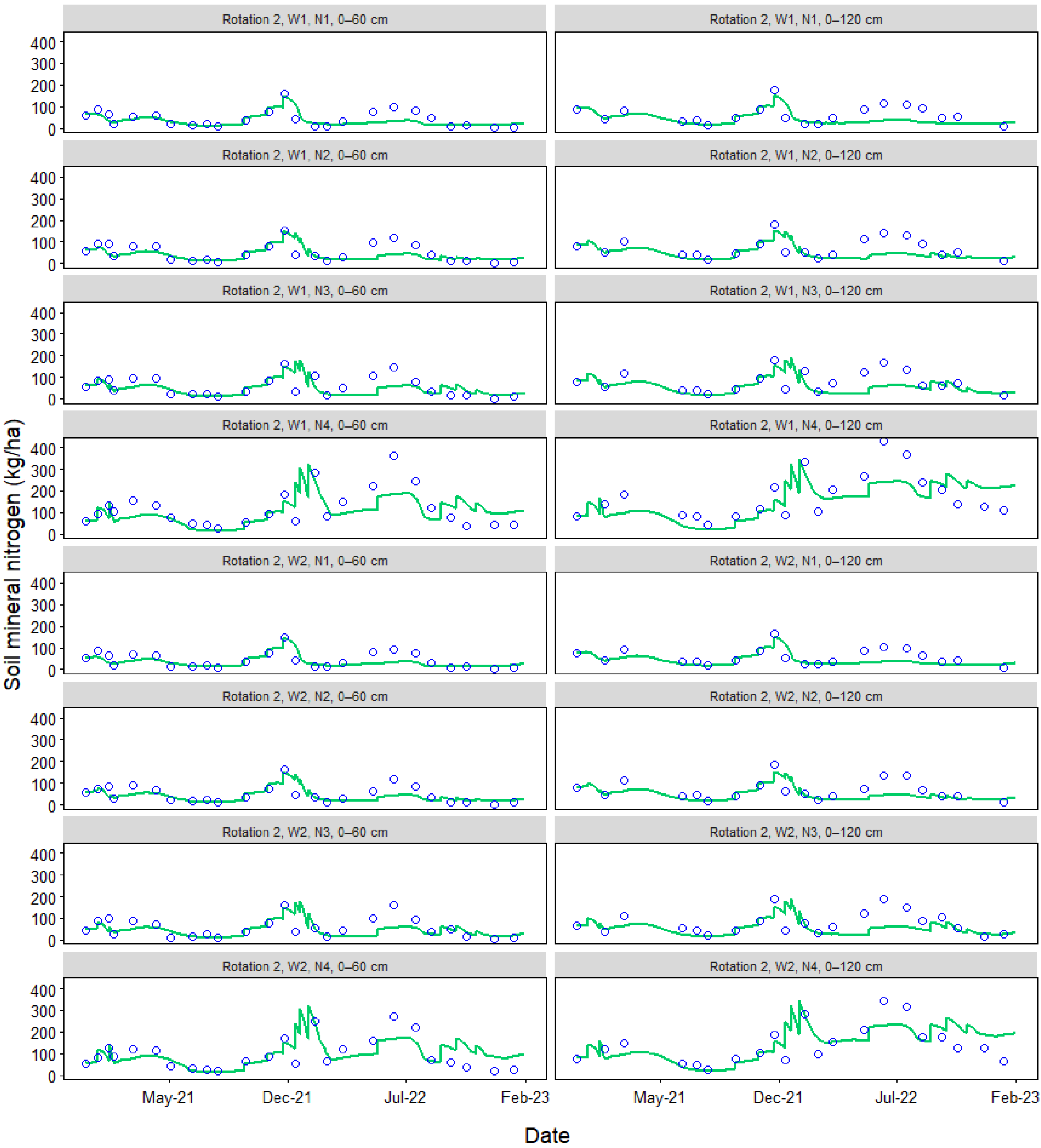

Figure 38. Measured (symbols) and predicted (lines) mineral nitrogen (N) in 0–60 cm and 0–120 cm layers of the soil profile from a pak choi-oats-potatoes-ryegrass rotation established at Lincoln under irrigation and fertiliser N managements. N1=no added fertiliser N, N3=recommended fertiliser N, N2=0.5*N3 and N4=2*N3. Irrigation 1 and Irrigation 2 represent recommended and excessive rates, respectively.

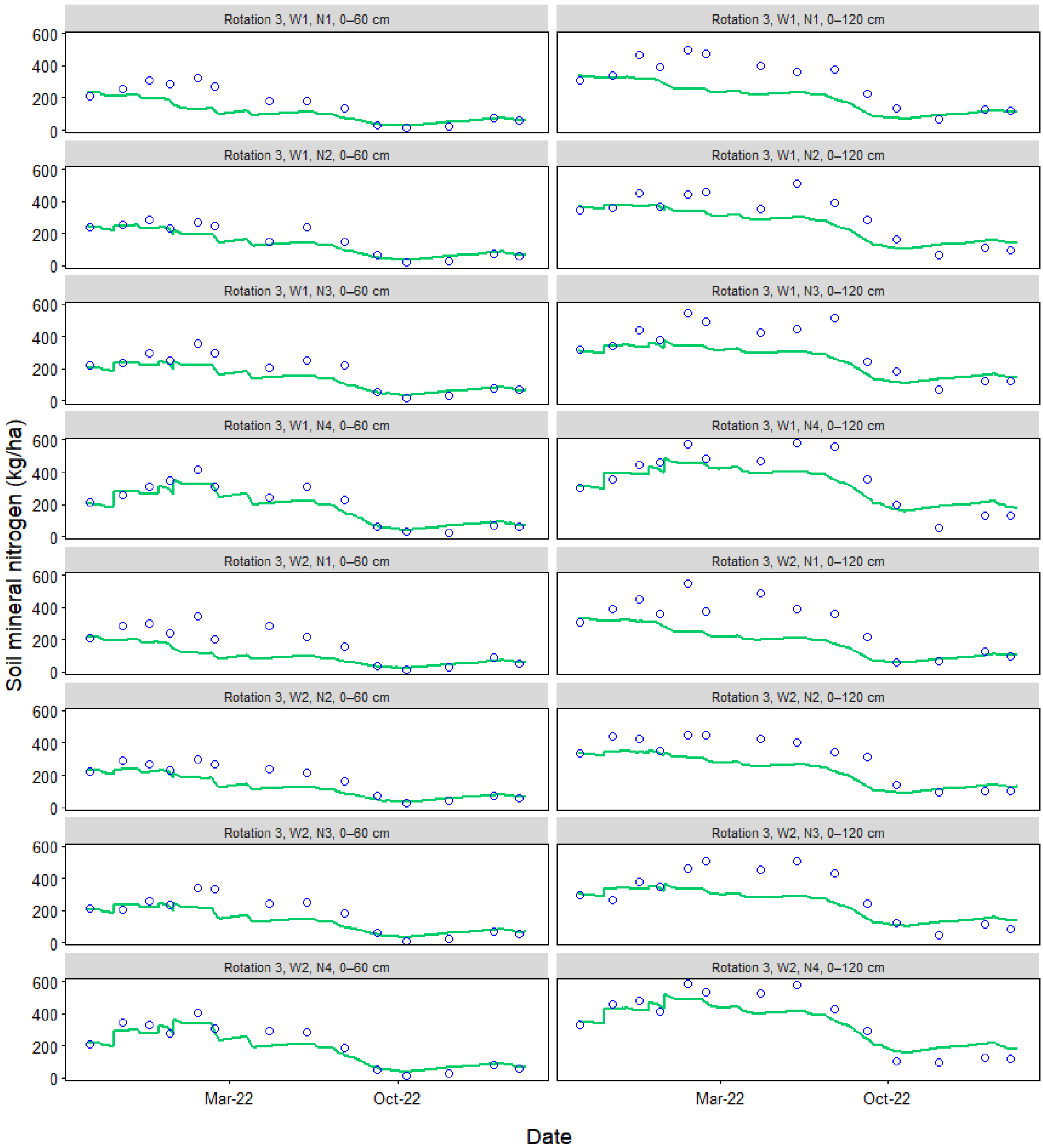

Figure 39. Measured (symbols) and predicted (lines) mineral nitrogen (N) in 0–60 cm and 0–120 cm layers of the soil profile from an onion-ryegrass rotation established at Hawke's Bay under irrigation and fertiliser N managements. N1=no added fertiliser N, N3=recommended fertiliser N, N2=0.5*N3 and N4=2*N3. Irrigation 1 and Irrigation 2 represent recommended and excessive rates, respectively.

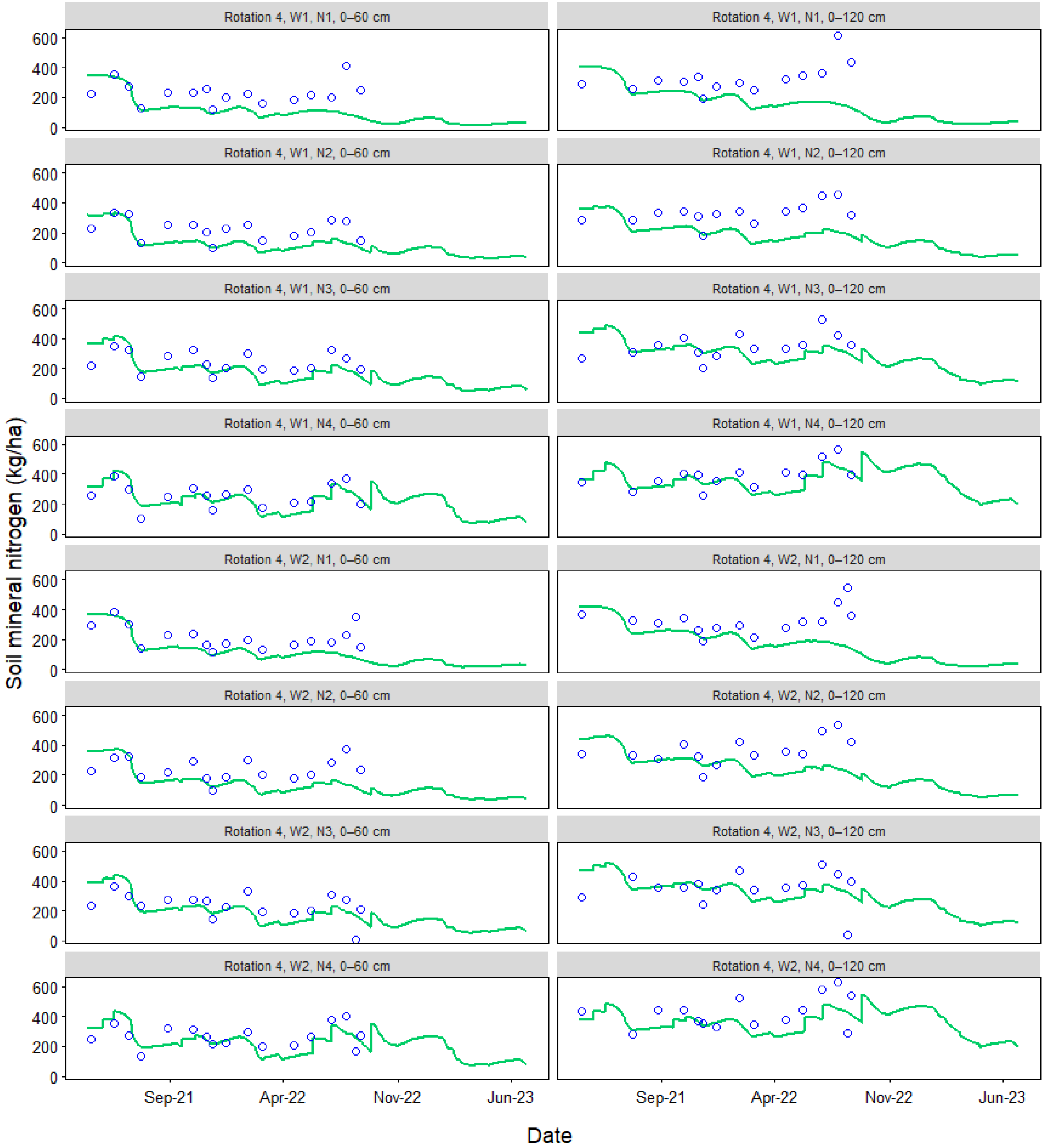

Figure 40. Measured (symbols) and predicted (lines) mineral nitrogen (N) in 0–60 cm and 0–120 cm layers of the soil profile from a pak choi-lettuce-peas-cauliflower-ryegrass rotation established at Hawke's Bay under irrigation and fertiliser N managements. N1=no added fertiliser N, N3=recommended fertiliser N, N2=0.5*N3 and N4=2*N3. Irrigation 1 and Irrigation 2 represent recommended and excessive rates, respectively.

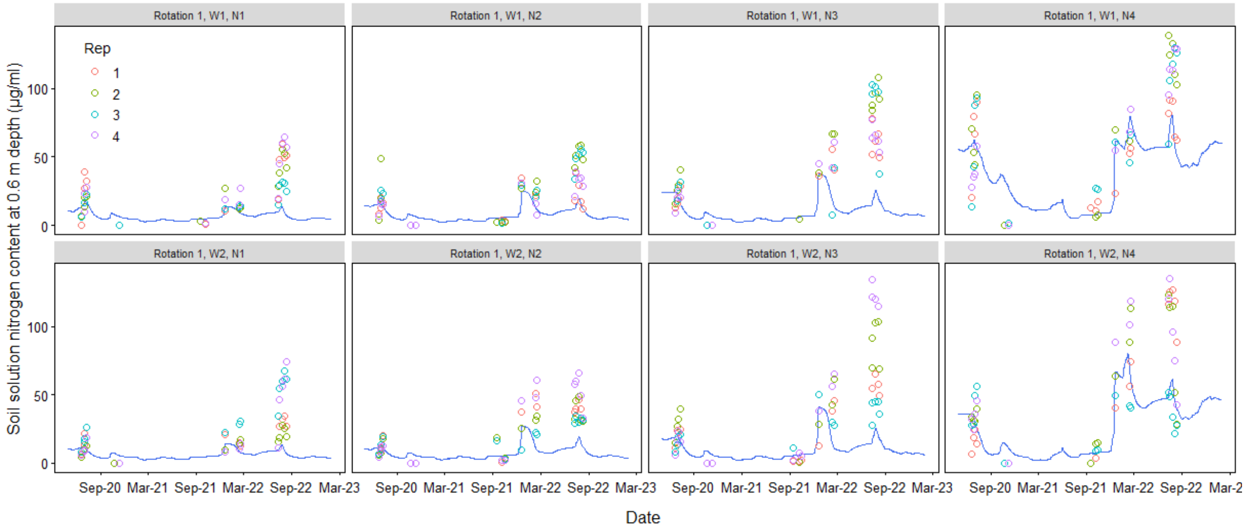

Figure 41. Measured (symbols) and predicted (lines) soil solution nitrogen (N) concentration (at 60 cm depth) from a wheat-broccoli-onion-ryegrass rotation established at Lincoln under irrigation and fertiliser N managements. N1=no added fertiliser N, N3=recommended fertiliser N, N2=0.5*N3 and N4=2*N3. Irrigation 1 and Irrigation 2 represent recommended and excessive rates, respectively.

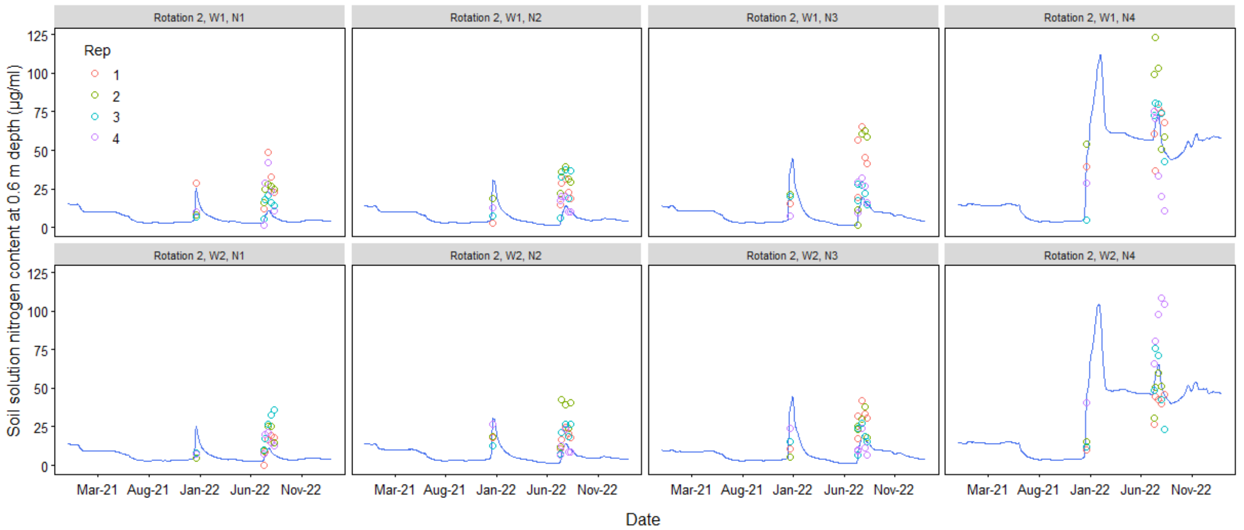

Figure 42. Measured (symbols) and predicted (lines) soil solution nitrogen (N) concentration (at 60 cm depth) from a pak choi-oats-potatoes-ryegrass rotation established at Lincoln under irrigation and fertiliser N managements. N1=no added fertiliser N, N3=recommended fertiliser N, N2=0.5*N3 and N4=2*N3. Irrigation 1 and Irrigation 2 represent recommended and excessive rates, respectively.

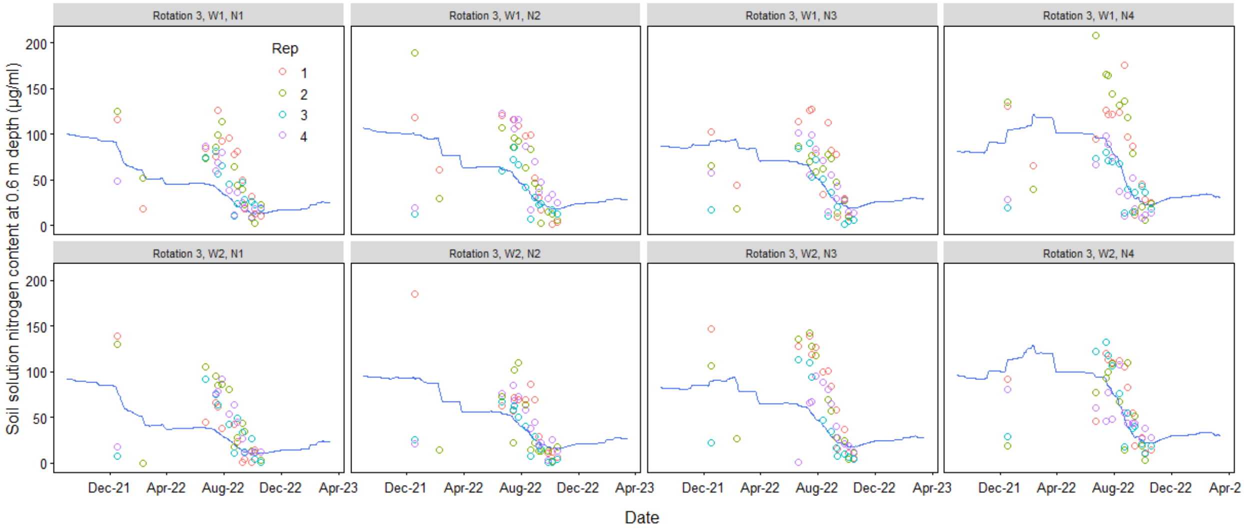

Figure 43. Measured (symbols) and predicted (lines) soil solution nitrogen (N) concentration (at 60 cm depth) from an onion-ryegrass rotation established at Hawke's Bay under irrigation and fertiliser N managements. N1=no added fertiliser N, N3=recommended fertiliser N, N2=0.5*N3 and N4=2*N3. Irrigation 1 and Irrigation 2 represent recommended and excessive rates, respectively.

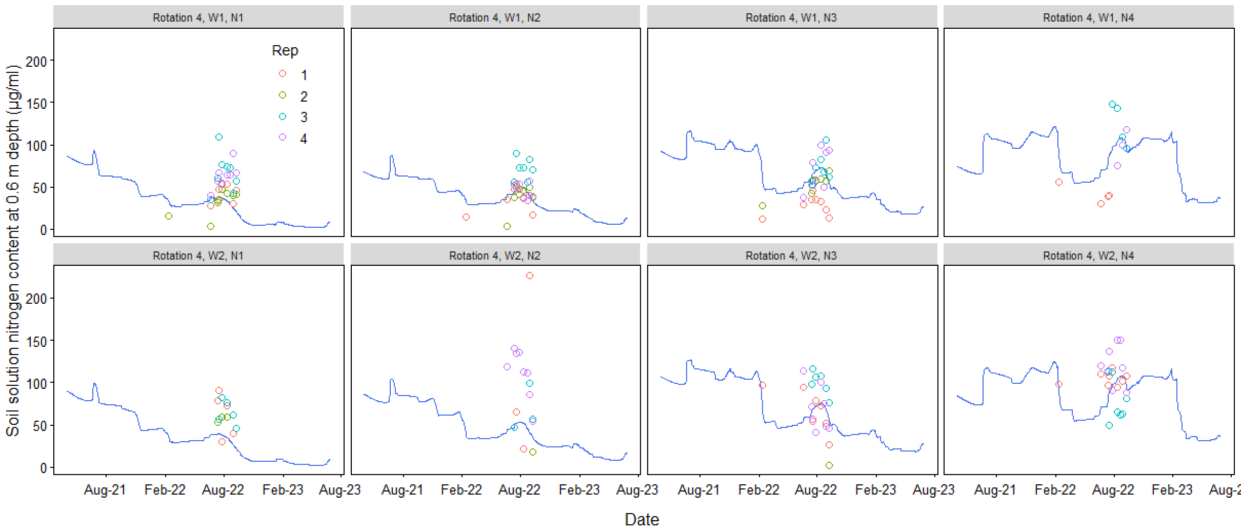

Figure 44. Measured (symbols) and predicted (lines) soil solution nitrogen (N) concentration (at 60 cm depth) from a pak choi-lettuce-peas-cauliflower-ryegrass rotation established at Hawke's Bay under irrigation and fertiliser N managements. N1=no added fertiliser N, N3=recommended fertiliser N, N2=0.5*N3 and N4=2*N3. Irrigation 1 and Irrigation 2 represent recommended and excessive rates, respectively.

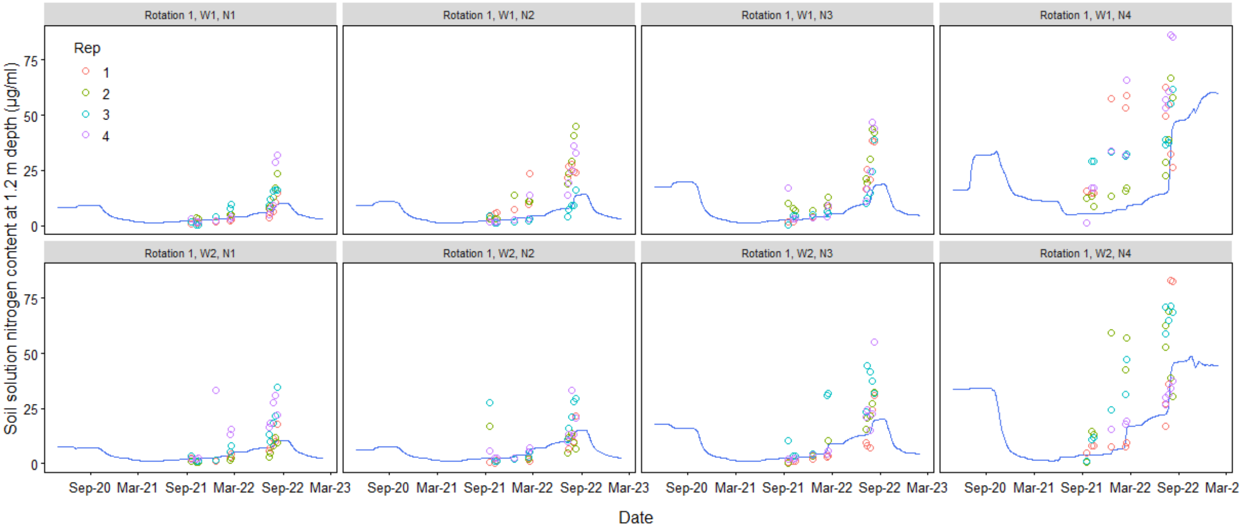

Figure 45. Measured (symbols) and predicted (lines) soil solution nitrogen (N) concentration (at 120 cm depth) from a wheat-broccoli- onion-ryegrass rotation established at Lincoln under irrigation and fertiliser N managements. N1=no added fertiliser N, N3=recommended fertiliser N, N2=0.5*N3 and N4=2*N3. Irrigation 1 and Irrigation 2 represent recommended and excessive rates, respectively.

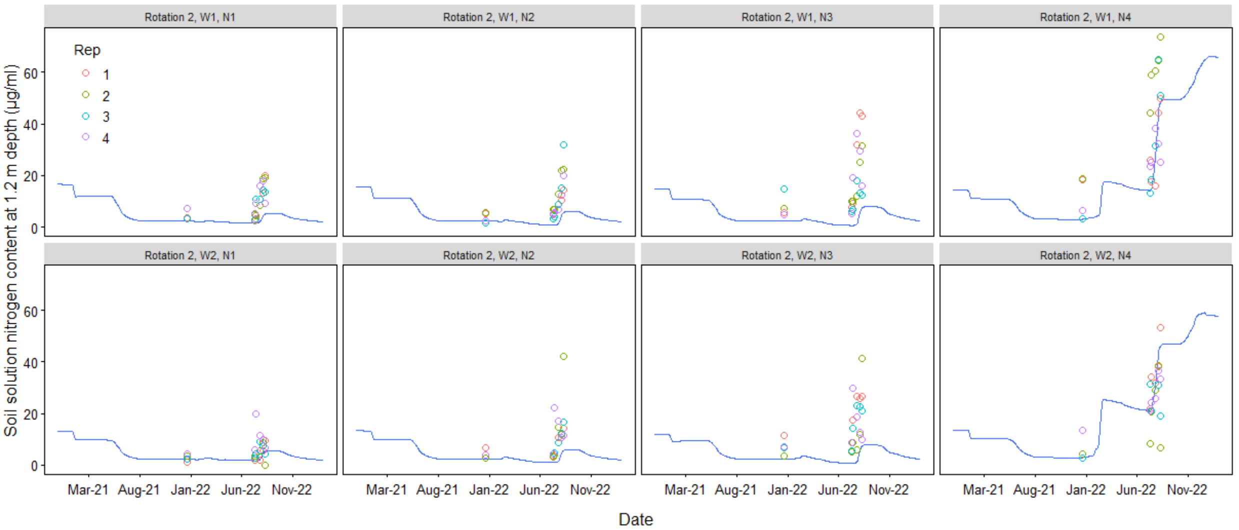

Figure 46. Measured (symbols) and predicted (lines) soil solution nitrogen (N) concentration (at 120 cm depth) from a pak choi-oats-potatoes-ryegrass rotation established at Lincoln under irrigation and fertiliser N managements. N1=no added fertiliser N, N3=recommended fertiliser N, N2=0.5*N3 and N4=2*N3. Irrigation 1 and Irrigation 2 represent recommended and excessive rates, respectively.

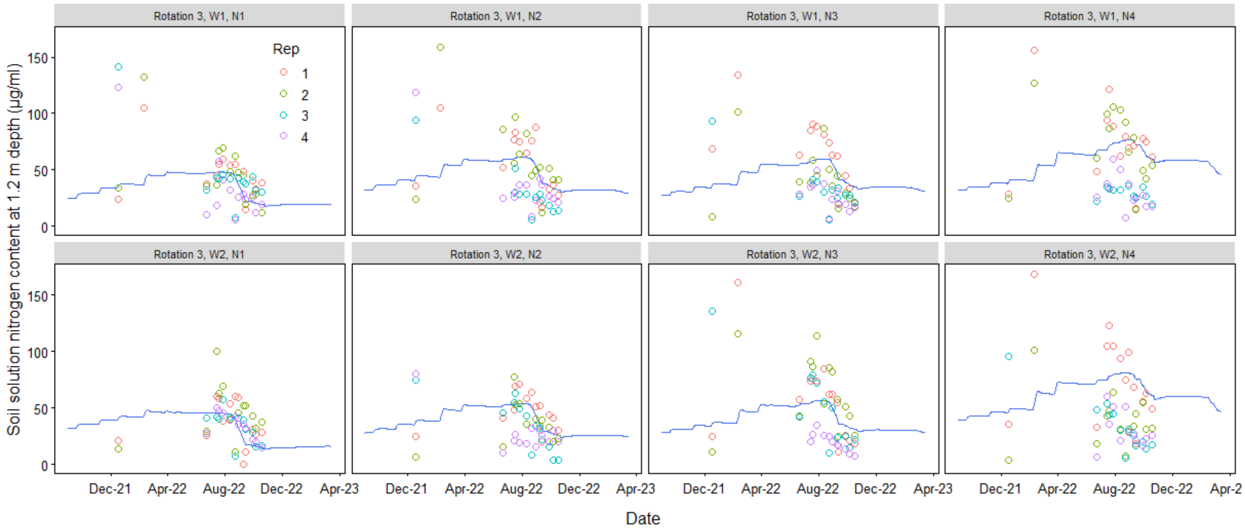

Figure 47. Measured (symbols) and predicted (lines) soil solution nitrogen (N) concentration (at 120 cm depth) from an onion-ryegrass rotation established at Hawke's Bay under irrigation and fertiliser N managements. N1=no added fertiliser N, N3=recommended fertiliser N, N2=0.5*N3 and N4=2*N3. Irrigation 1 and Irrigation 2 represent recommended and excessive rates, respectively.

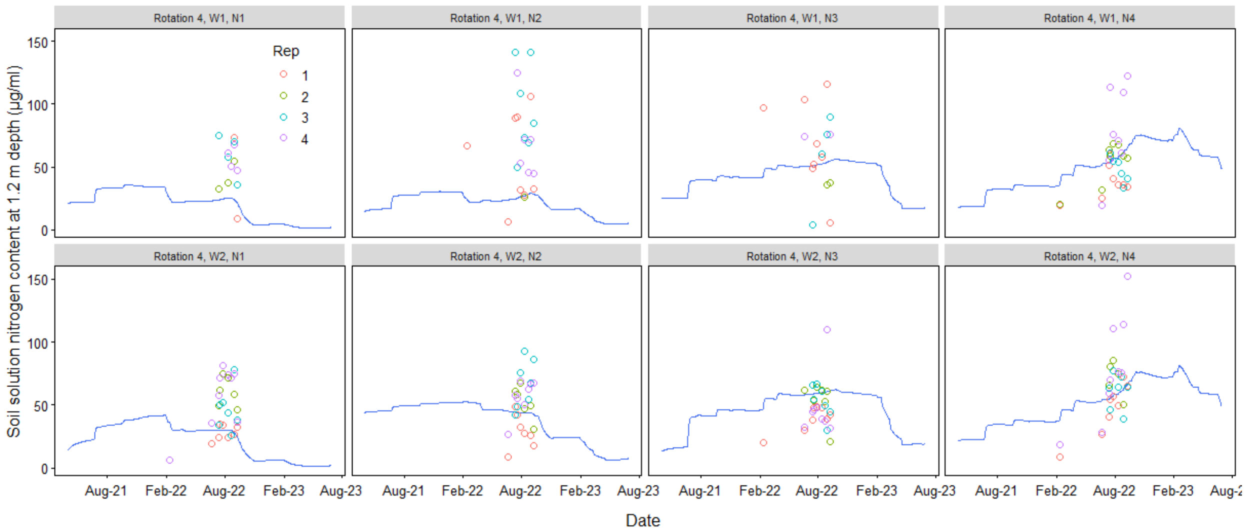

Figure 48. Measured (symbols) and predicted (lines) soil solution nitrogen (N) concentration (at 120 cm depth) from a pak choi-lettuce-peas-cauliflower-ryegrass rotation established at Hawke's Bay under irrigation and fertiliser N managements. N1=no added fertiliser N, N3=recommended fertiliser N, N2=0.5*N3 and N4=2*N3. Irrigation 1 and Irrigation 2 represent recommended and excessive rates, respectively.

After ascertaining satisfactory prediction of soil water and the N balance components (uptake and soil mineral N), simulated and measured (calculated) N leaching data during the wheat crop were compared. Note: SCRUM-APSIM-predicted drainage was used to calculate measured leaching. Figure 49 indicates that SCRUM-APSIM-predicted N leaching during the wheat crop followed the same trend as measured (calculated) values.

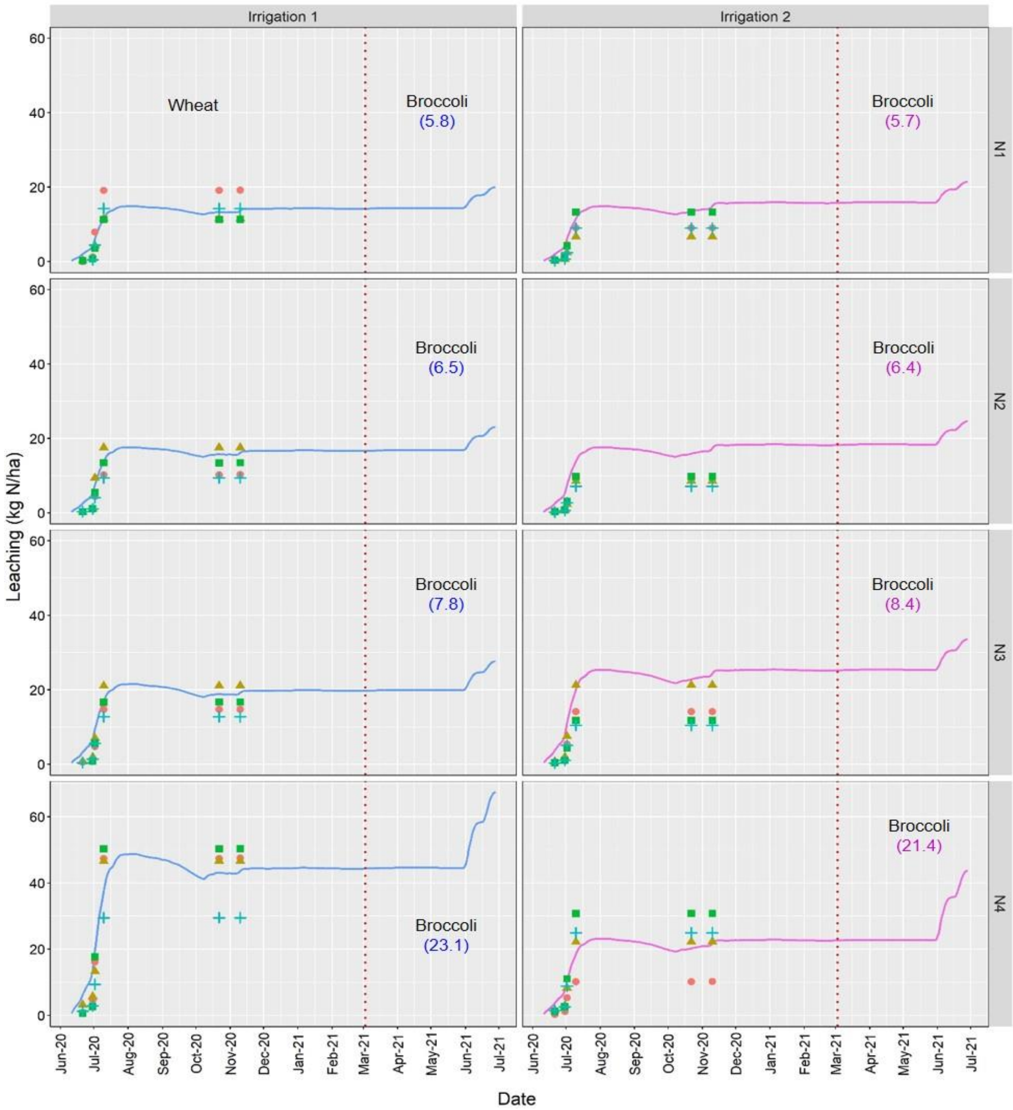

Figure 49. Cumulative nitrogen (N) leaching comparisons between calculated (symbols; replicates) and SCRUM-APSIM-predicted (lines) during the wheat and broccoli crops growing at the New Zealand Institute for Plant and Food Research Limited farm at Lincoln. The wheat crop received a flat rate of 150 kg N/ha across all fertiliser N treatments. Broccoli crops received 0, 30, 60 and 120 kg N/ha under the N1, N2, N3 and N4 fertiliser N treatments, respectively. A total of 275 and 320 mm was applied to the wheat crop under Irrigation 1 and Irrigation 2 treatments, respectively. The broccoli crop received 135 mm in each irrigation treatment. Total leaching (kg N/ha) under the broccoli crop is shown in parentheses.

SCRUM-APSIM estimates indicated N leaching during the broccoli crop increased with N fertiliser input (Figure 15). Leachate measurements were not taken under the broccoli crop. Leaching occurred during the last month (June) of the crop season when there was substantial rainfall to cause drainage events. The same amount of water was applied to all broccoli treatments, hence the marginal differences between irrigation treatments for the respective fertiliser N treatments (Figure 15).

Graphical representation of data (Figure 16) showed a strong relationship between the observed and SCRUM-APSIM estimates of N leaching (R^2 = 0. 92) but only for Rotations 1 and 2. Drainage was not able to be accurately estimated for leaching calculation due to the high-water table in Rotations 3 and 4. This was supported by other statistical indices. The absolute root mean squared error (RMSE), which measures the scatter of data points around the 1:1 relationship line, was 4.4, relative RMSE (rRMSE) was 43% and indicated that simulated data explained 57% of the variation in the measured data. Positive Nash-Sutcliffe model efficiency (NSE), which measures the proportion of variance in the observations accounted for by the model's prediction, was 0.83. Across treatments, the average measured and predicted N leaching was 10.3 and 13.3 kg N/ha, respectively.

4.2.1 Implications of the leaching values calculated

The N leached from the wheat crops raises some points for consideration, and a general conclusion:

1. The difficulty of estimating leaching in soils where there are high water tables and water table movement, means that leaching is not a suitable indicator of management practices in these soils. This was observed in the Hawke's Bay soils for Workstream 1 data. There may be similar water table considerations in many floodplain soils, and this should be evaluated.

2. Leaching in the wheat crop occurred before any fertiliser applied to the crop, which indicates that the differences in leaching levels between the N treatments were due to the N management of the previous potato crop.

3. There was still leaching from the wheat crop even when no fertiliser had been applied to the previous potato crop. In this case, the leaching when no N fertiliser was provided to either the potato or the wheat crop was 15 kg N/ha. The inputs provided prior to the leaching event were the soil mineral N (47 kg N/ha in the top 60 cm of soil), 10 kg N/ha from potato residues, of which only a very small portion would have been converted into mineral N), and the mineralisation that would have happened between the potato crop being harvested in May and the rain events in early July. The application of an optimal 200 kg N/ha to the previous potato crop resulted in a leaching of 21 kg N/ha, which is 6 kg N/ha more than if no fertiliser was applied. In this case it could be said that good fertiliser management practice of 200 kg N/ha resulted in 21 kg N/ha leached, when in fact it was only 6 kg N/ha leached over and above that caused by natural soil processes. This should be taken into account in some way when leaching is considered for evaluation of fertiliser practices.

4. The leaching value of 21 kg under good fertiliser N management is the interactions of variables in two dimensions – it is essentially the interaction of environmental conditions with specific timing of various management events. The environmental dimension – the rainfall, temperature, solar radiation – influences the soil N mineralisation, crop growth, N uptake and leaching losses. It is well recognised that environmental conditions vary with season and usually an average leaching value would consider this seasonal variability. However, it ignores the second dimension – the starting point, including the timing of plantings, fertiliser applications, irrigation applications and other management events – which are unlikely to be repeated exactly season after season. This would mean that a range of leaching values would be more representative of the complexities of a cropping system's outcomes, considering the interaction of management with seasonal factors.

5. A conclusion is that a N leaching value does not give an indication of good management practice; it reveals wide interactions of environment, climate history, crop type history, and only a small component of management. A more reliable indicator of good management is needed, of which the N balance from the SVS tool is one and is an approach adopted elsewhere (See Section 3.5, refs). Further evaluation across a wide range of crops and environments, wider than those used here, is recommended.

5 Model testing

The model that underlies the SVS tool has been tested against all the field observations collected in the SVS project including:

- Workstream 1 – detailed N balance of four separate crop rotations on experimental farms in Hawke's Bay and Canterbury are discussed below.
- Workstream 2 – N balance monitoring of crop rotations on 9 commercial farms across New Zealand. These data are in Appendix 8.

Testing was facilitated by setting up runs of the SVS model that were configured to be analogous to each of the test crops in the above groupings, using long term average weather. Outputs of soil mineral nitrogen and crop N uptake were output daily over the duration from the end of the prior crop to the end of the current crop so testing encompassed fallow and crop growth periods.

There was generally good agreement between the model's predictions and the field observations. The three main phenomena observed where the model did not appear to perform well were:

1. **Not accounting for luxury N uptake.** The coefficients in the SVS model for predicting crop N uptake are set at values to achieve an optimal yield of saleable quality. For some crops N% of product and stover required to achieve this is lower than the N% that will be achieved if surplus N is available in the system. In these situations, the model predicted less crop N uptake and more soil N than was observed. In our testing this occurred in cereal, grass and green manure crops that are planted to control surplus N in the rotation. The model's failure to account for luxury N uptake will not influence the accuracy of its N recommendations as the crops where this phenomenon was observed were unfertilised catch crops. However, it does influence the model's ability to demonstrate the effectiveness of these crops to mitigate higher N in rotations. It is possible to add luxury N uptake mechanisms into future versions of the model to capture this.
2. **Under prediction of crop N uptake and soil N.** This could be caused by under prediction of mineral N entering the system from predicted mineralisation of soil or plant organic matter. Further testing of these components of the model is warranted to build confidence in predictions of N fertiliser N supply. It may also be caused by and over prediction of losses from the system. The loss model was developed specially for the SVS tool by fitting a simplified model to loss predictions from the APSIM farm systems model. APSIM's predictions of losses were validated against losses measured in WS1 and against other experiments in the past. However, a number of assumptions had to be made to simplify measurements based on actual weather events to a model that uses long term average weather to forecast fertiliser requirements. Further testing of the loss model is required to build further confidence in this component of the SVS tool. It is also possible fertiliser was added to the system but not recorded so not all the inputs were included in the model's configuration.
3. **Over prediction of soil N occurred in some situations.** This could be caused by the opposite of the factors described above, an over prediction of mineralisation or an under prediction of leaching. From the data collected it is not possible to attribute an exact cause to these over and under predictions.

5.1 Model predictions by Rotation in WS1

In Rotation 1 grown in Lincoln (Figure 50) the model under predicted N uptake by up to 100 kg/ha in the higher N treatments in the ryegrass seed crop which resulted in an equivalent over prediction of soil N in these treatments. This is related to the model not predicting luxury N uptake in crops; when crops receive more N than in required for maximum biomass yield but continue to take up N and achieve a higher N% in product and stover. The model's coefficients have been derived to ensure adequate N for a saleable product so it would have recommended enough N to achieve that in this case.

Model fit of Rotation 2 grown in Lincoln (Figure 51) there was good agreement for the Potato and Pak Choy crops but an under prediction in the early uptake for the oat crop and for the higher N treatments for the ryegrass seed crop. This is related to the luxury N uptake issue outlined above

For Rotation 3 and 4 grown in Hawke's Bay, there is generally good agreement for the soil mineral N content and crop N uptake of measured values with predicted values. The trends in uptake of N by the forage ryegrass crop and onion crop of Rotation 3 are follow the general trend of observed data (Figure 52). There is good agreement for all crops (Figure 53) except the cauliflower crop which took up considerably less N that was predicted and had a higher soil N at the end of the crop as a result. This is because the cauliflower crop did not perform as anticipated and gave a poor yield.

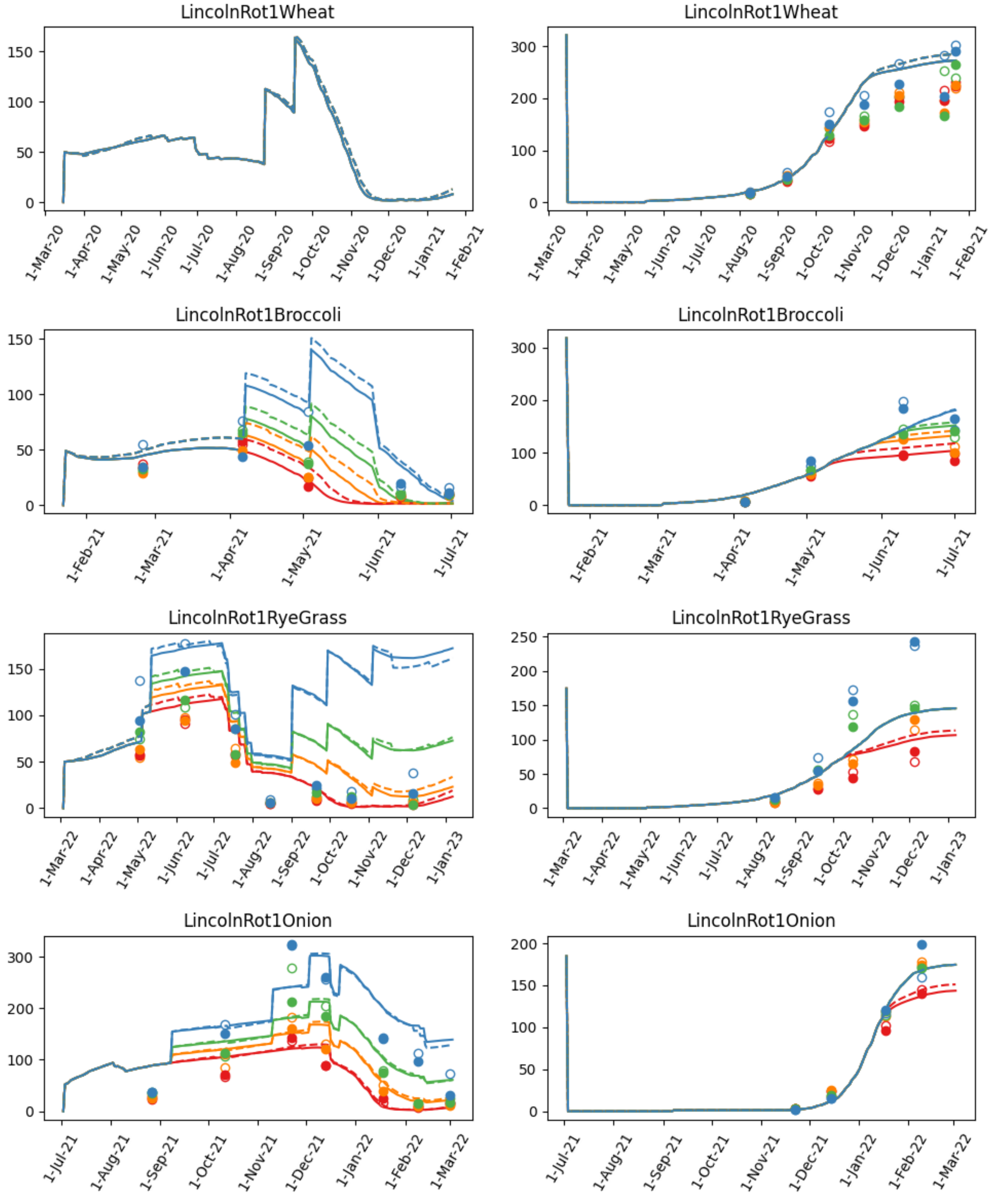

Figure 50. Observed (circles) and simulated data (lines) of soil mineral N levels (plots on left) and crop N uptake (plots on right) for Rotation 1 grown at The New Zealand Institute for Plant and Food Research Limited, Lincoln research site, Canterbury. Colours red, orange, green and blue represent N treatments N0, N1, N2, and N3 respectively, closed circles are Irrigation 1 and open circles are Irrigation 2 treatments. Units are kg N/ha.

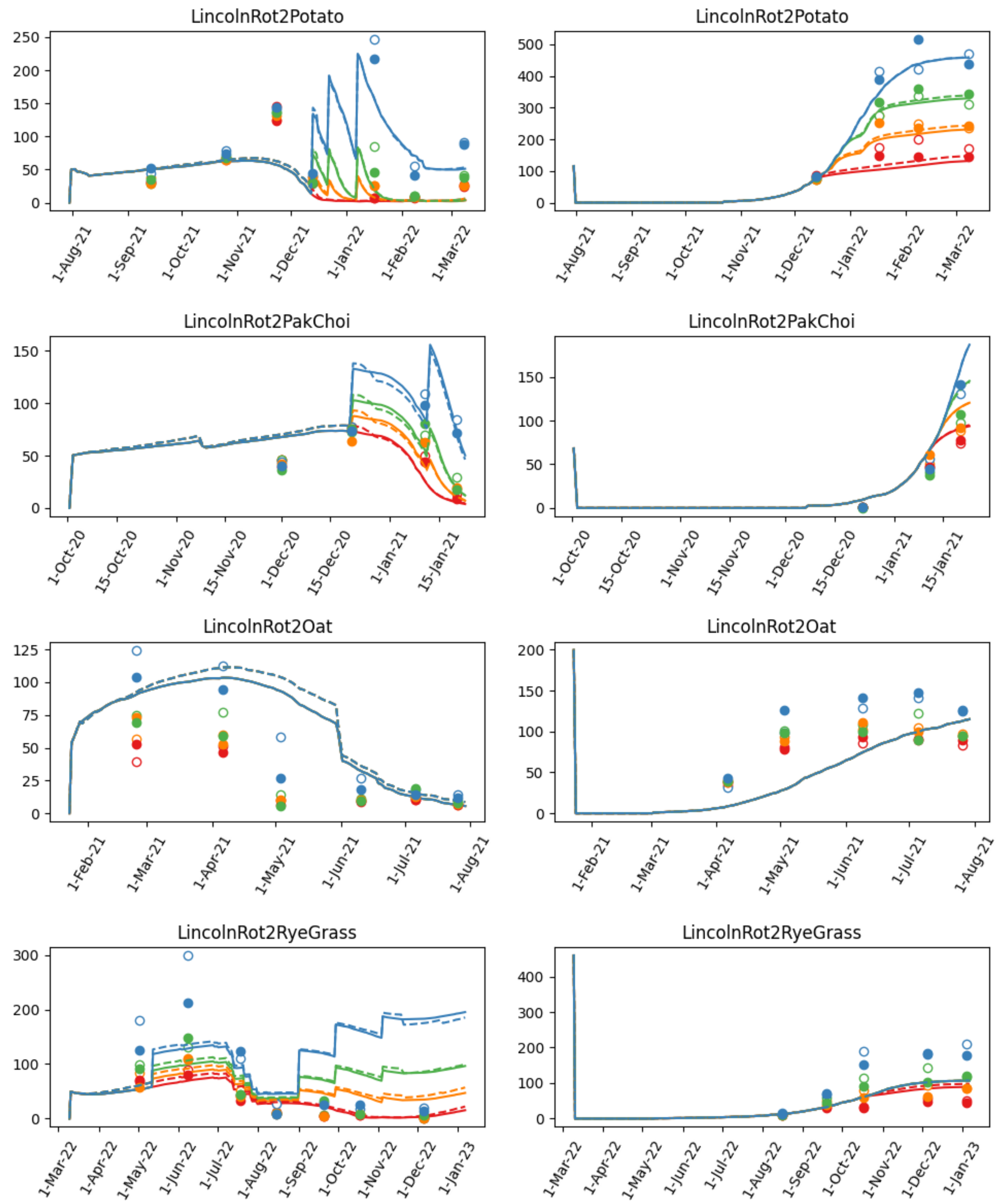

Figure 51. Observed (circles) and simulated data (lines) of soil mineral N levels (plots on left) and crop N uptake (plots on right) for Rotation 2 grown at The New Zealand Institute for Plant and Food Research Limited, Lincoln research site, Canterbury. Colours red, orange, green and blue represent N treatments N0, N1, N2, and N3 respectively, closed circles are Irrigation 1 and open circles are Irrigation 2 treatments. Units are kg N/ha.

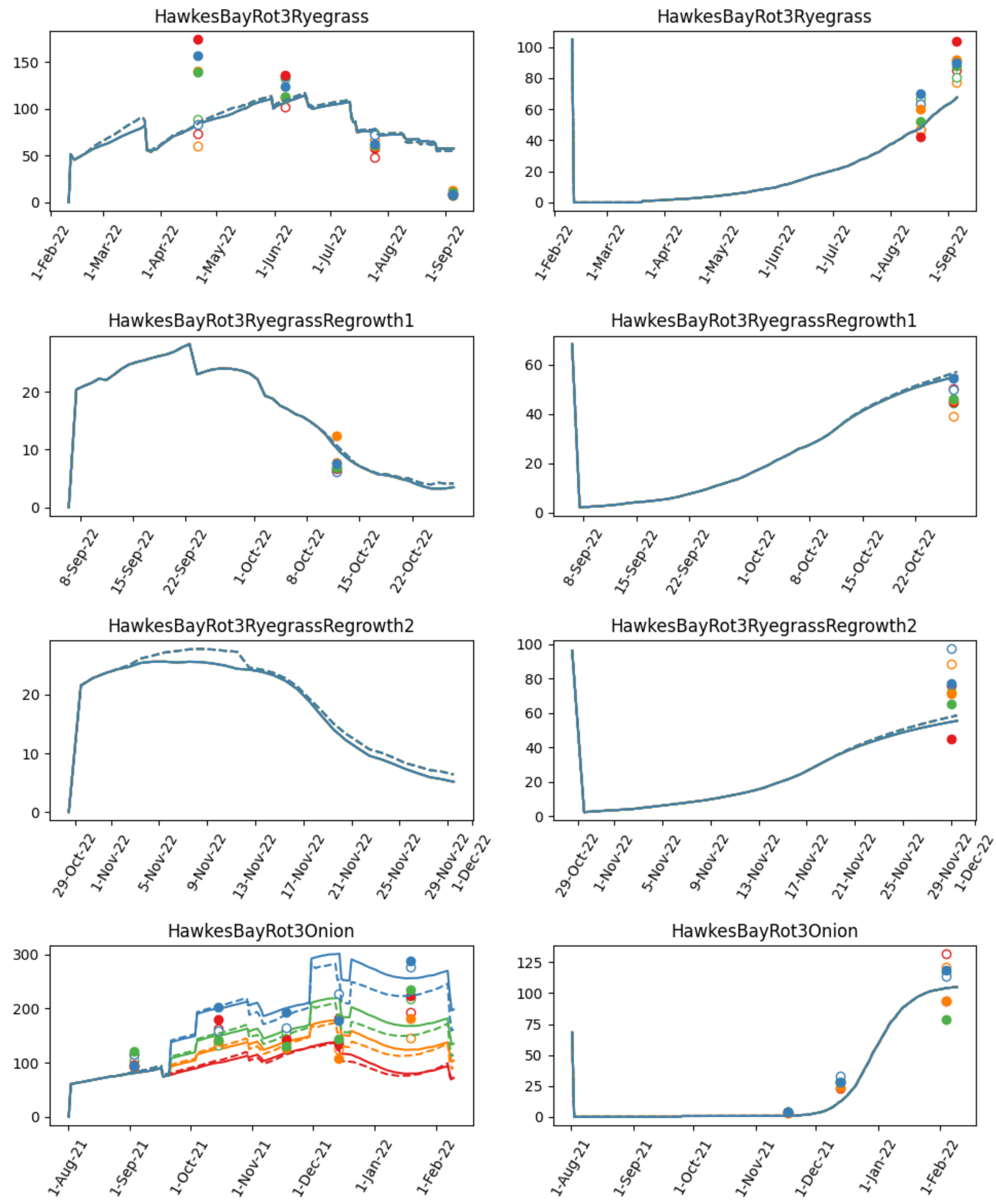

Figure 52. Observed (circles) and simulated data (lines) of soil mineral N levels (plots on left) and crop N uptake (plots on right) for Rotation 3 grown at The New Zealand Institute for Plant and Food Research Limited, Havelock North research site, Hawke's Bay. Colours red, orange, green and blue represent N treatments N0, N1, N2, and N3 respectively, closed circles are Irrigation 1 and open circles are Irrigation 2 treatments. Units are kg N/ha.

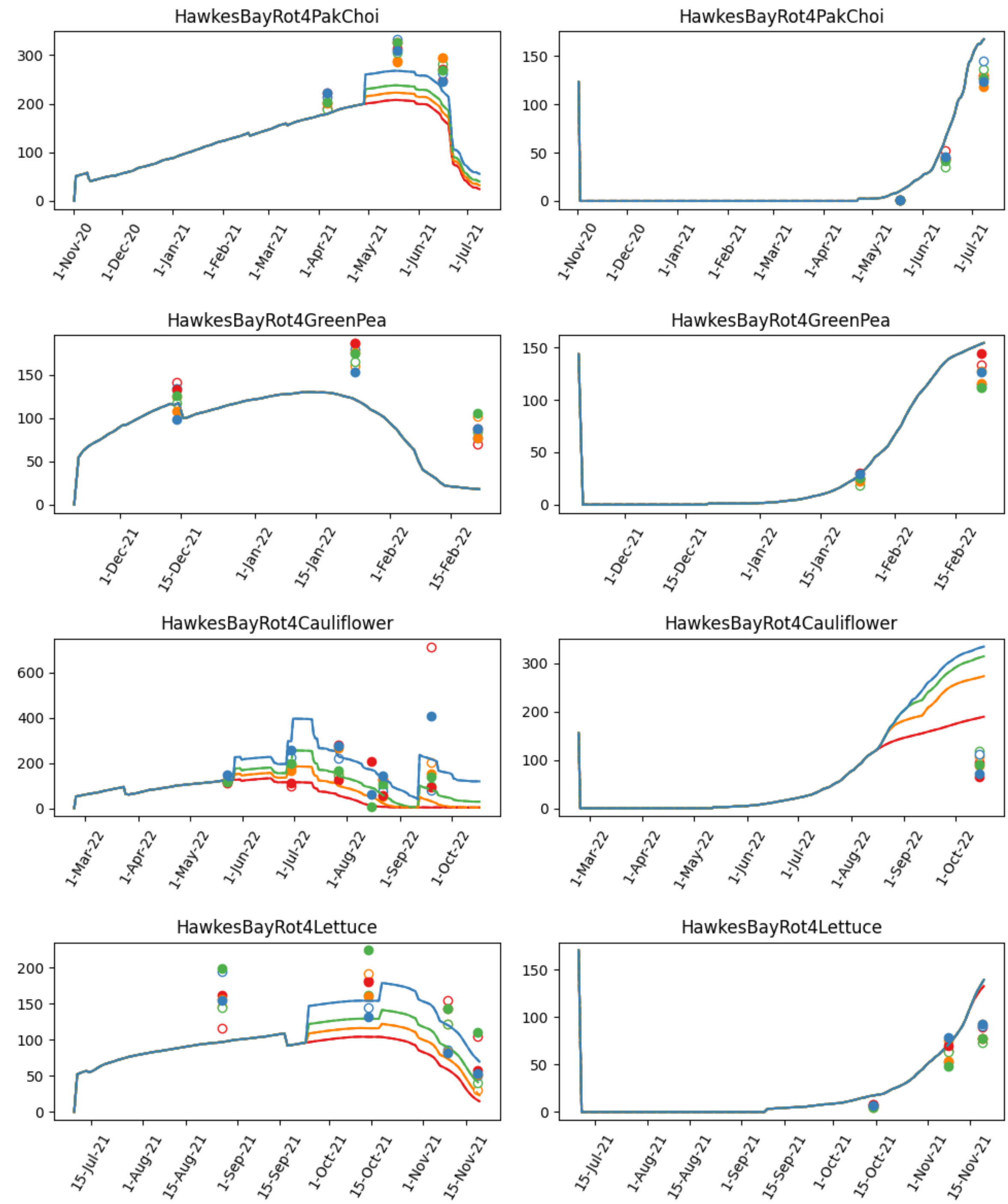

Figure 53. Observed (circles) and simulated data (lines) of soil mineral N levels (plots on left) and crop N uptake (plots on right) for Rotation 4 grown at The New Zealand Institute for Plant and Food Research Limited, Havelock North research site, Hawke’s Bay. Colours red, orange, green and blue represent N treatments N0, N1, N2, and N3 respectively, closed circles are Irrigation 1 and open circles are Irrigation 2 treatments. Units are kg N/ha.

6 Workstream 4

Understanding what is enabling and useful for growers in nutrient management was a key focus of the SVS project. We recognised that there is little value in designing the 'perfect tool or process' unless it will be used by growers, and so, it needs to be fit for purpose. The only way to do this well was to spend time with growers and agronomists, understanding what they do, why they do it, what is difficult, and what they see the shape of the future being. Overall, the work in this workstream fell in two areas: designing and developing the tool based on input from industry, and developing understanding of the tool through workshops, presentations and articles.

6.1 Tool design and development

This started with workshops that provided insight into requirements for a functional tool. This information provided information to support focus groups and one-to-one interviews. Finally as a tool was developed, it was discussed by one-to-one presentations with growers and agronomists to fine tune the design.

6.1.1 Modelling design and development workshops

The first modelling workshop was held 28 July 2021. The aim of the workshop was to understand what data were being collected in WS1, the key modelling components that would be needed to predict crop N uptake and fertiliser N requirement, and to discuss how such a model should be implemented and used. Present were PFR scientists involved in the work, agronomists and growers, and model users from councils and environmental companies. Some key summaries of this workshop were:

- A tool should primarily help demonstrate good practice
- The tool should provide information on changes in the various N pools within the system, to give visibility to growers and make the invisible visible.

A second modelling workshop was held via Zoom (Figure 54) spread over 2 days (1–2 December 2021). The workshop was broken into two sessions, with a session held on each day. The workshop involved agronomists, growers, model users and scientists involved modelling, with the aim of identifying key factors needed to make a tool functional and usable by growers. Key factors were:

- A tool should help indicate that grower practice is improving in terms of sustainability
- The tool should act as a guide for users, and indicate a range within which good practice could be achieved
- The tool should focus on providing information for best practice, rather than as a compliance tool as initially thought.

Figure 54. Sustainable Vegetable Systems modelling discussion via Zoom.

6.1.2 Interviews and focus groups

Several interviews and focus groups were held in 2021 with growers and agronomists from Pukekohe, the East Coast (Gisborne – Hawke's Bay), Ohakune, Manawatu-Horowhenua, and the Canterbury region. Information for the interviews and workshops was developed from ongoing work in WS1 and WS2, together with findings from the workshops. Details of interviews and focus groups are provided by Paul and White (2022).

In the workshops and interviews, both growers and agronomists signalled enthusiasm to try new tools and practices if they are proven to be successful, and if they are involved in the decision-making process of what the tool or practice looks like. There is currently no single tool that covers all aspects of nutrient management. Any tools or practices developed need to consider the depth of soil tests and speed at which a result is given, the ease of use, ability to use data from other tools, ability to adapt to different crops (both vegetable and cover crops), ability to adapt to different environments, and accuracy in terms of calculating nutrient availability. For adoption of any new tool or practice, it will be important to consider whether it is a stand-alone tool/practice or is packaged with other tools/practices to optimise effectiveness.

Growers and agronomists recognised several areas where more research is needed. These included the mineralisation of N, the effect of cultivation on nutrient availability and a better understanding of cover crops. Also key to improving nutrient management practices are the relationships that exist between growers, agronomists, researchers, industry representatives and policy makers. More transparency is needed in this space.

These findings guided subsequent development during demonstration of the tool.

6.1.3 Tool demonstration

The PFR modelling team developed an initial prototype for how such a tool might work and was initially used to estimate the fertiliser requirement for the potato experiment in WS1 (see Section 1.1.3). The tool and its approach was presented to the SVS Technical Panel as part of the process of deciding on fertiliser recommendations for crops in WS1 (Section 3.4). The tool example was used for the fresh market potato crop, and inputs considered with the SVS Technical Panel were:

- User inputs the sowing date, expected harvest date and expected yield. The tool then calculates pattern of crop N uptake from assumptions of the dry matter content of tubers, Nitrogen Harvest index, N content to tubers, haulms and fine roots. These values have been obtained from experimentation. The daily N uptake is calculated from an assumed sigmoidal growth pattern.
- User inputs soil mineral N and PMN test values. The depth for these measurements should be appropriate for the crop. In this case a depth of 30 cm was used.
- The N that is released from residues over the growth of the crop depends on the residue type, soil and environment conditions. In this case, the residues were the roots of the previous oat crop, and the amount of N available was estimated.
- The N that is released from soil mineralisation is calculated from the PMN test and the soil and environmental conditions.
- The user enters a ‘trigger’ soil N content – when the soil reaches this N content, fertiliser must be applied. Presently this is set at 35 kg N/ha. This is an estimated value at which the ability of the crop to access the nitrogen it needs is likely to be limited, and the point from which additional supply will be needed for optimum growth.
- The user can also set the number of times the fertiliser is applied. In this case there are three side-dressings, as well as one application at sowing.
- The tool calculates the amount of fertiliser needed, and the times when it should be applied.

The output (Figure 55) based on these inputs were graphs of crop N uptake, mineralisation of soil organic matter, returns from previous crop residue decomposition, and changes in the soil mineral N levels, together with the timing and amount of fertiliser needed by the crop.

Feedback from these presentations lead to developing the model to include the addition of a crop rotation, as well as the soil N test inputs. A model design for ongoing discussion with growers (Figure 56) had all the inputs aligned on one page and this was shared in one-to-one discussions.

Feedback was that this was tool design was too complicated, requiring too many inputs. and it also raised many questions from growers and agronomists about what the results were showing.

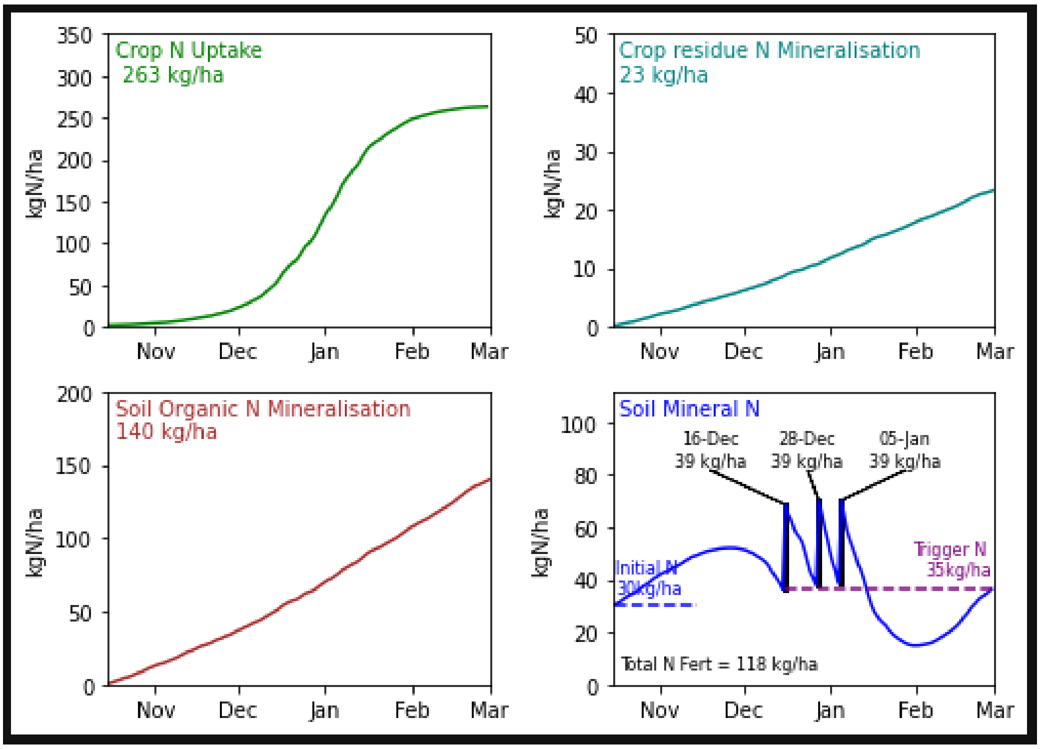

Figure 55. Output from first prototype farmer-facing tool, providing indication of prediction for soil nitrogen (N) supply to optimise fresh market potato yield in the Canterbury Vegetable rotation.

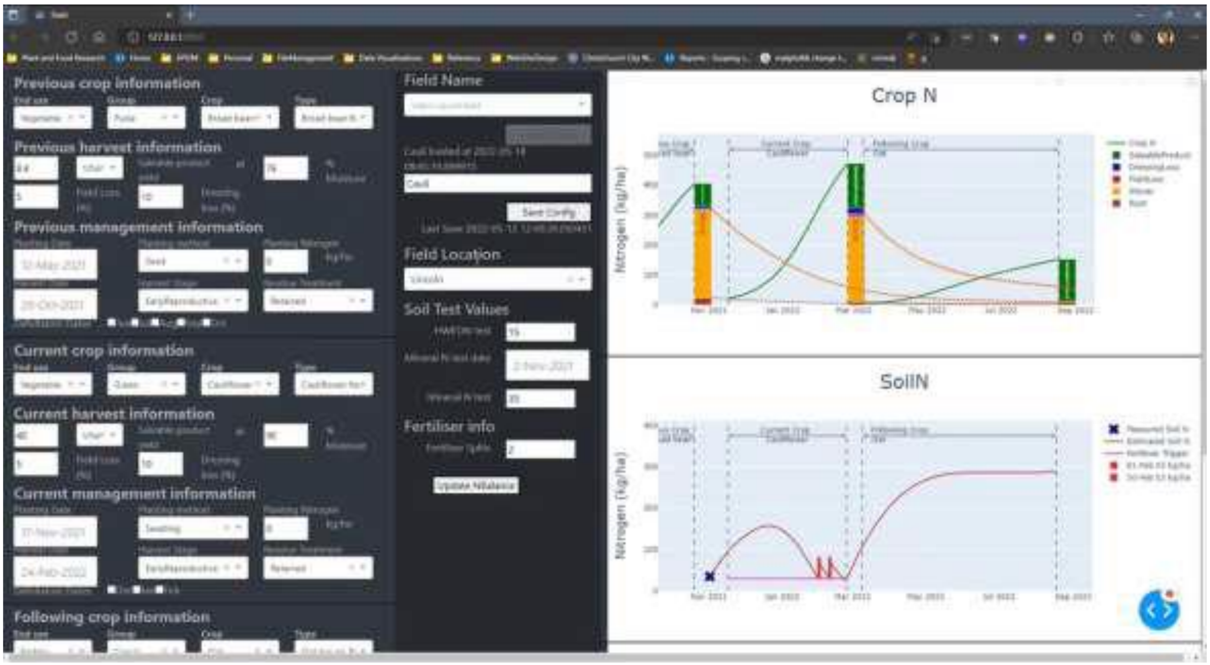

Figure 56. Second prototype of Sustainable Vegetable Systems (SVS) tool, with input panels on the left, and output panels on the right.

As a result of these discussions, a model with a different framework was designed that had three layers or levels, depending on the grower interest and input (Figure 57). This had the benefit of simplifying input pages, depending on layer:

Basic level – this is the default opening layer and inputs are only crop type, planting, and harvest date. There is no input of soil N levels. The model uses average parameters to estimate supply and uptake by the crop as well as suggest fertiliser rates. Minimising inputs allows users to produce a modelled output without being put off by too many input options. The output often raises questions and prompts use of other inputs in subsequent layers. All other inputs are visible but greyed out, so can provide prompts for further considering the additional layers of the model.

Soil N tests level –allows the user to enter soil N test results. The values can be entered in the soil mineral N test results, either from a laboratory test, or from a N quick test result, and the potentially mineralisable N (PMN) or Hot Water Extractable Organic N (HWEON) test result that indicates the amount of mineralised N that will be available to the crop. On this layer, soil N values can be updated if a quick-N test is carried out during the growth period, to fine tune fertiliser application rates and timings. At this layer the user can also input their actual fertiliser rates and timings, which provides numeric and visual outcomes for reviewing management choices.

Crop rotation level – allows details of previous and subsequent crops to be included. This allows the N supply to be evaluated at a system point, and not just as a per crop issue, as residues from a crop could directly influence N management decisions of a current crop.

The SVS Tool also allows users to save their scenarios both within the tool and as downloaded PDF or Excel CSV files. An example of the PDF report generated from the SVS Tool is shown in Figure 72. While regulatory or commercial compliance was not the main objective when designing the tool, allowing users to easily manage their paddocks and crops and store their scenarios will allow operations to store bodies of evidence against which they can provide as evidence in their Farm Environment Plan (FEP) or other commercial sustainability schemes (particularly for supplying certain export markets).

The development of the tool and software is more fully described by Barber et al. (2024).

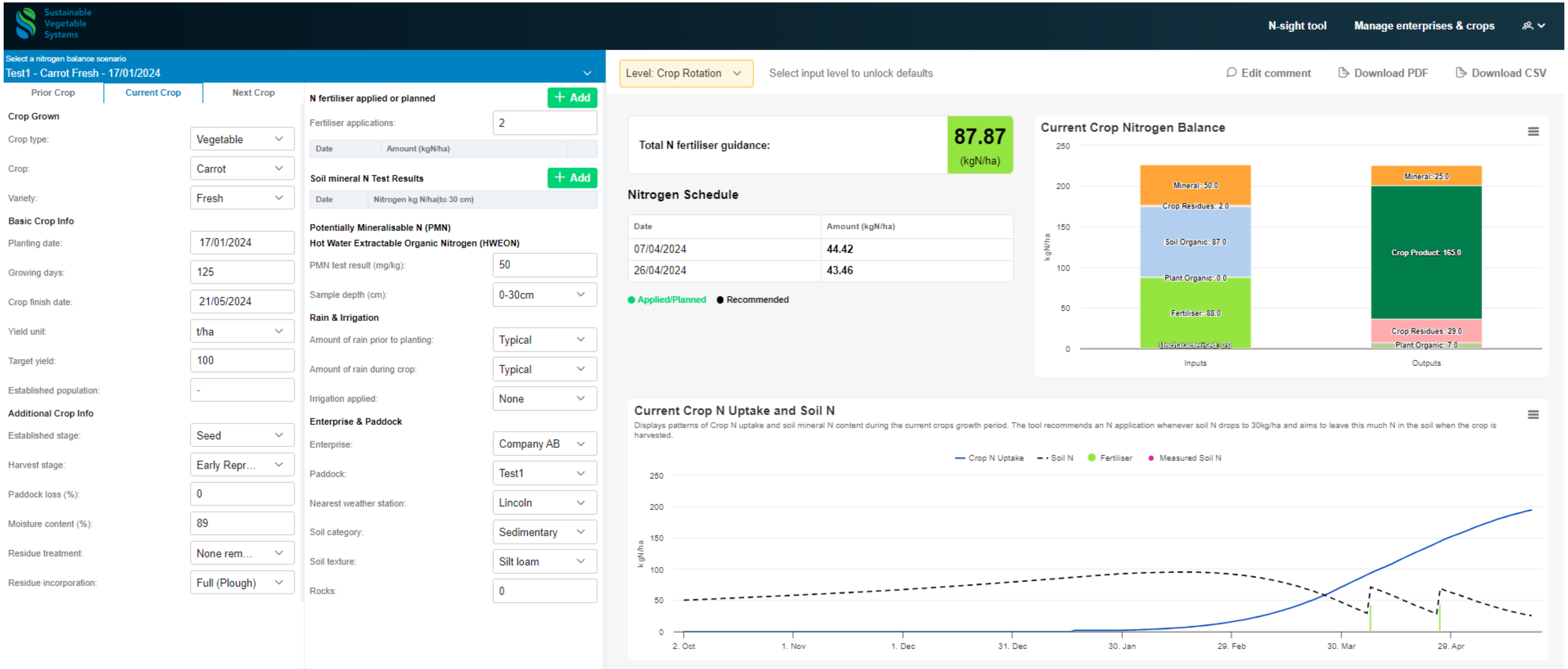

Figure 57. Screenshot of final Sustainable Vegetable Systems (SVS) tool open in Rotation Layer. This is the most comprehensive layer in the tool and includes information on the system including previous and subsequent crops, soil nitrogen (N) tests, and crop details such as planting date. Output is a fertiliser recommendation and a N balance summary,

6.2 Articles, presentations and workshops

Articles published include:

- Fraser T and Searle B. *Understanding soil nitrogen* NZ Grower December 2021.
- Searle B, Fraser T, Sharp J. Plant & Food Research. *Nitrogen balance – understanding management and environmental implications of nitrogen use in crop production.* April 2022.
- B Searle, Fraser T. *What is happening in the soil?* NZ Grower June 2023.
- Barber A, Fraser T, Searle B. *Crop residues, fallow periods, and management practices.* NZ Grower Aug 2023.

A list of articles facilitated by SVS partners is detailed by Barber et al. 2024.

Conferences

New Zealand Society of Soil Science 2022.

- Fraser P; Searle B and Brown H. 2022. *Improving our understanding of nitrate leaching from vegetable cropping rotations*. Presentation at "Soil - Aotearoa's most precious resource – past, present, future". NZ Society of Soil Science Conference, Blenheim 28 November – 1 December 2022.

Horticulture NZ Conference 2022.

- Searle B and Beare M. *Nitrogen management for sustainable vegetable systems*. Horticulture NZ conference August 2022
- Searle B, Fraser T, Brown H. *Sustainable Vegetable systems – how to manage N in vegetable crop systems*. August 2022.

Potatoes New Zealand Conference August 2023.

- Barber A. Sustainable Vegetable Systems. August 2023.
- Searle B. Soil and crop nitrogen dynamics in vegetable cropping systems. August 2023.
- Faser T and Searle B. Residues in vegetable cropping systems. August 2023.
- Brown H. Nitrogen management tool(s) for minimised leaching. August 2023.

ONZ Research Summit August 2023:

- Sustainable Vegetable Systems and risk management – Andrew Barber
- SVS updates – mineral N and residue decomposition – Bruce Searle.

Workshops

There were numerous workshops and SVS Technical panel discussions contributed to as well. These included:

2021

- Searle B. Science approach to optimising N in Vegetable Systems
- Brown H. Modelling N response
- Sharp J. Modelling residues
- Cichota R. Modelling drainage and leaching

2023

- Searle B. Exploring SVS trial results
- Brown H. Demonstration of the tool
- Beare M. Discussion on HWEON use.

7 Challenges for further research

Key to ensuring the success and ongoing production of vegetables and crops in New Zealand, are tools that enable good management practice and justify fertiliser applications to all stakeholders. The tool developed in the SVS programme is an opportunity to achieve this. We have developed the tool based on data from controlled experiments and from some grower fields, but it has not been well tested on independent data or thoroughly validated.

For this to happen, some key issues need to be addressed, and we have grouped these under tool use and tool improvement to achieve an integrated development and application of the approach to improve outcomes of N use.

Tool use

The N balance approach and tool needs ground-truthing, particularly showing that the N balance approach does reflect good management and improves sustainability outcomes. To do this we suggest:

- Establish farmer data-driven approach to enhance tool implementation in practice, so that the tool becomes a standard part of management.
- Develop a structured use-case evaluation of in-farm field trials, across as many regions and crops as possible. This structured use case should evaluate if soil N mineralisation is under predicted, if losses are overpredicted, if crops are obtaining N from deeper in the profile. Or if residue decomposition is not predicted correctly.
- Develop farm field trials to contribute to use case evaluation that validate the N balance approach and identify any key concerns. The use cases would include standard practice compared with use of the SVS tool to validate the N balance approach across a wide range of environments and crops and demonstrate that the approach improves sustainability and N balance outcomes. These data are necessary to ground the tool in commercially relevant situations. It will also help improve the tool parameter values and predictive capacity. This evaluation should also compare increase in soil N content below 60 cm depth under conventional practice with that when the SVS tool is used.
- Compare the use of the SVS tool with and without the use of nitrate test strips during the season to adjust N management. Evaluations would include yield outcomes, but particularly the N balance components and Uncharacterised N of the crop system.
- The tool uses soil N samples to a depth of 30 cm. However, evaluation of soil tests to 60 cm ad effects on subsequent fertiliser recommendations and N balances should be implemented, to compare with previous recommendations (e.g.) where soil mineral N measurement in the to 60 cm is recommended for a range of crops (e.g. carrots, potatoes, Reid et al. (2019)). Confirming this for a wider range of crops and sampling depths is recommended.

Tool improvement

Key science questions have arisen and should link closely with tool use, to ensure any improvements are included in the farmer data driven evaluation. These include:

- Comparing outcomes of the N balance and yield where side-dressings rates and date of application are set by SVS tool prediction compared to changes in rates and dates of side-dressing from using soil nitrate quick test assessment during growth.
- Comparing the same varieties of selected crops grown in different environmental conditions – to evaluate the yield potential effect on N balance outcomes.
- The residue model is based on published data, mostly from overseas. This model needs to be fine-tuned for New Zealand conditions and for how the residue is treated (crimpled, mulched, left on surface, buried). An approach for this work is described in Figure 58. This process should also be conducted with structured approach to develop case studies to understand users' perceptions, concerns, and preferences, to help improve overall impact and use of the tool.
- Construction of a rotation. Different crops seem to have different levels of Uncharacterised N, and depths from which soil mineral N can be accessed. This has implications for how rotations should be structured for best N management and environmental outcomes.
- Understanding soil types where N movement throughout the profile differs due to high water tables.
- Evaluation, identified by stakeholder discussion and use cases, of other potential tool uses such as application to predicting requirements for other nutrients (P, K).

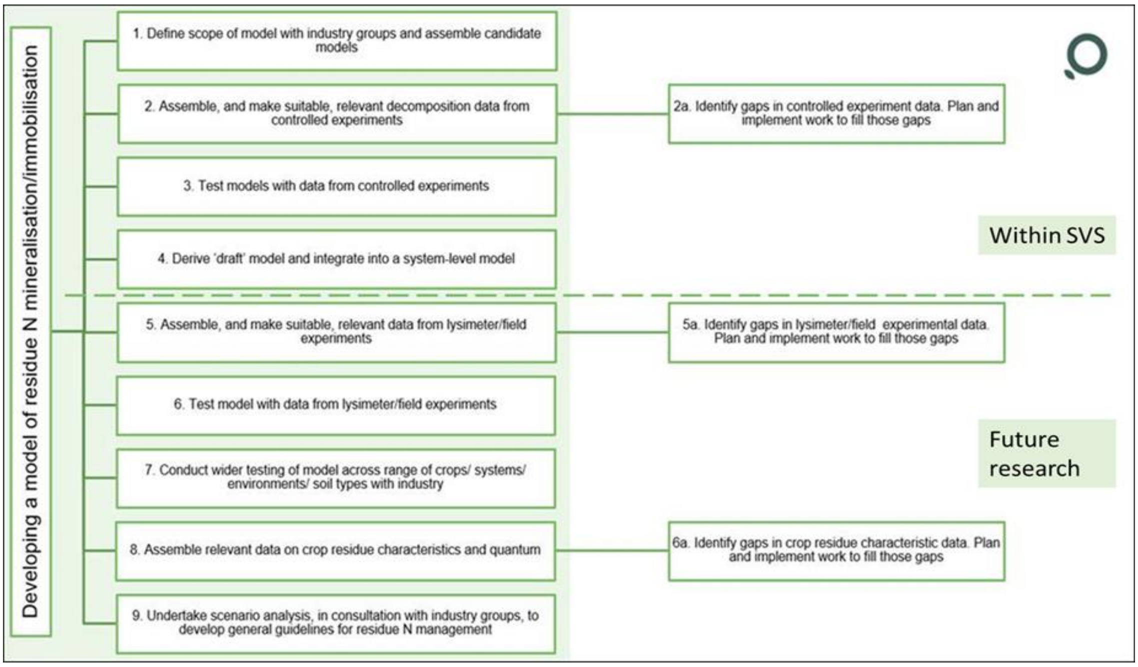

Figure 58. Step plan of developing decomposition model of crop residue nitrogen (N) mineralisation and immobilisation with steps in the current Sustainable Vegetable Systems (SVS) project, and steps needed in subsequent research to develop a comprehensive model.

8 General conclusion

A key economic and environmental driver within a complex and dynamic vegetable growing system is the application of N fertiliser at the correct rate and time, to ensure good yields, but also environmental sustainability. Decisions on fertiliser N rates for successful outcomes are difficult to make and require significant information, much of it difficult to attain simply and quickly.

The SVS project has developed a tool that growers can use to estimate the amount and timing of N fertiliser applications. Feedback from growers and agronomists during the project helped to develop the structure of the tool. At its very simplest, the tool only requires information on the crop type, sowing date and where the crop is grown. This gives a general overview of how much N the crop has taken up, how soil N has changed, and the fertiliser needed. Where users note that this is not representative of their crop and requirements, subsequent points allow for grower input on soil N tests, both mineral N and mineralised N rates, and further information on previous crops to account for N becoming available by residue decomposition. The tool uses plots of crop N uptake, soil N changes to give visibility of the different processes of crop N use, and effects these decisions have on N balance outcomes. In addition, the SVS tool allows the within season input of soil N measurements with subsequent corrections of N fertiliser rates and timings, allowing adjustments for season and conditions,

To develop the tool, experiments evaluating effect of N rate on different crops were conducted across four rotations, two located in Canterbury and two located in Hawke’s Bay. Detailed data on crop and soil N components were collected, and effects on N balance were evaluated. Comparison of two potato crops, one grown using the SVS prototype tool, with recommended fertiliser rates and timings adjusted by in-season soil N tests using quick N test strips, significantly improved N balance outcomes, improving yield and sustainability.

This data were used to develop a model of changes in crop and soil N over time with the SCRUM-APSIM model, using daily weather data recorded during the experiments. This model had good agreement between predicted and estimated outputs. This model structure was used to develop the SVS tool, based on long-term average weather data. It was validated with data from the detailed experiments of four rotations, plus data gathered from rotations across nine commercial fields across Aotearoa-New Zealand. This gave good fits to the data, but in some instances may have under predicted supply of soil N though N mineralisation or residue decomposition, or overpredicted losses, or ability of the crop to obtain N from deeper layers of the soil. Structured case evaluations in farmers’ fields are recommended to further understand how these factors effect crop N uptake, and ways to improve the tool.

9 Acknowledgements

The growing of crops in Workstream 1 relied heavily on the input of the SVS Technical Panel, as well as industry agronomists and growers for advice in terms of management, in particular the timing and types of different agrichemicals to be applied for crop protection and to produce a high-quality product. This input is input is appreciated. Thanks to all those industry collaborators who provided seed and agrichemicals for the work. A big thank you to the Regional Monitors in Workstream 2, who collect arguably the most representative data of current practices, which are key to the outcome of this work. And finally, a huge thanks to the field teams in Canterbury and Hawke's Bay, who have collected large amounts of data, often in physically demanding conditions, and to the lab team who work tirelessly to analyse the countless samples collected.

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Appendix 1. Workstream 1 experimental approach

Experimental Crops and N applications

These data are in Tables A1–A4.

Table A1. Rotation 1 crops general information, including variety, sowing date, and amount of nitrogen (N) fertiliser (kg/ha) applied. Rotation 1 was grown at The New Zealand Institute for Plant and Food Research Limited, Lincoln research site. Multiple side-dressing applications of the N fertiliser are indicated by "/".

Crop	Variety	Sow date	N1	N2	N2	N4
Potatoes (processed	'Russet Burbank'	22 Oct 2019				
Fertiliser rate (kg N/ha)			21	121	221	421
Side dressings			21*	21*/25/25/25/25	21*/50/50/50/50	21*/100/100/100/100
Wheat	'Catherine'	19 May 2020				
Fertiliser rate (kg N/ha)			150	150	150	150
Side dressings			75/75	75/75	75/75	75/75
Broccoli	'Nobel'	3 Mar 2021				
Fertiliser rate (kg N/ha)			0	30	60	120
Side dressings				15/15	30/30	60/60
Onion	'Tilbury'	7 Sep 2021				
Fertiliser rate (kg N/ha)			0	60	120	140
Side dressings				30/30	60/60	120/120
Perennial ryegrass – seed	'Nui'	6 May 2022				
Fertiliser rate (kg N/ha)			29	74	119	209
Side dressings			29*	29*/20/15/10	29*/40/30/20	29*/80/60/40

Table A2. Rotation 2 crops general information, including variety, sowing date, and amount of nitrogen (N) fertiliser (kg/ha) applied. Rotation 2 was grown at The New Zealand Institute for Plant and Food Research Limited, Lincoln research site. Multiple side-dressing applications of the N fertiliser are indicated by "/".

Crop	Variety	Sow date	N1	N2	N2	N4
Pak choy	'Shangai'	7 Dec 2020				
Fertiliser rate (kg N/ha)			0	30	60	140
Side dressings			0	15/15	30/30	60/80
Oats	'Milton'	2 Mar 2021				
Fertiliser rate (kg N/ha)			No fertiliser N was applied to the crop.			
Potatoes (fresh)	'Agria'	22 Oct 2021				
Fertiliser rate (kg N/ha)			0	103	206	412
Side dressings			0	31/31/41	62/62/82	124/124/164
Perennial ryegrass - seed	'Nui'	6 May 2022				
Fertiliser rate (kg N/ha)			0	60	120	240
Side dressings			0	15/20/15/10	30/40/30/20	60/80/60/40

Table A3. Rotation 3 crops general information, including variety, sowing date, and amount of nitrogen (N) fertiliser (kg/ha) applied. Rotation 3 was grown at The New Zealand Institute for Plant and Food Research Limited, Havelock North research site. Multiple side-dressing applications of the N fertiliser are indicated by "/".

Crop	Variety	Sow date	N1	N2	N2	N4
Onion	'Tilbury'	7 Dec 2020				
Fertiliser rate (kg N/ha)			0	30	60	140
Side dressings			0	15/15	30/30	60/80
Ryegrass	50:50 mix of 'Asset' and 'Tama' ryegrass	2 Mar 2021				
Fertiliser rate (kg N/ha)			No fertiliser N was applied to the crop.			

Table A4. Rotation 4 crops general information, including variety, sowing date, and amount of nitrogen (N) fertiliser (kg/ha) applied. Rotation 4 was grown at The New Zealand Institute for Plant and Food Research Limited, Havelock North research site. Multiple side-dressing applications of the N fertiliser are indicated by "/".

Crop	Variety	Sow date	N1	N2	N2	N4
Pak choy	'Shangai'	7 Dec 2020				
Fertiliser rate (kg N/ha)			0	30	60	140
Side dressings			0	15/15	30/30	60/80
Lettuce	'Contessa'	2 Mar 2021				
Fertiliser rate (kg N/ha)			No fertiliser N was applied to the crop.			
Peas	'Ashton'	22 Oct 2021				
Fertiliser rate (kg N/ha)			0	103	206	412
Side dressings			0	31/31/41	62/62/82	124/124/164
Cauliflower	'Casper'	6 May 2022				
Fertiliser rate (kg N/ha)			0	60	120	240
Side dressings			0	15/20/15/10	30/40/30/20	60/80/60/40
Forage ryegrass	'Winter Star II'	13 Dec 2022				
Fertiliser rate (kg N/ha)			0	0	0	0
Side dressings						

Appendix 2. Soil Physical measurements for Rotation 1–4 of Workstream 1

Values for soil water content parameters averaged across profiles within each of the rotation sites are shown in Table A5 for the Canterbury rotations (Rotation 1 and 2) and A6 for the Hawke's Bay rotations (Rotation 3 and 4).

Pits were dug to depths of 180 cm at the Canterbury site and Hawke's Bay site, and profiles identified. Samples were collected from each profile horizon to obtain measures of soil physical properties to estimate water uptake and movement in the soil. These included of soil bulk density (BD). LL15 (Lower Limit at 15 bar pressure) refers to the driest point at which plants can still extract water from the soil – beyond this point, plants cannot access any more water. DUL (Drained Upper Limit) is the point at which the soil has absorbed as much water as it can after excess water has drained away (and also referred to as Field Capacity, FC). Between LL15 and DUL is where plants can take up water for growth. SAT (Saturation) represents when the soil is completely filled with water, with no room for air, which can impact plant roots if the soil stays waterlogged for too long. Lastly, Ksat (Saturated Hydraulic Conductivity) measures how easily water can move through the soil when it's fully saturated, helping us understand the soil's ability to drain or allow water to flow.

Table A5. Soil physical measurements for soils of Rotation 1 ad 2 in Canterbury. Measurements include bulk density (BD), the lower limit of water extraction (LL15), the drained upper limit (DUL), the saturated limit (SAT) and the rate of water movement through the profile (Ksat).

Horizon	Profile depth	BD	LL15	DUL	SAT	Ks
	cm	g/cm³	cm³/cm³	cm³/cm³	cm³/cm³	mm/day
Ah1	0-10	1.230	0.190	0.360	0.535	480.0
Ah2	10-20	1.235	0.195	0.365	0.530	420.0
AB(f)	20-40	1.370	0.185	0.350	0.482	240.0
Bw(f)	40-60	1.660	0.150	0.335	0.374	24.0
Bw(g)1	60-80	1.590	0.185	0.375	0.400	24.0
BC(g)1	80-100	1.440	0.100	0.325	0.450	1200.0
Bw(g)2	100-120	1.525	0.120	0.340	0.425	480.0
Bw(g)3	120-140	1.360	0.070	0.280	0.475	720.0
BC(g)3	140-160	1.350	0.080	0.300	0.460	1200.0
BC(g)4	160-180	1.350	0.080	0.300	0.460	1140.0

Table A6. Soil physical measurements for soils of Rotation 3 and 4 in Hawke's Bay. Measurements include bulk density (BD), the lower limit of water extraction (LL15), the drained upper limit (DUL), the saturated limit (SAT) and the rate of water movement through the profile (Ksat).

Horz	Depth	BD	AirDry	LL15	DUL	SAT	Ks
	cm	g/cm^3	cm^3/cm^3	cm^3/cm^3	cm^3/cm^3	cm^3/cm^3	mm/day
Ap1	0-11	1.271	0.074	0.223	0.431	0.508	258.5
Ap2	11-28	1.274	0.216	0.240	0.430	0.507	166.9
Bg/A	28-44	1.273	0.268	0.268	0.428	0.506	108.3
Bg	44-67	1.193	0.250	0.250	0.410	0.517	401.5
BCg	67-102	1.202	0.243	0.243	0.421	0.507	125.0
BCtr	102-118	1.159	0.316	0.316	0.466	0.528	42.4
2C	118-150	0.896	0.220	0.220	0.406	0.476	455.7

Appendix 3. Soil moisture content during rotation in Workstream 1

These graphs show estimated percentage of soil water relative to field capacity (FC, or drained upper limit) for Irrigation 1 treatment (best management irrigation practice). Values above 100% indicate that free water is sitting in the profile that is not draining.

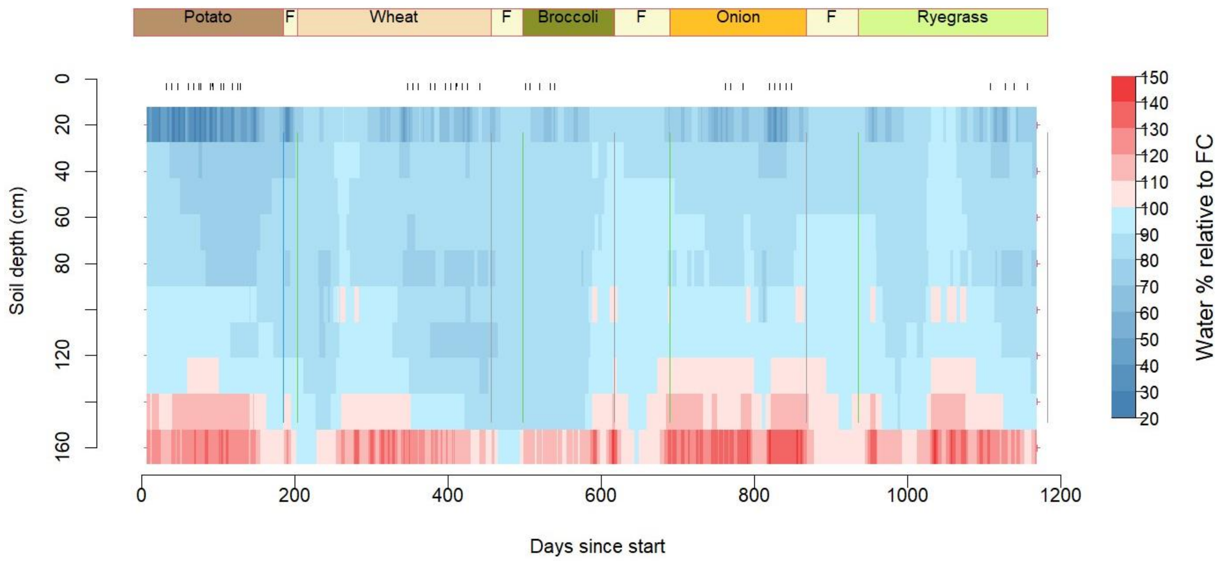

Figure A1. Estimated percentage of water content relative to soil field capacity (FC) for Rotation 1 grown at The New Zealand Institute for Plant and Food Research Limited, Lincoln research site, Canterbury. Crop durations are shown and black lines indicate irrigation events.

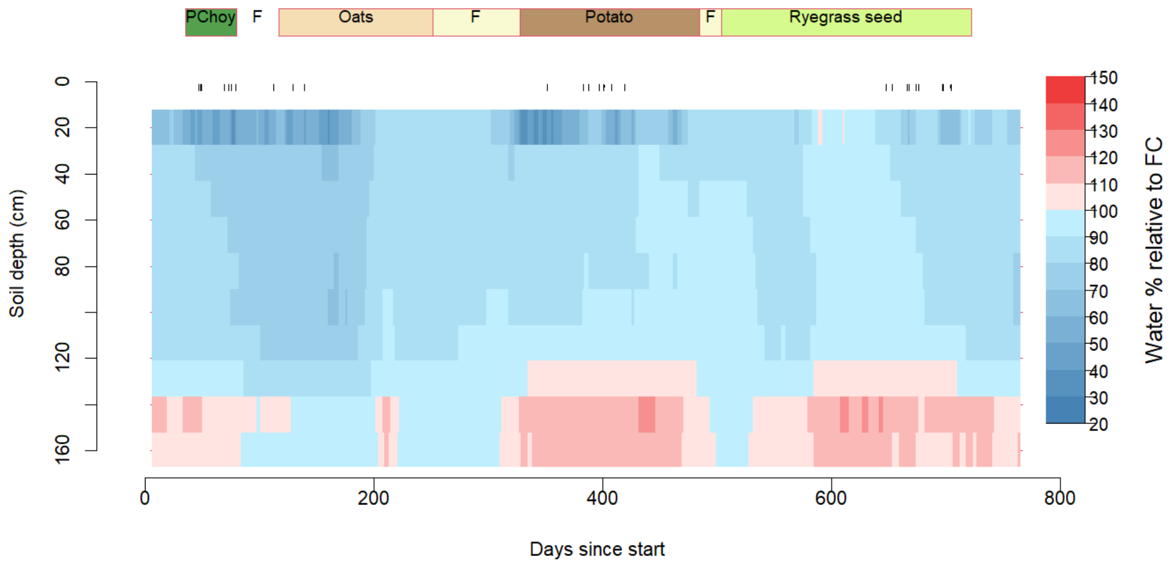

Figure A2. Estimated percentage of water content relative to soil field capacity (FC) for Rotation 2 grown at The New Zealand Institute for Plant and Food Research Limited, Lincoln research site, Canterbury. Crop durations are shown and black lines indicate irrigation events.

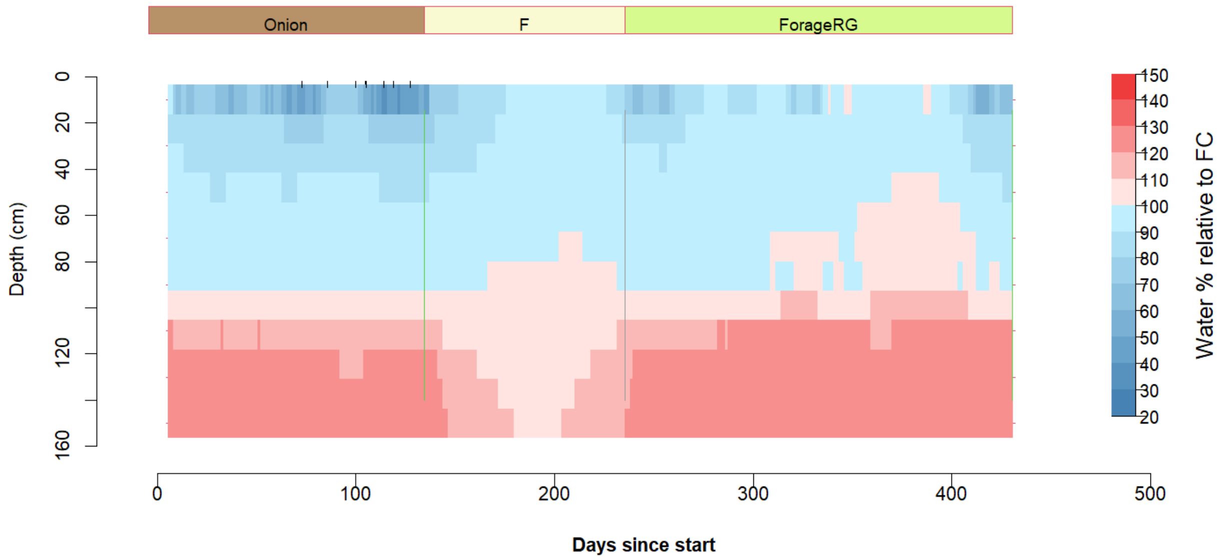

Figure A3. Estimated percentage of water content relative to soil field capacity (FC) for Rotation 3 grown at The New Zealand Institute for Plant and Food Research Limited, Havelock North research site, Hawke's Bay. Crop durations are shown and black lines indicate irrigation events.

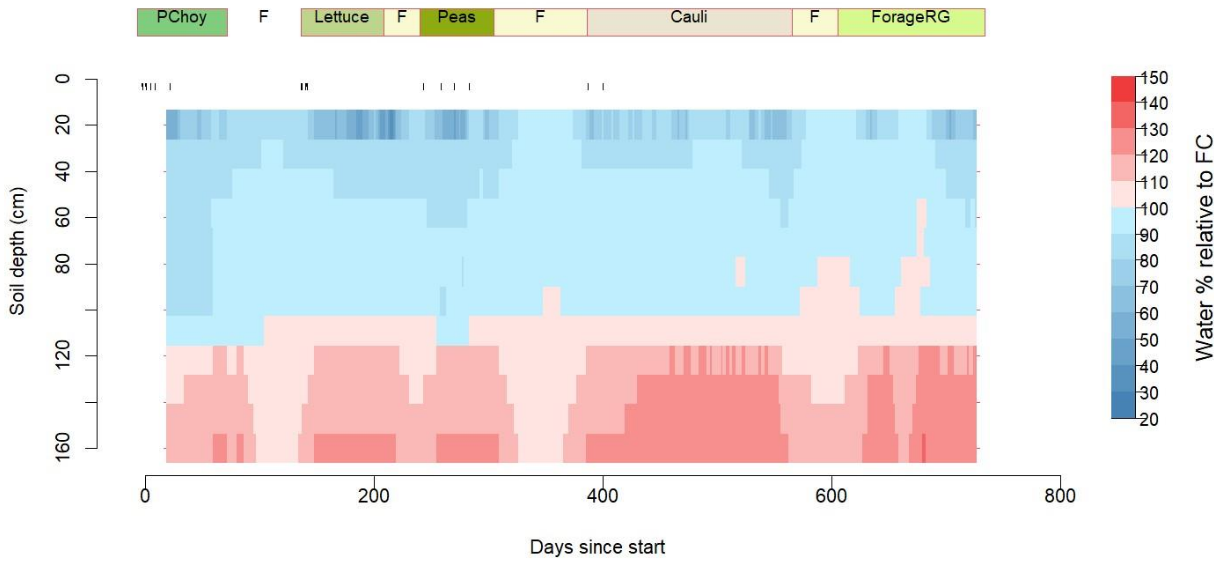

Figure A4. Estimated percentage of water content relative to soil field capacity (FC) for Rotation 4 grown at The New Zealand Institute for Plant and Food Research Limited, Havelock North research site, Hawke's Bay. Crop durations are shown and black lines indicate irrigation events.

Appendix 4. Soil nitrogen content across time and depth in Workstream 1

Rotation 1

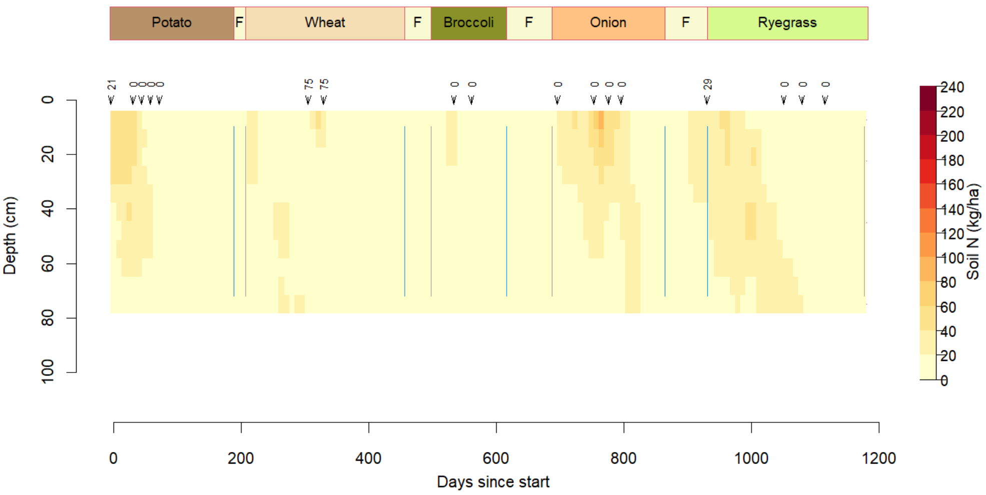

Figure A5. Soil nitrate across depth and time for the N1 treatment of Rotation 1 grown at The New Zealand Institute for Plant and Food Research Limited, Lincoln research site, Canterbury. Crop durations are shown, and black arrows indicate fertiliser applications.

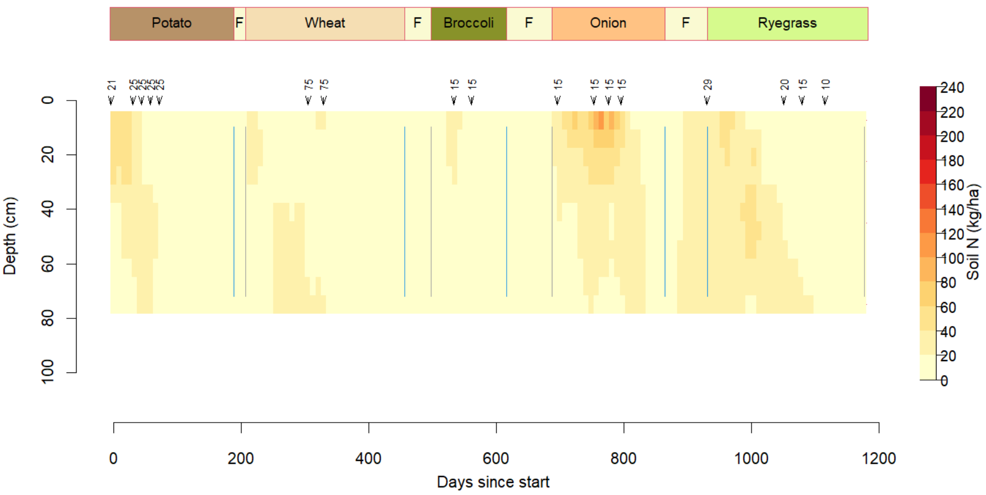

Figure A6. Soil nitrate across depth and time for the N2 treatment of Rotation 1 grown at The New Zealand Institute for Plant and Food Research Limited, Lincoln research site, Canterbury. Crop durations are shown, and black arrows indicate fertiliser applications.

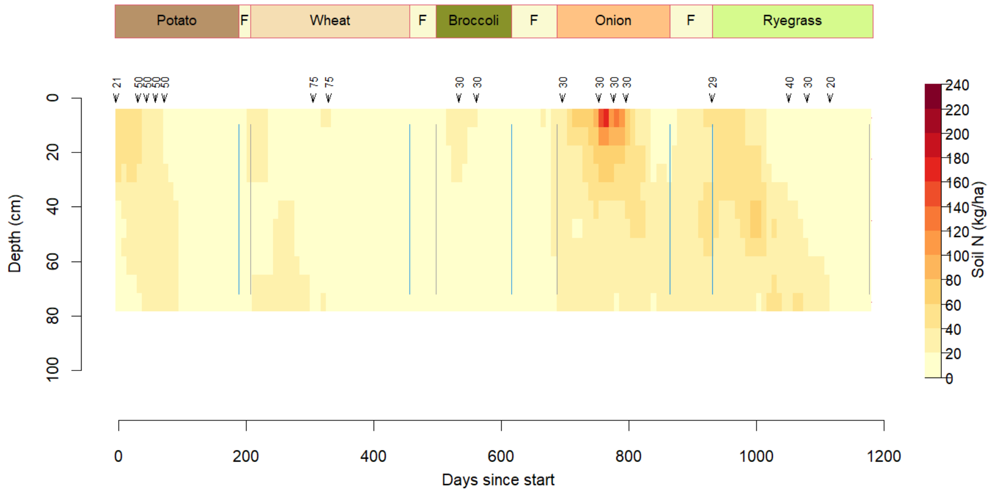

Figure A7. Soil nitrate across depth and time for the N3 treatment of Rotation 1 grown at The New Zealand Institute for Plant and Food Research Limited, Lincoln research site, Canterbury. Crop durations are shown, and black arrows indicate fertiliser applications.

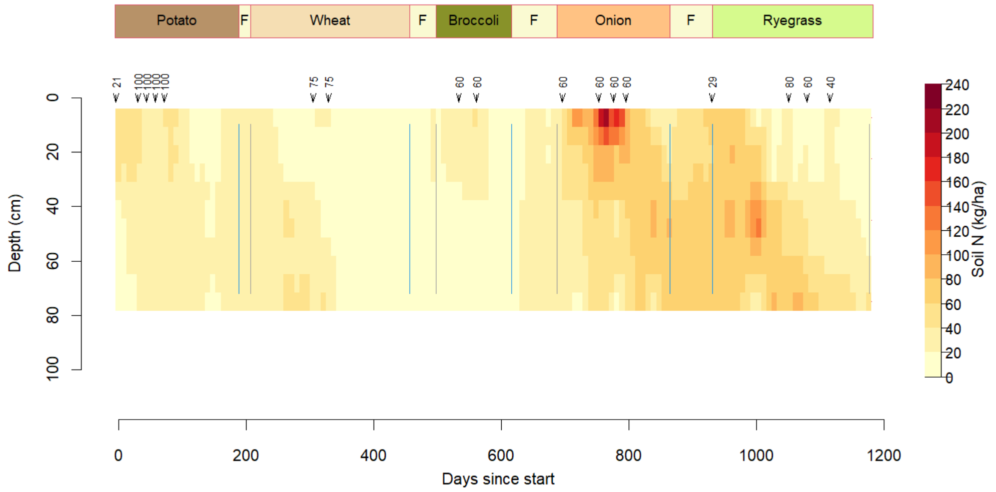

Figure A8. Soil nitrate across depth and time for the N4 treatment of Rotation 1 grown at The New Zealand Institute for Plant and Food Research Limited, Lincoln research site, Canterbury. Crop durations are shown, and black arrows indicate fertiliser applications.

Rotation 2

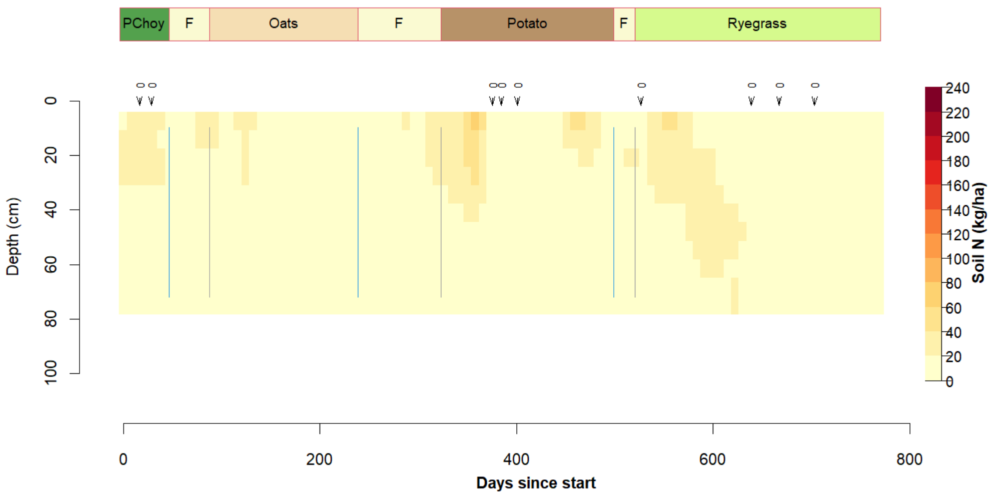

Figure A9. Soil nitrate across depth and time for the N1 treatment of Rotation 2 grown at The New Zealand Institute for Plant and Food Research Limited, Lincoln research site, Canterbury. Crop durations are shown, and black arrows indicate fertiliser applications.

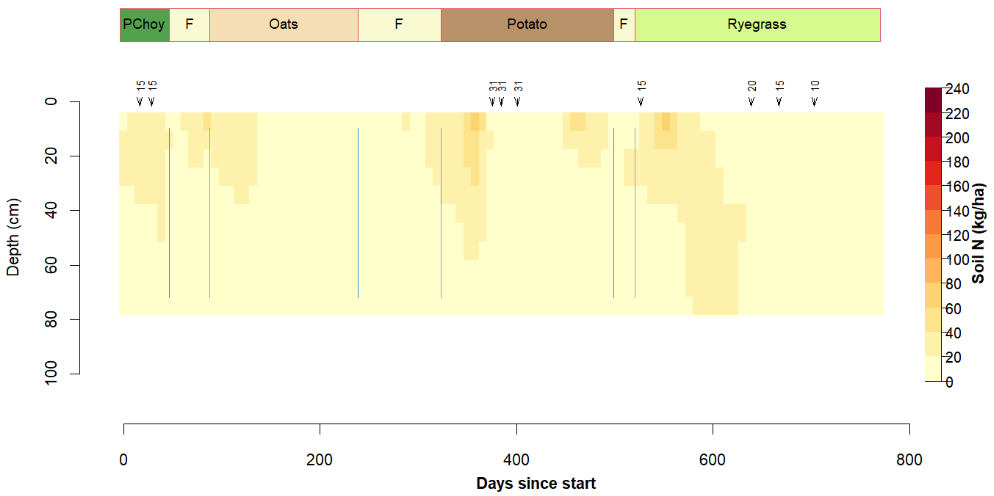

Figure A10. Soil nitrate across depth and time for the N2 treatment of Rotation 2 grown at The New Zealand Institute for Plant and Food Research Limited, Lincoln research site, Canterbury. Crop durations are shown, and black arrows indicate fertiliser application.

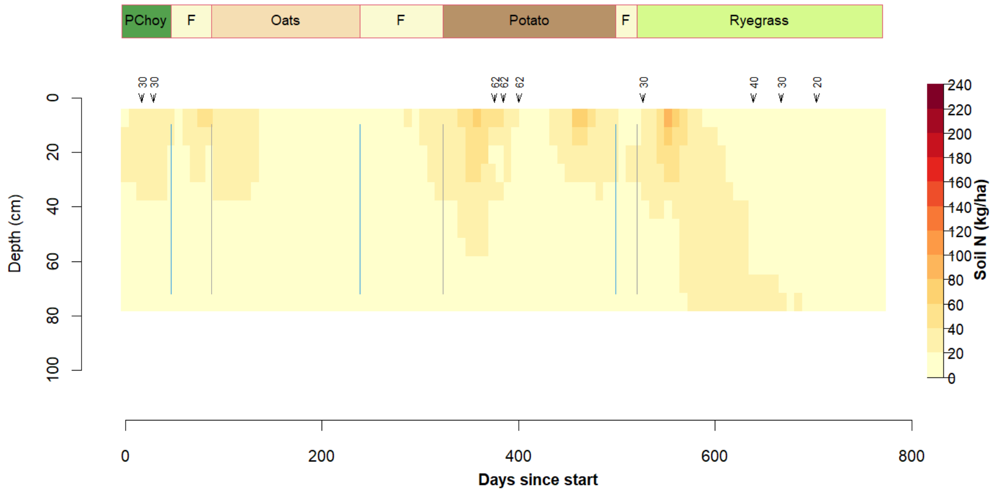

Figure A11. Soil nitrate across depth and time for the N2 treatment of Rotation 2 grown at The New Zealand Institute for Plant and Food Research Limited, Lincoln research site, Canterbury. Crop durations are shown, and black arrows indicate fertiliser application.

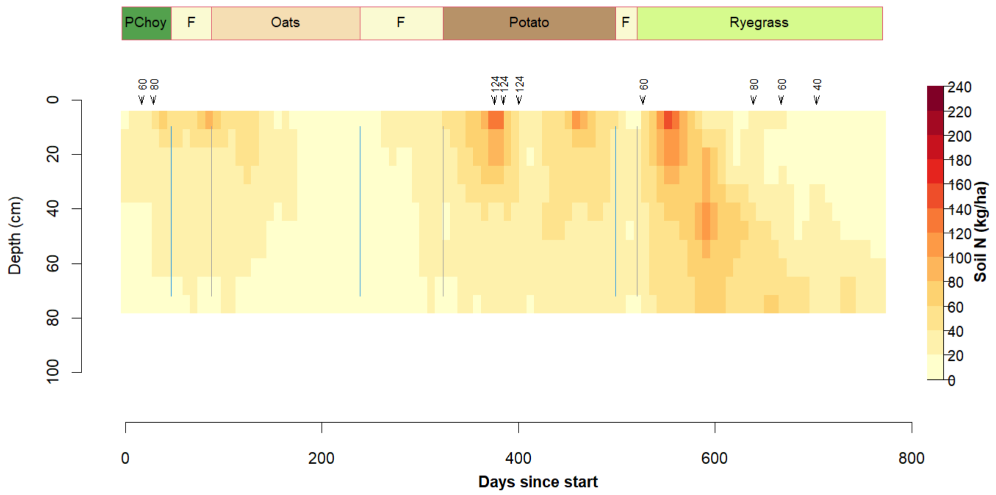

Figure 12. Soil nitrate across depth and time for the N4 treatment of Rotation 2 grown at The New Zealand Institute for Plant and Food Research Limited, Lincoln research site, Canterbury. Crop durations shown, and black arrows indicate fertiliser application.

Rotation 3

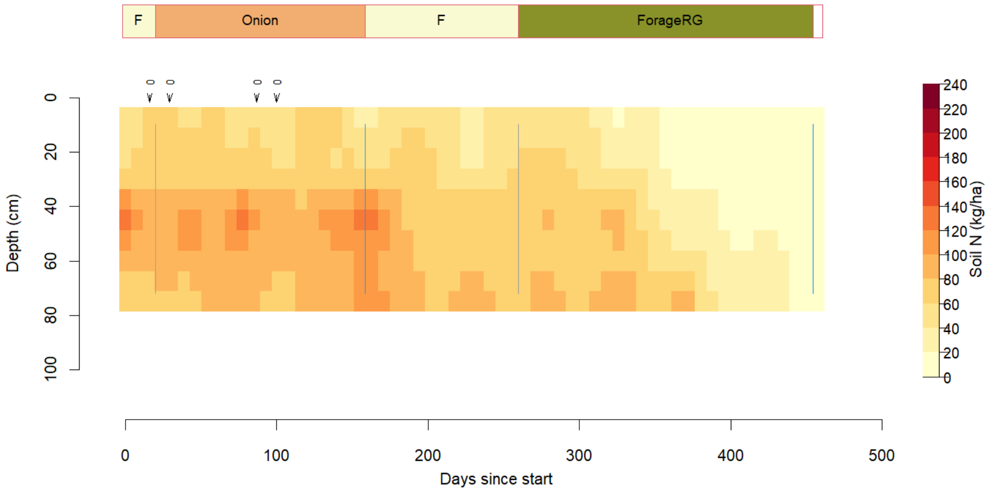

Figure A13. Soil nitrate across depth and time for the N1 treatment of Rotation 3 grown at The New Zealand Institute for Plant and Food Research Limited, Havelock North research site, Hawke's Bay. Crop durations are shown, and black arrows indicate fertiliser application.

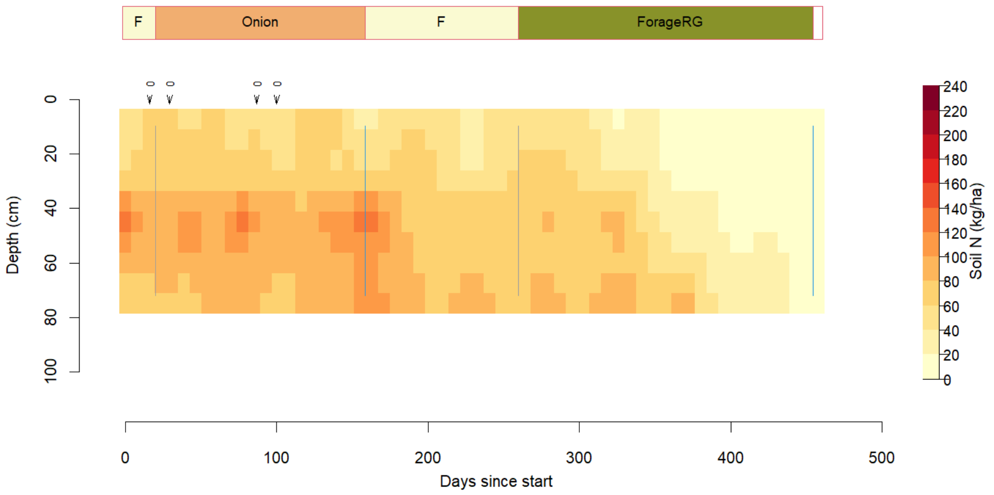

Figure A14. Soil nitrate across depth and time for the N2 treatment of Rotation 3 grown at The New Zealand Institute for Plant and Food Research Limited, Havelock North research site, Hawke's Bay. Crop durations are shown and black arrows indicate fertiliser application.

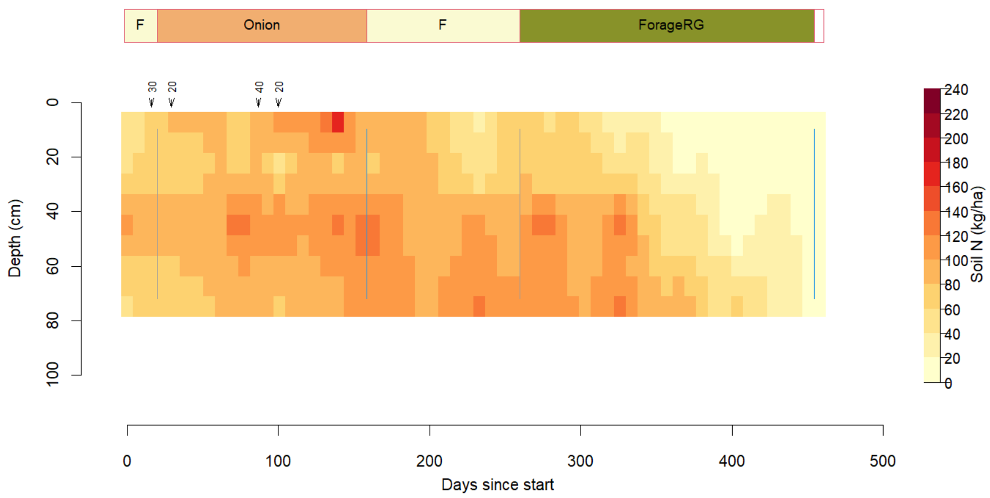

Figure A14. Soil nitrate across depth and time for the N3 treatment of Rotation 3 grown at The New Zealand Institute for Plant and Food Research Limited, Havelock North research site, Hawke's Bay. Crop durations are shown and black arrows indicate fertiliser application.

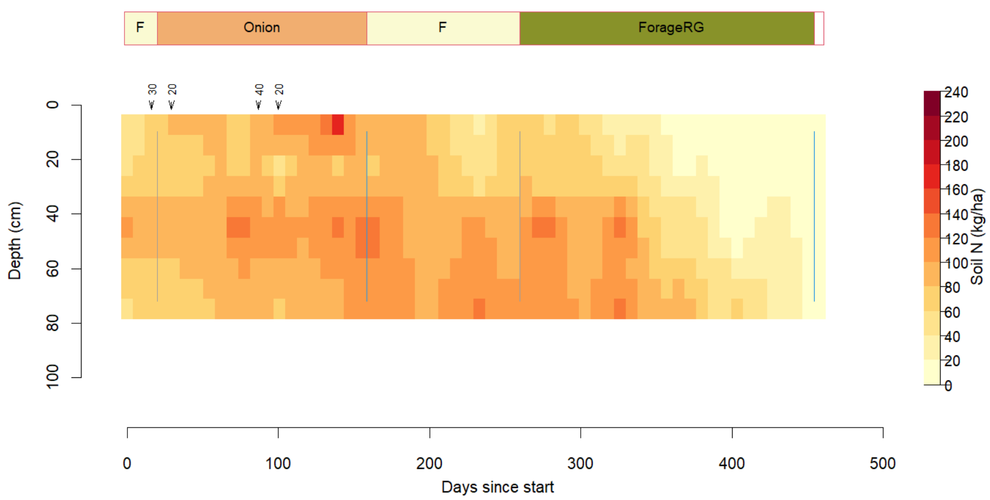

Figure A15. Soil nitrate across depth and time for the N4 treatment of Rotation 3 grown at The New Zealand Institute for Plant and Food Research Limited, Havelock North research site, Hawke's Bay. Crop durations are shown and black arrows indicate fertiliser application.

Rotation 4

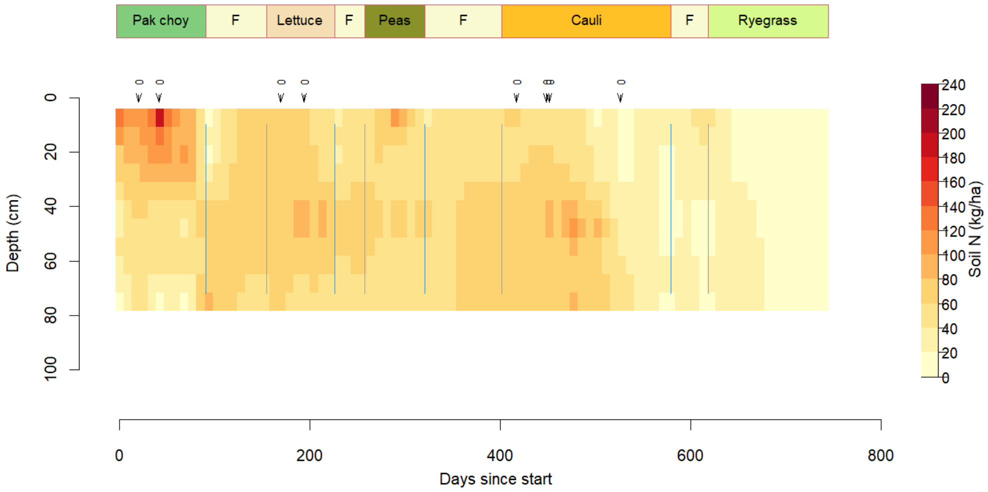

Figure A16. Soil nitrate across depth and time for the N1 treatment of Rotation 4 grown at The New Zealand Institute for Plant and Food Research Limited, Havelock North research site, Hawke's Bay. Crop durations are shown and black arrows indicate fertiliser application.

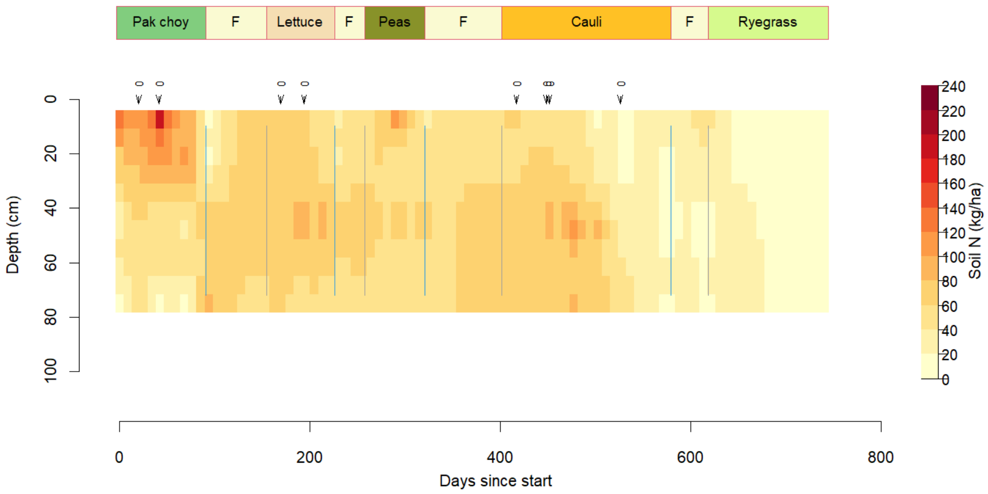

Figure A17. Soil nitrate across depth and time for the N2 treatment of Rotation 4 grown at The New Zealand Institute for Plant and Food Research Limited, Havelock North research site, Hawke's Bay. Crop durations are shown and black arrows indicate fertiliser application.

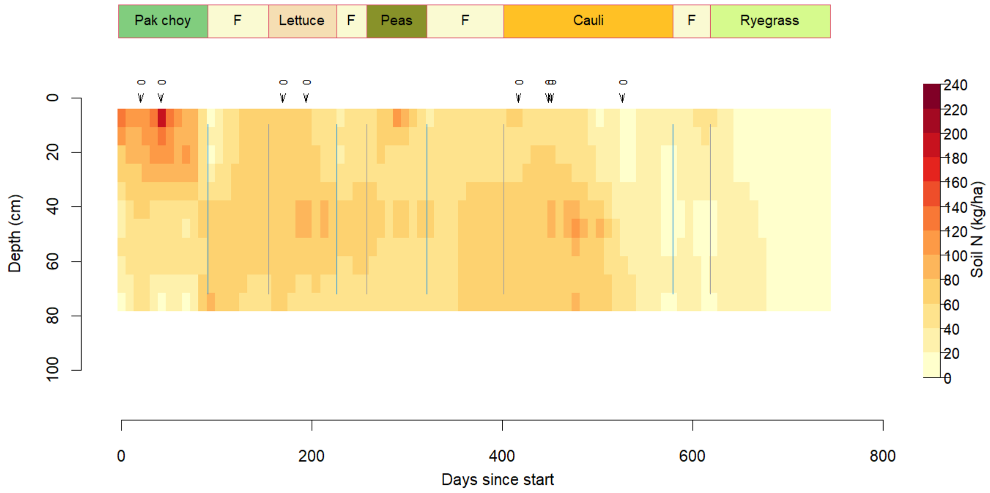

Figure A18. Soil nitrate across depth and time for the N3 treatment of Rotation 4 grown at The New Zealand Institute for Plant and Food Research Limited, Havelock North research site, Hawke's Bay. Crop durations are shown and black arrows indicate fertiliser application.

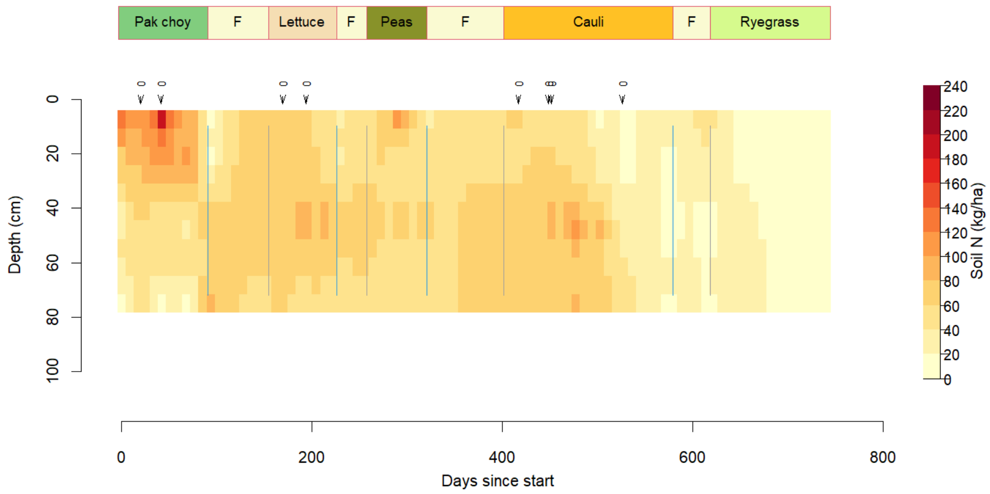

Figure A19. Soil nitrate across depth and time for the N4 treatment of Rotation 4 grown at The New Zealand Institute for Plant and Food Research Limited, Havelock North research site, Hawke's Bay. Crop durations are shown and black arrows indicate fertiliser application.

Appendix 5. Soil nitrogen content across time and depth in Workstream 2

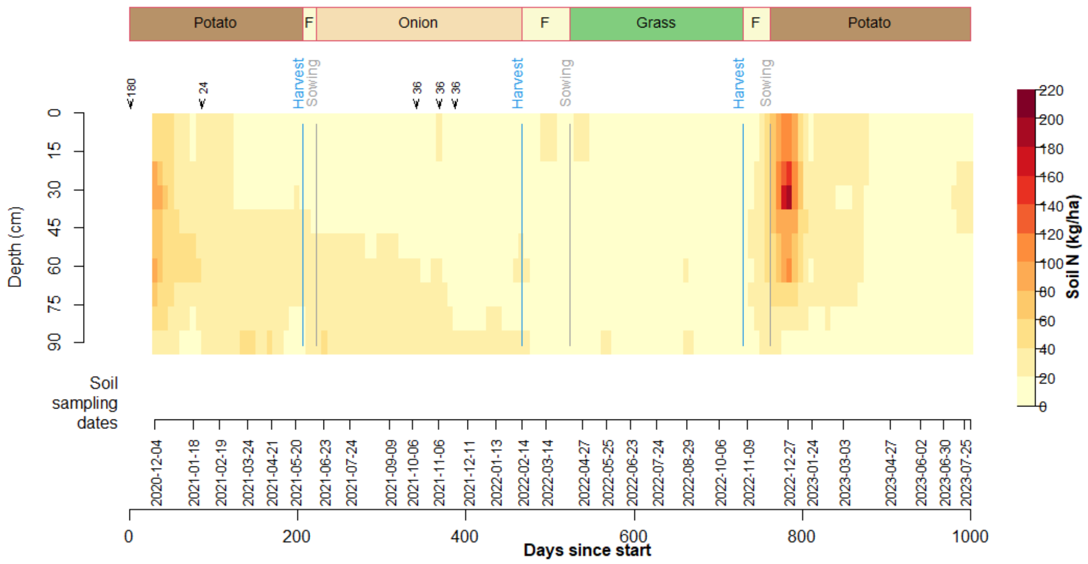

Figure A20. Soil nitrate across depth and time for Site 1. Crop durations are shown and black. Arrows indicate fertiliser application.

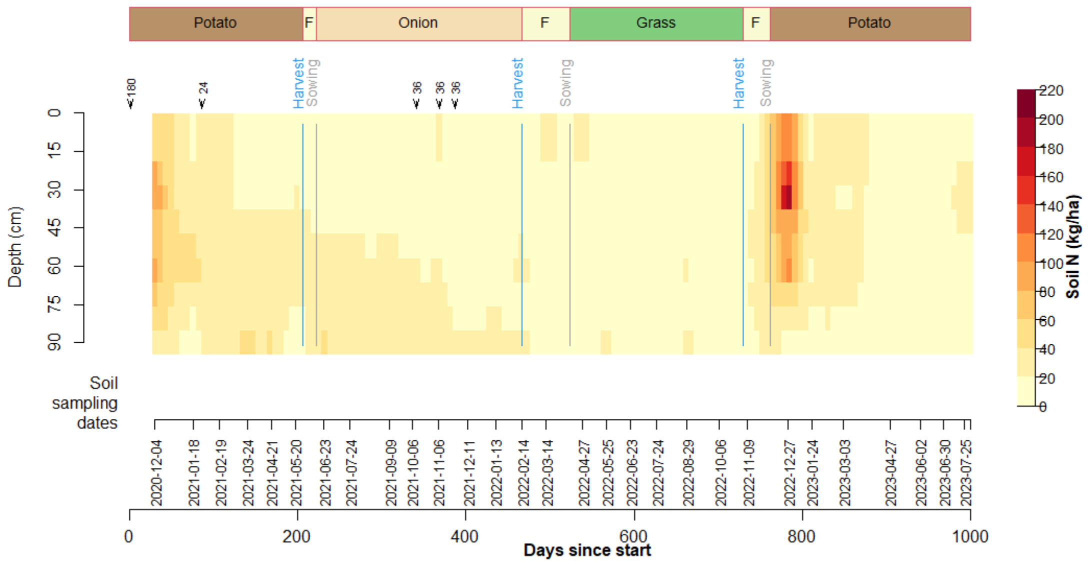

Figure A21. Soil nitrate across depth and time for Site 2. Crop durations are shown and black. Arrows indicate fertiliser application.

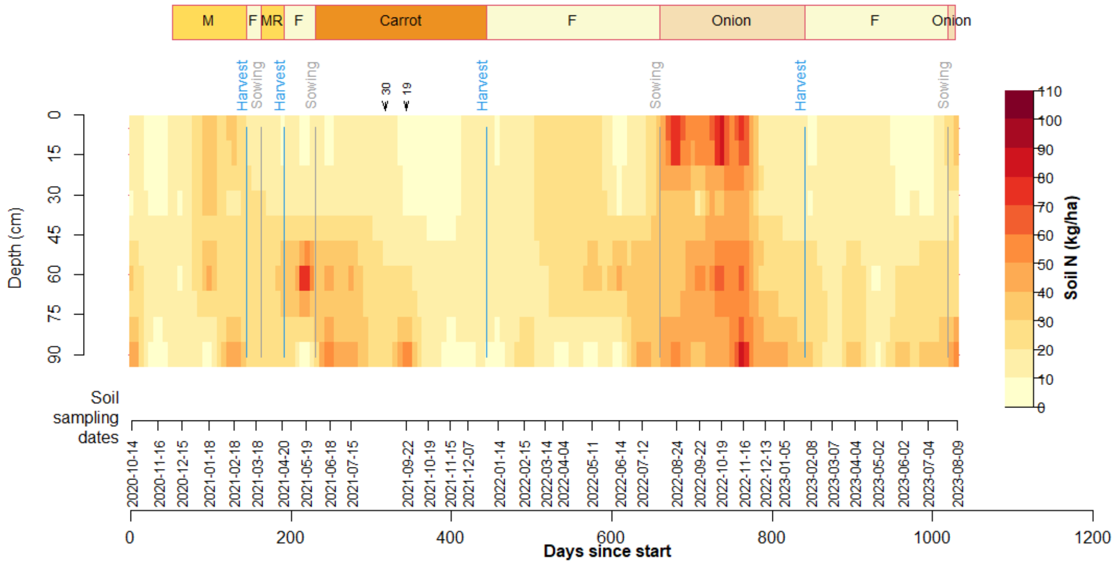

Figure A22. Soil nitrate across depth and time for Site 3. Crop durations are shown and black. Arrows indicate fertiliser application.

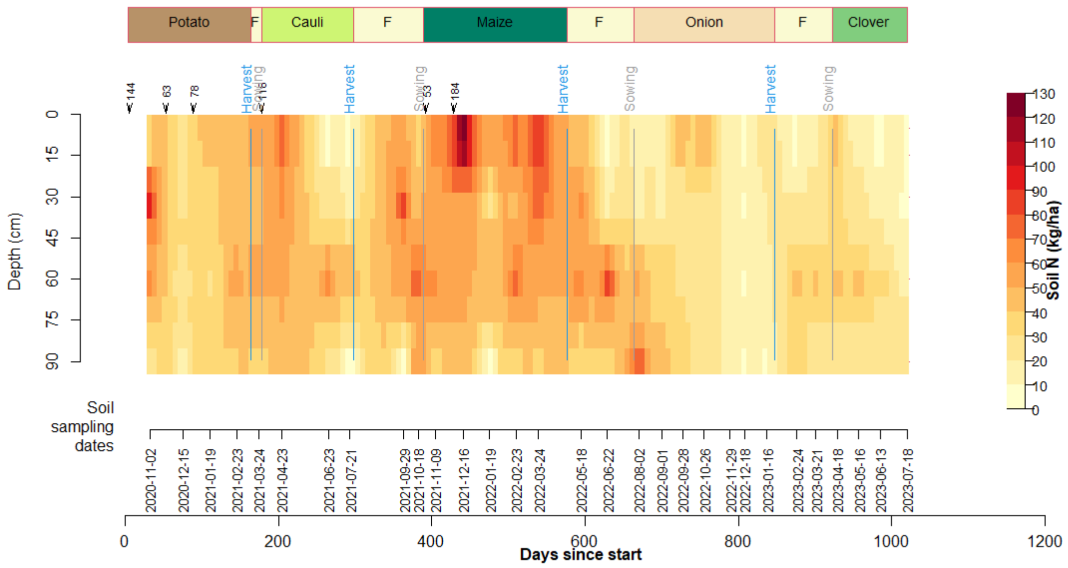

Figure A23. Soil nitrate across depth and time for Site 4. Crop durations are shown and black. Arrows indicate fertiliser application.

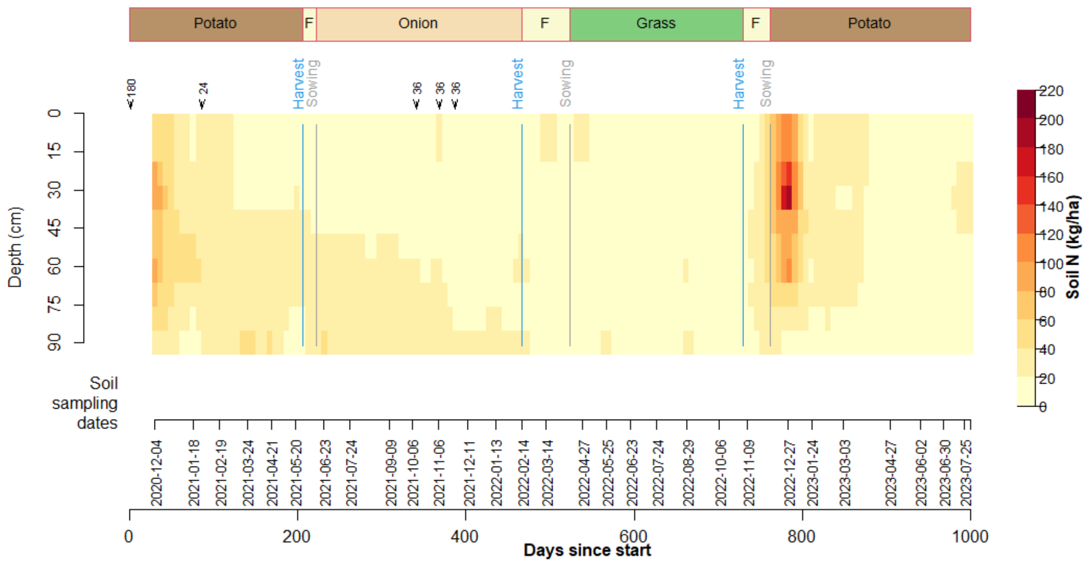

Figure A24. Soil nitrate across depth and time for Site 5. Crop durations are shown and black. Arrows indicate fertiliser application.

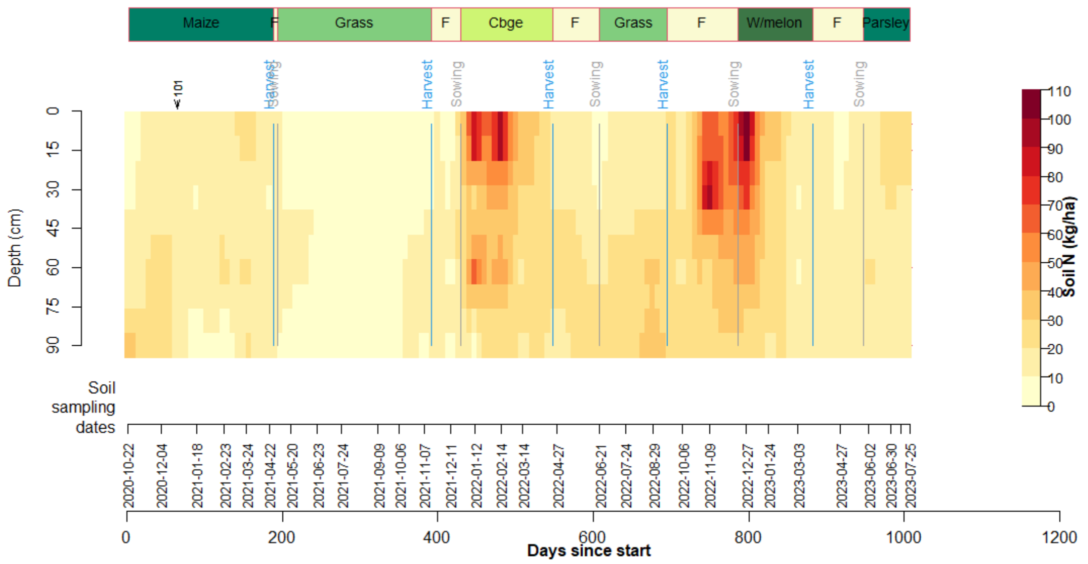

Figure A25. Soil nitrate across depth and time for Site 6. Crop durations are shown and black. Arrows indicate fertiliser application.

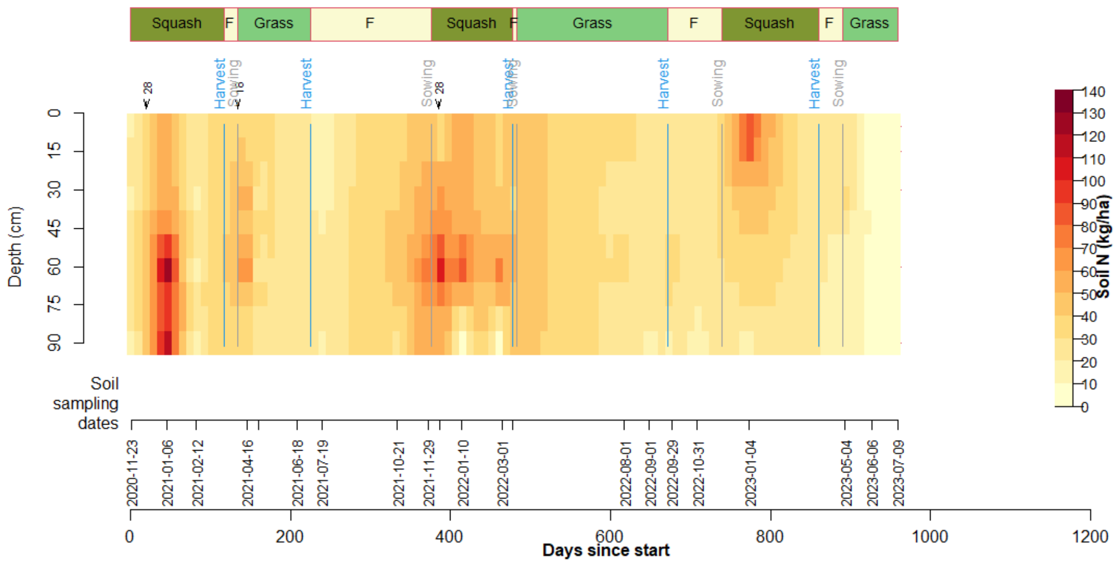

Figure A26. Soil nitrate across depth and time for Site 6. Crop durations are shown and black. Arrows indicate fertiliser application.

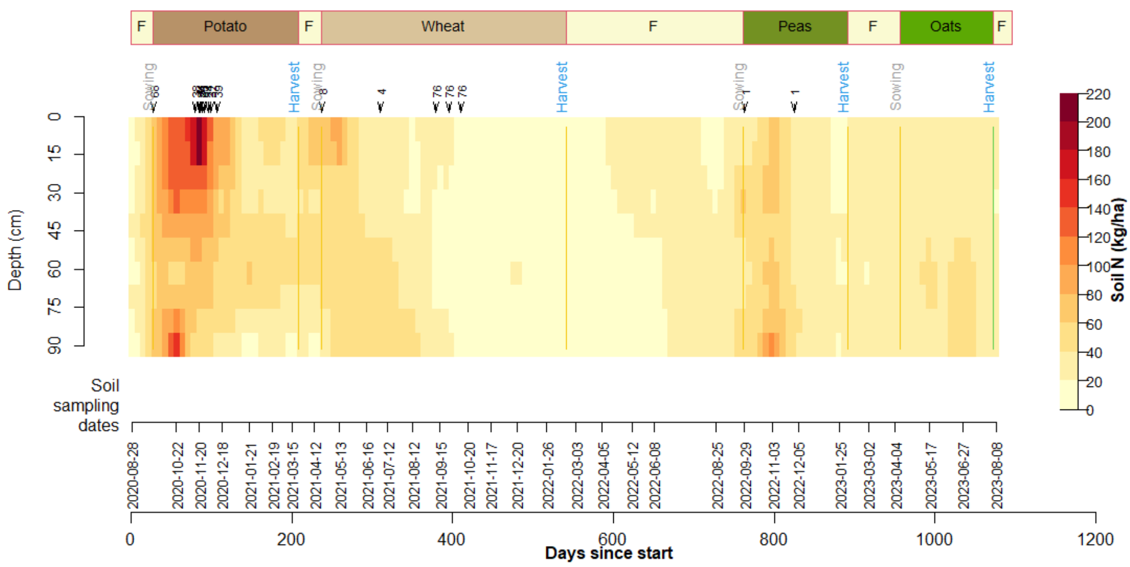

Figure A27. Soil nitrate across depth and time for Site 8. Crop durations are shown and black. Arrows indicate fertiliser application.

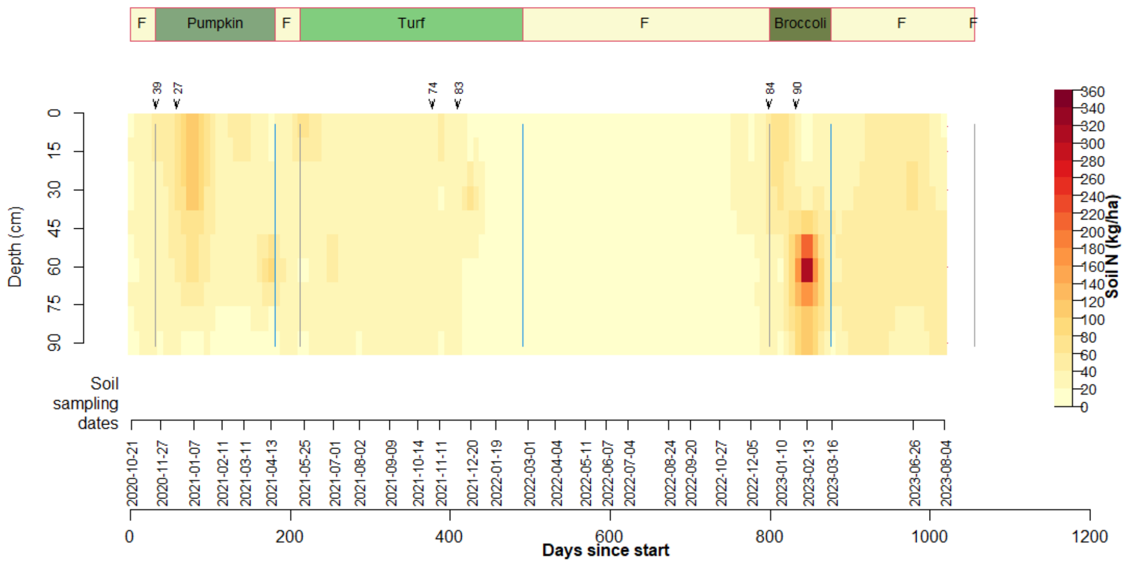

Figure A28. Soil nitrate across depth and time for Site 9. Crop durations are shown and black. Arrows indicate fertiliser application.

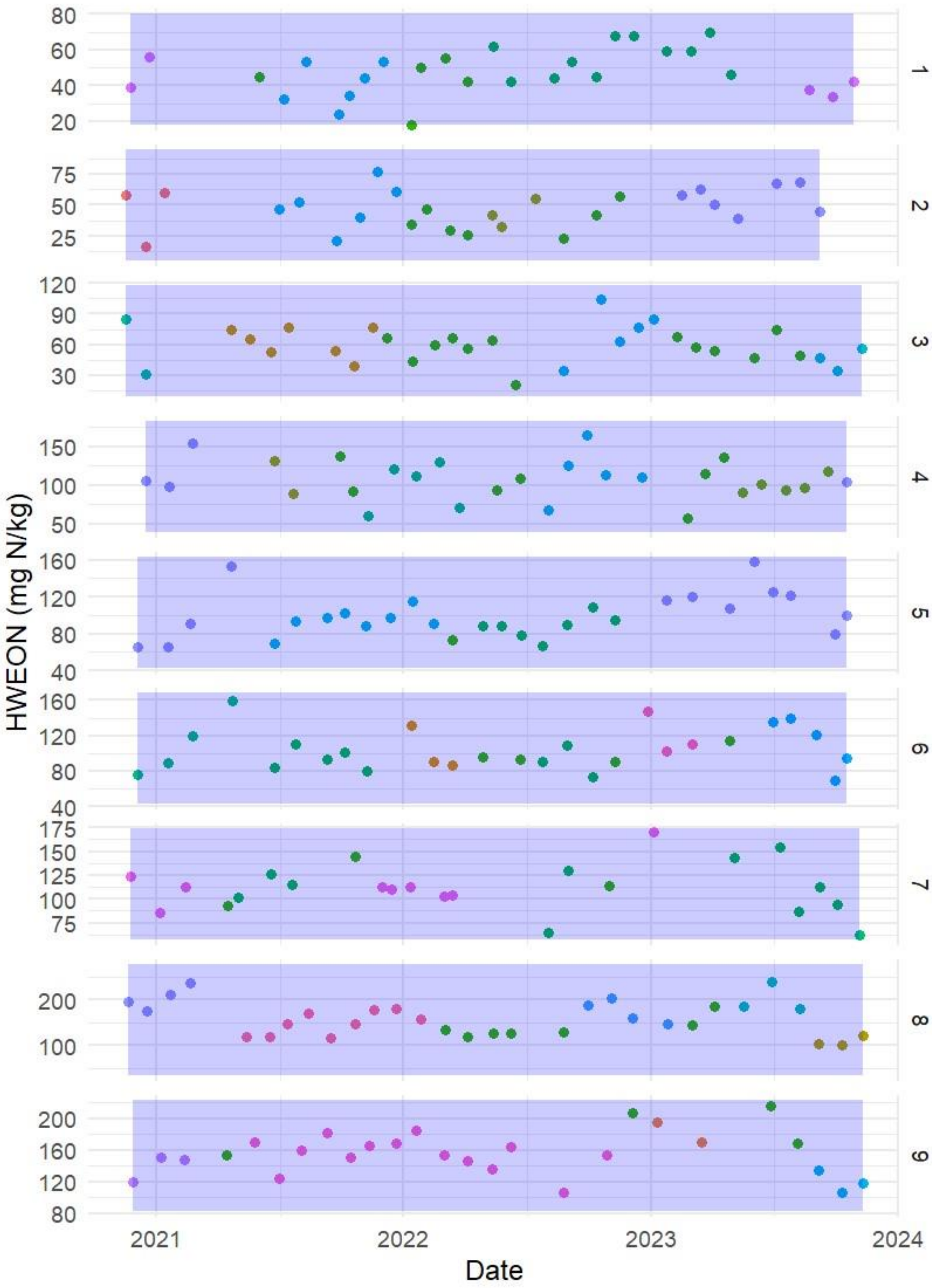

Figure A29. HWEON (Hot water extractable organic nitrogen) for the 0–30 cm layer of soil measured across the rotation period of the different sites in Workstream 2 (WS2). Sites were commercial fields in different regions of the country. The greyed ribbon indicates the range observed. Points are coloured to highlight the different crops in the rotation.

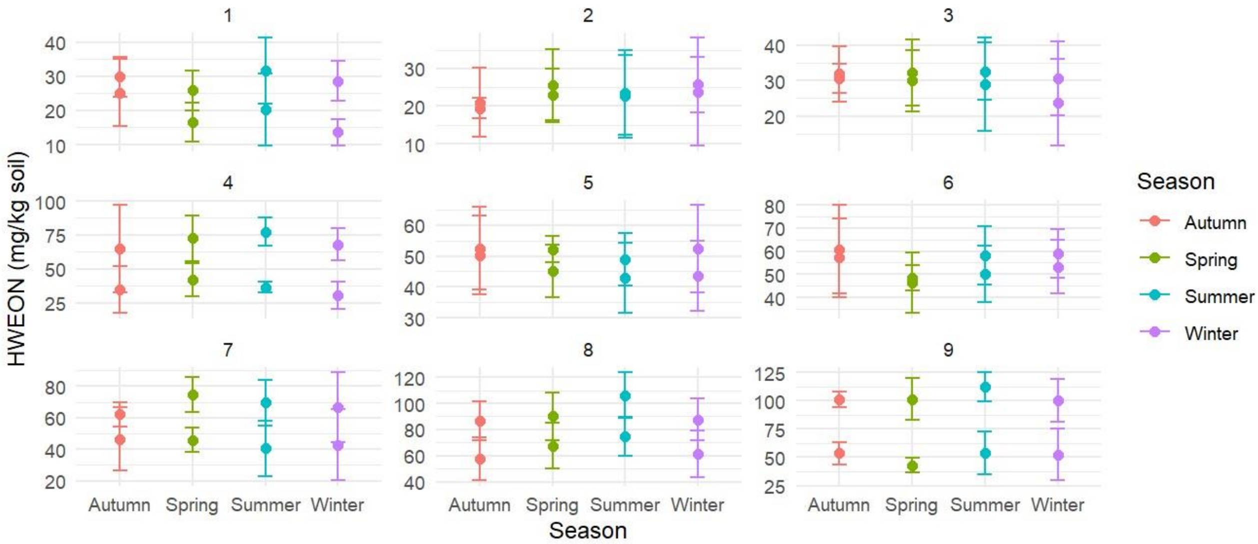

Figure A30. Variation in hot water extractable organic nitrogen (HWEON) with season for different commercial sites where crops were grown for Workstream (WS) 2. Averages with 95% CI are shown. Much lower CI's should be expected based on comparison with lower variability in WS1 data (Section 3.1.3). No significant difference between Season or interaction with Site was found.

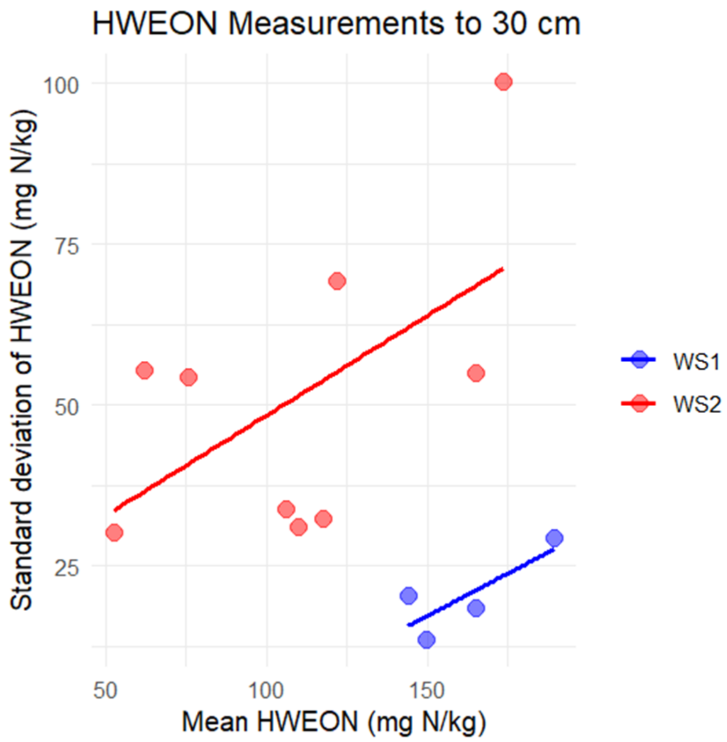

Figure A31. Relationship between mean values of hot water extractable organic nitrogen (HWEON) in the 0–30 cm soil profile, and standard deviation for Rotations in Workstream (WS)1 and fields in WS2.

The standard deviation is much higher in the Workstream (WS)2 data compared to the WS1 data (Figure A31). If variation in hot water extractable organic nitrogen (HWEON) values were similar, then all points would fall around a single line. However, the data show that there was much less variation in samples collected in WS1 than WS2. There are many factors that might influence this (such as sampling and transport methodology, recent crop residue incorporation, recent fertiliser additions), Reasons for the difference cannot be determined from the data, but evaluation of testing and standardising methods used for determining HWEON would provide insight. This is a significant difference in variation, and not consistent with previous work (Beare et al. 2023). Reasons for this inconsistent variation need to be explored.

Data from WS1 indicates that appropriate sampling, handling and analysis leads to consistent results.

Appendix 6. Crop coefficients used in the model

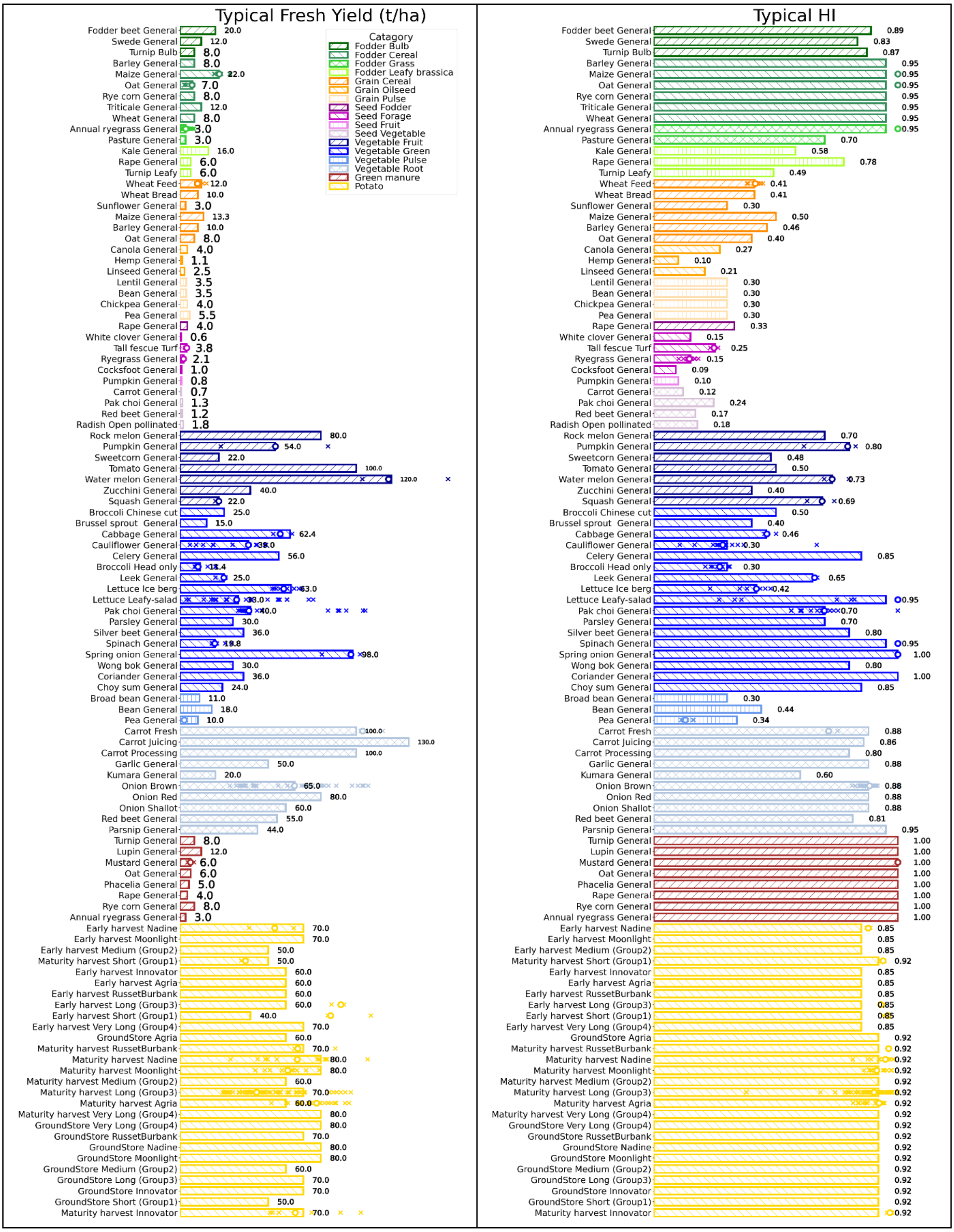

Figure A32. Typical fresh product yields (t/ha) and harvest index values for crops included in the Sustainable Vegetable Systems (SVS) tool. Where values were measured in SVS they are plotted as a ‘x’ against the respective crop and the median value of observations is plotted as a ‘o’.

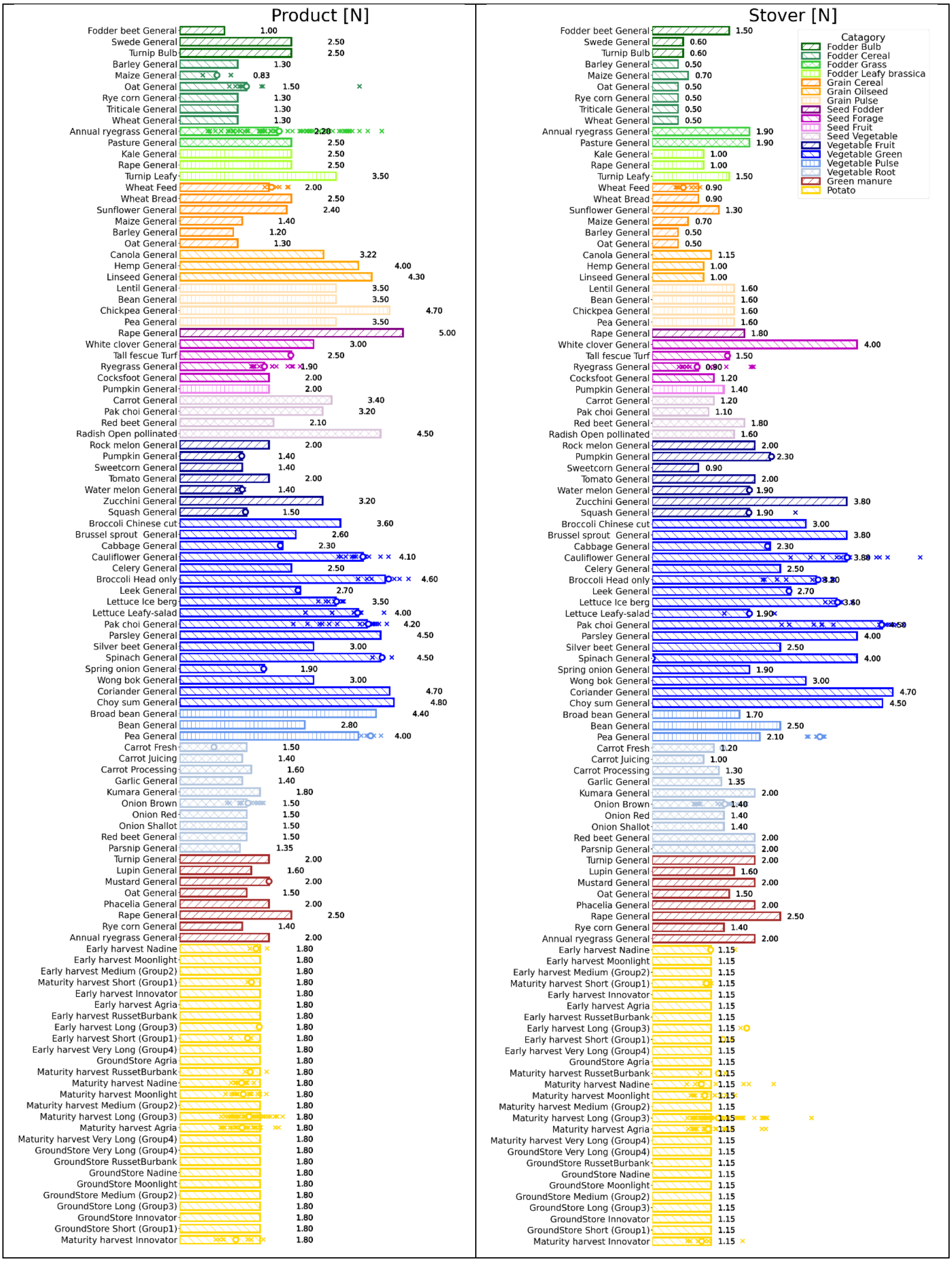

Figure A33. Nitrogen concentration (% N) in product and stover components for crops included in the Sustainable Vegetable Systems (SVS) tool. Where values were measured in SVS they are plotted as a ‘x’ against the respective crop and the median value of observations is plotted as a ‘o’.

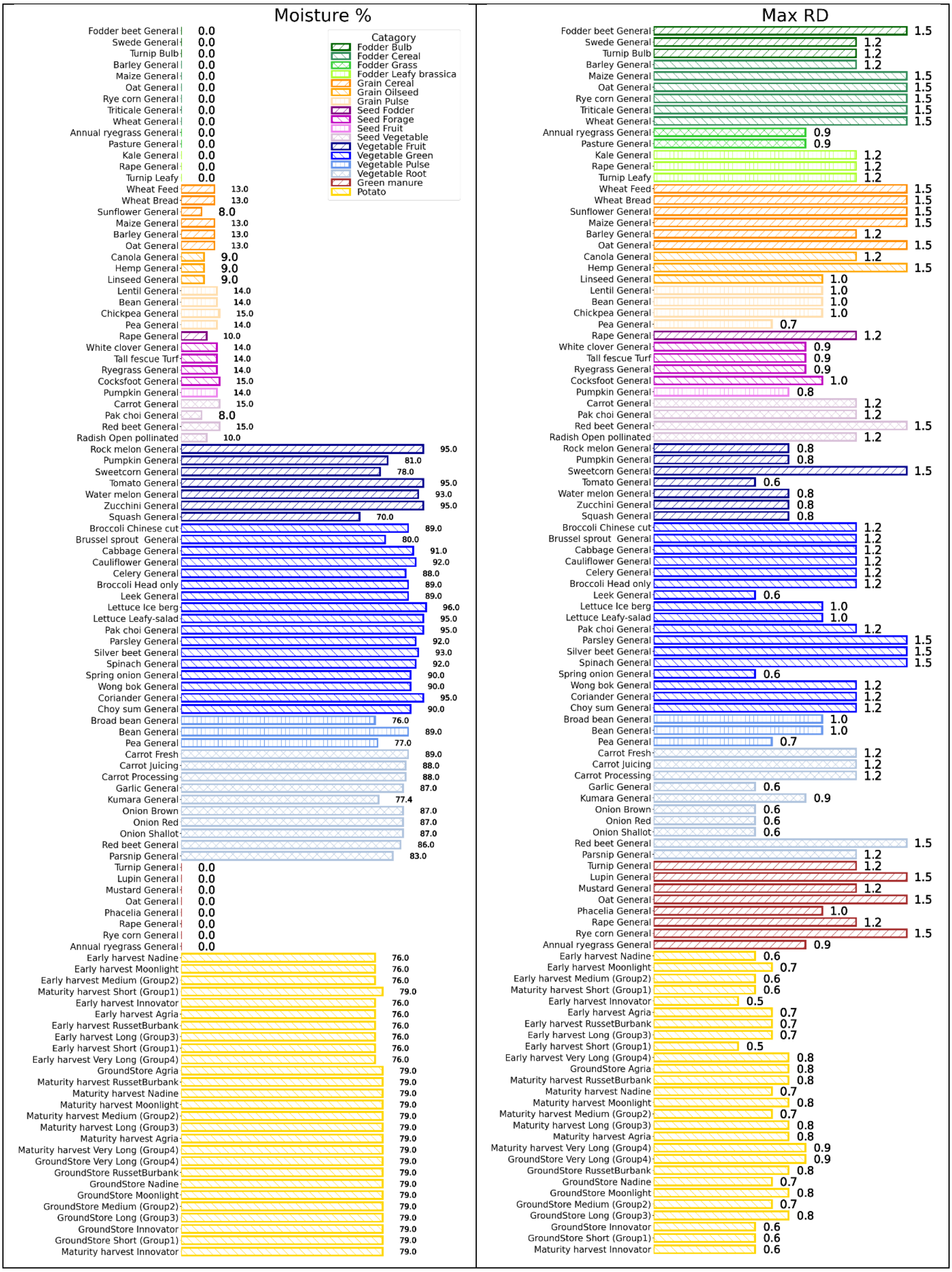

Figure A34. Moisture content and maximum rooting depth for crops included in the Sustainable Vegetable Systems (SVS) tool. Note that the SVS Tool models the nitrogen balance in the top 30 cm. The nitrogen (N) below 30 cm is part of the uncharacterised component in the budget. This is an area that has been identified as requiring further investigation, however it is considerably more complex and variable.

Appendix 7. N balance graphs for crops in Workstream 1

Rotation 1

Potato crop

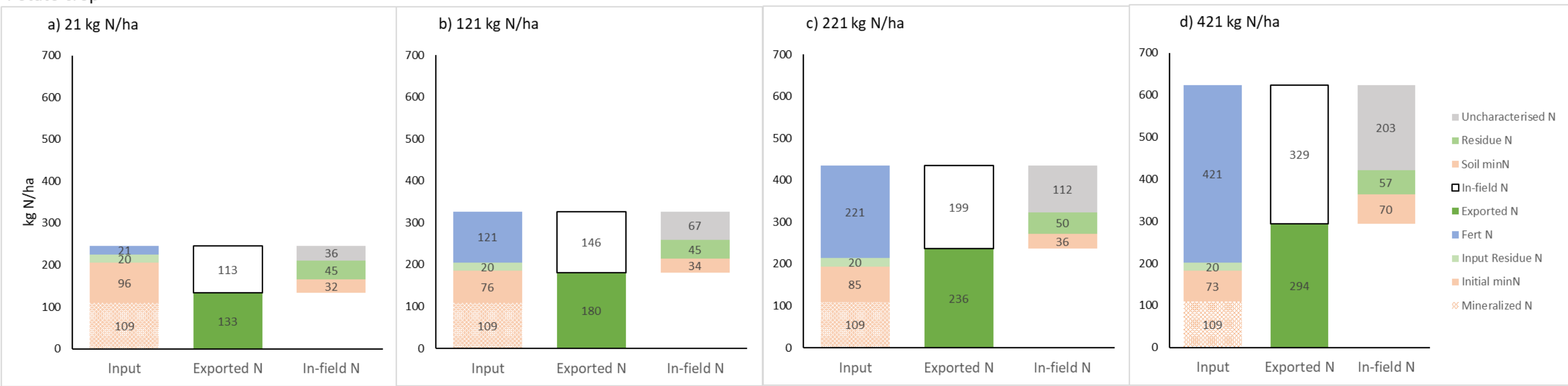

Figure A35. Nitrogen (N) balance graphs for potato crop of Rotation 1.

Wheat crop

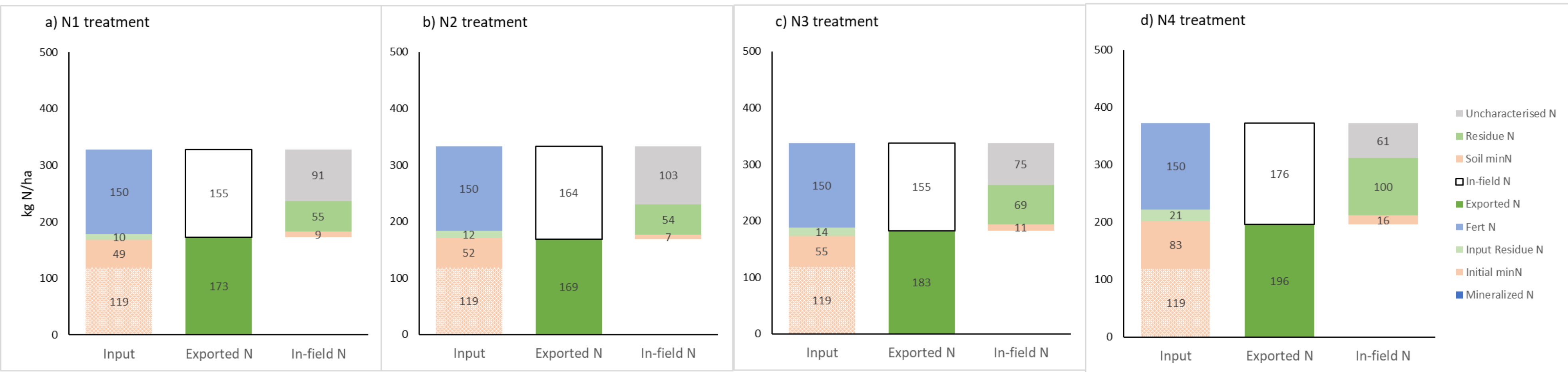

Figure A36. Nitrogen (N) balance graphs for wheat crop of Rotation 1.

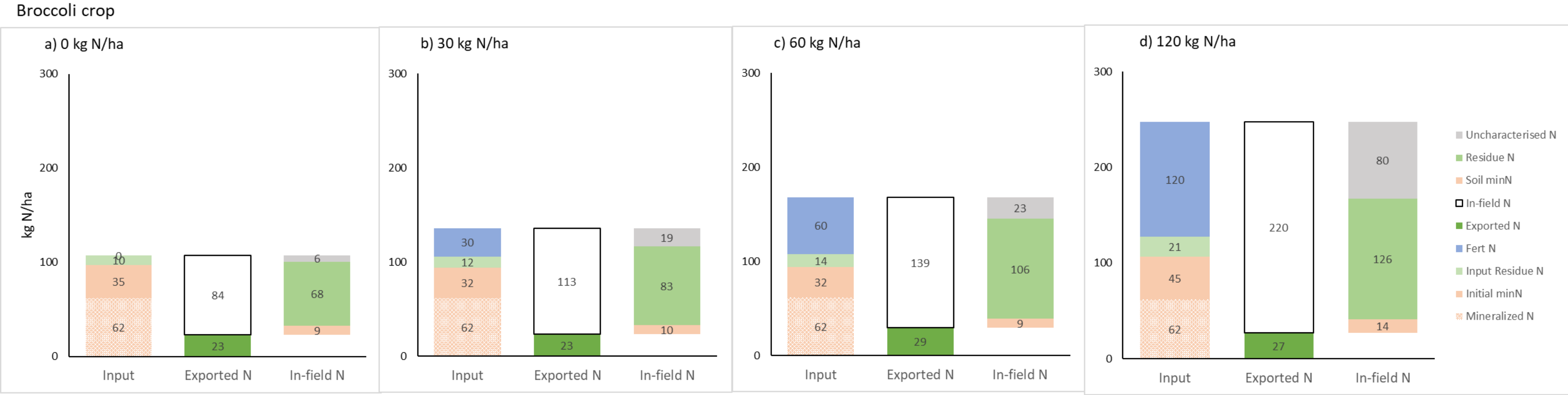

Figure A37. Nitrogen (N) balance graphs for broccoli crop of Rotation 1.

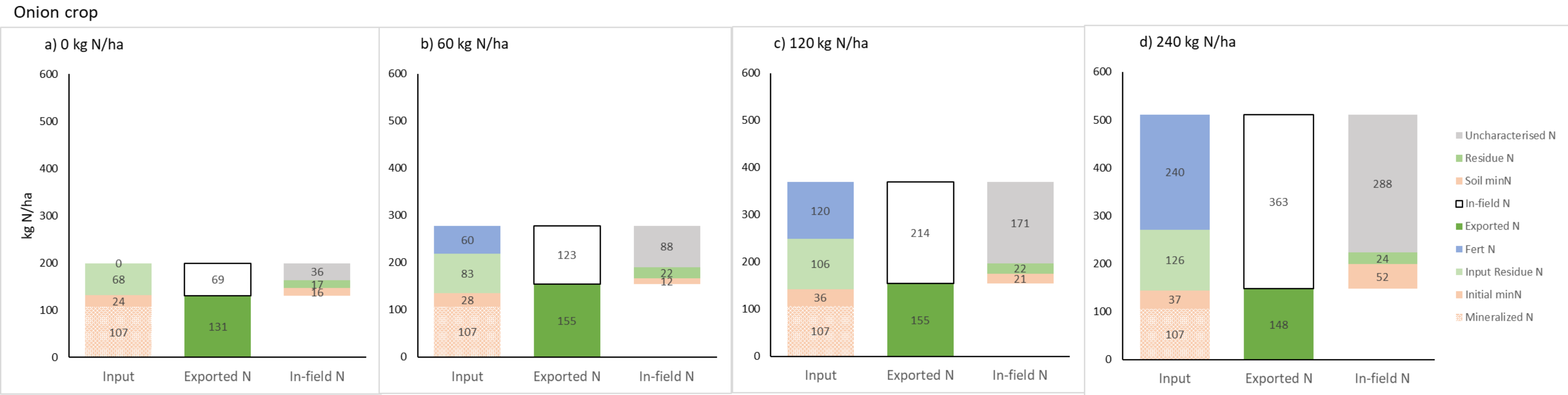

Figure A38. Nitrogen (N) balance graphs for onion crop of Rotation 1.

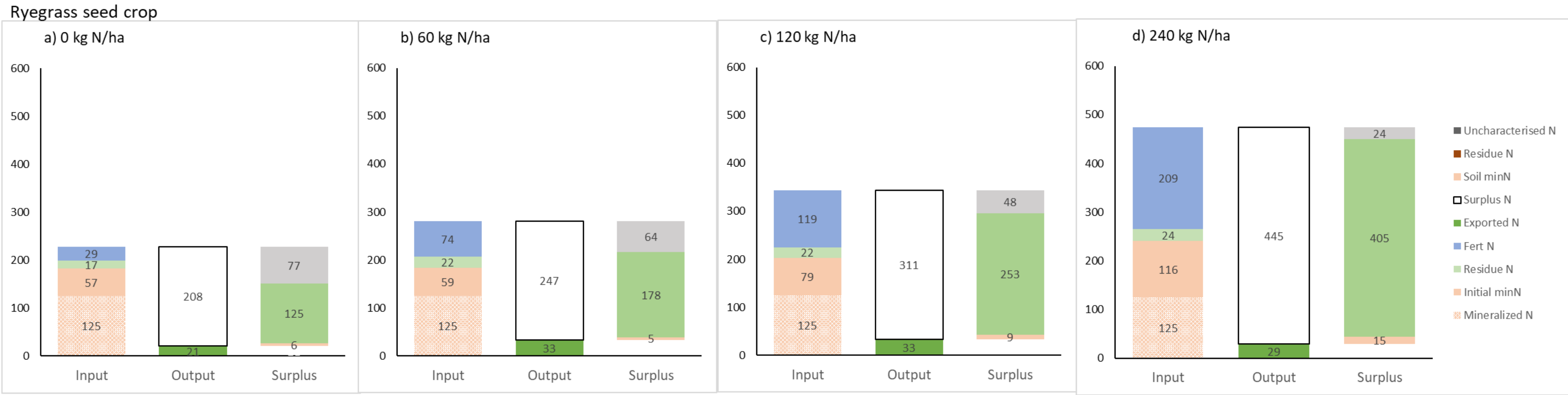

Figure A38. Nitrogen (N) balance graphs for ryegrass seed crop of Rotation 1.

Rotation 2

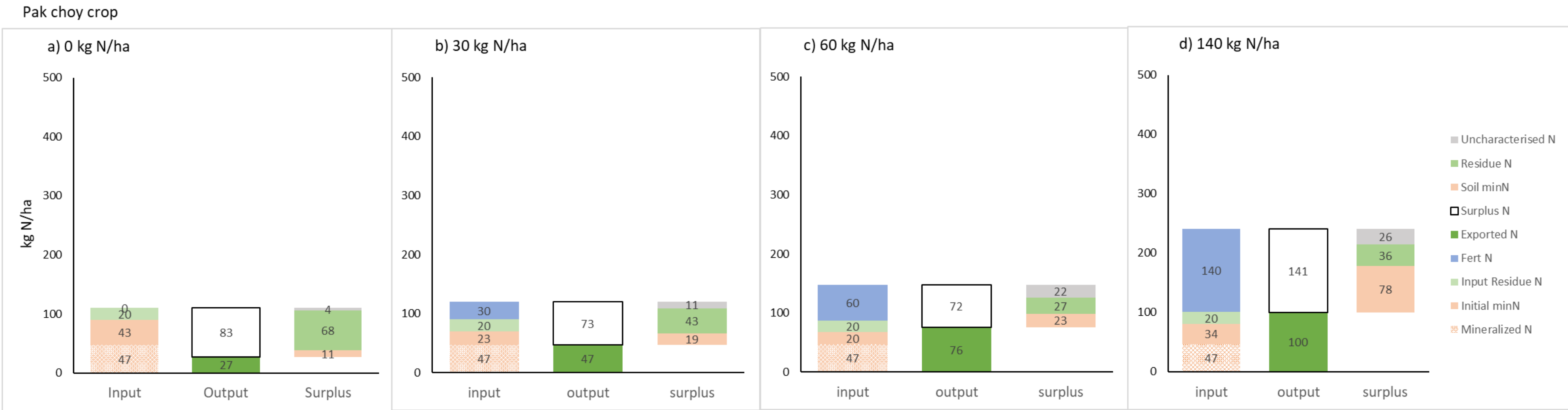

Figure A39. Nitrogen (N) balance graphs for pak choy crop of Rotation 2.

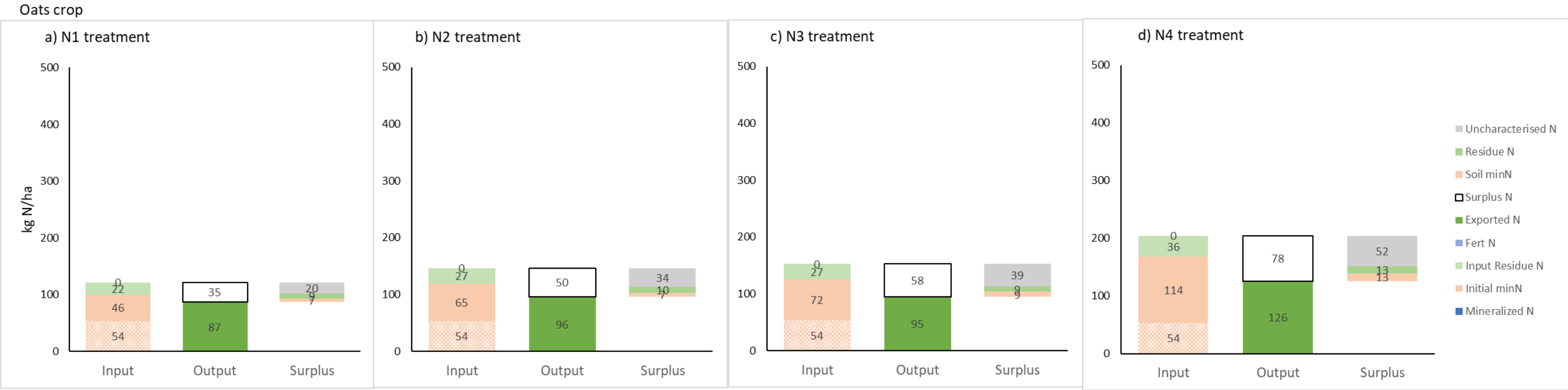

Figure A40. Nitrogen (N) balance graphs for oats crop of Rotation 2.

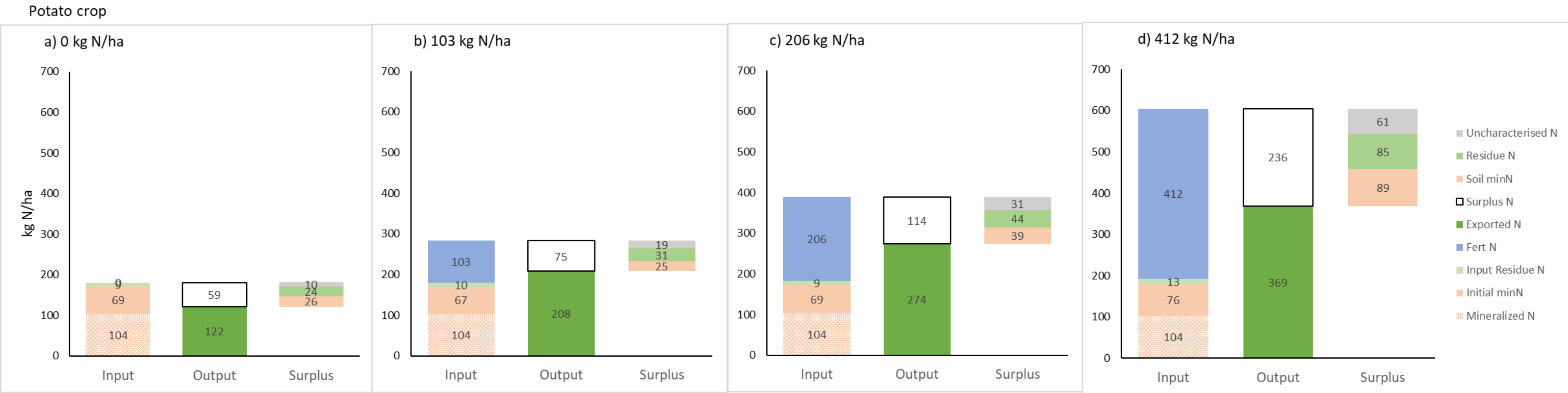

Figure A41. Nitrogen (N) balance graphs for potato crop of Rotation 2.

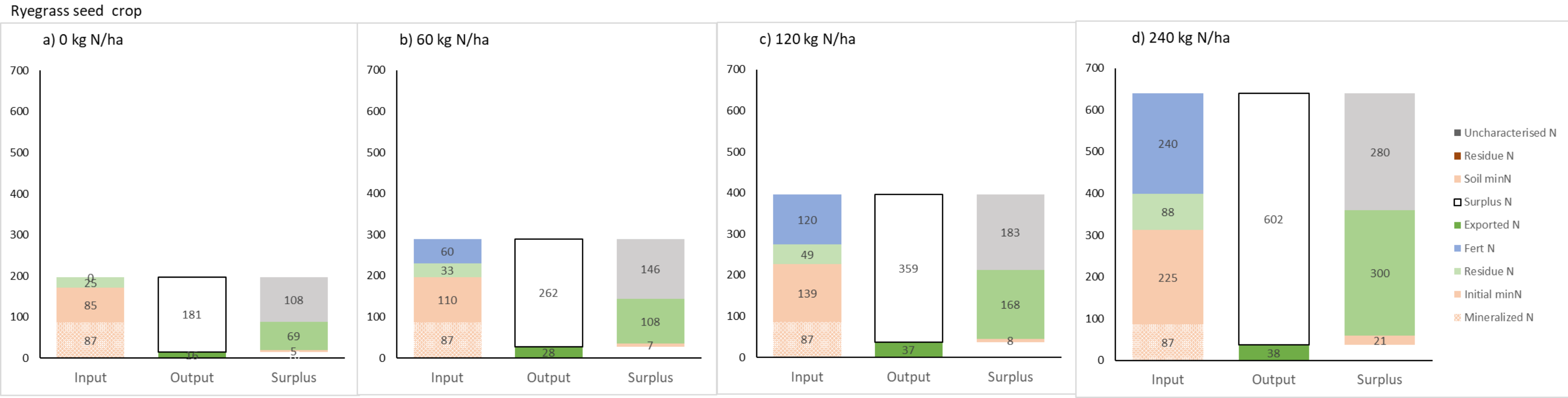

Figure A42. Nitrogen (N) balance graphs for ryegrass seed crop of Rotation 2.

Rotation 3

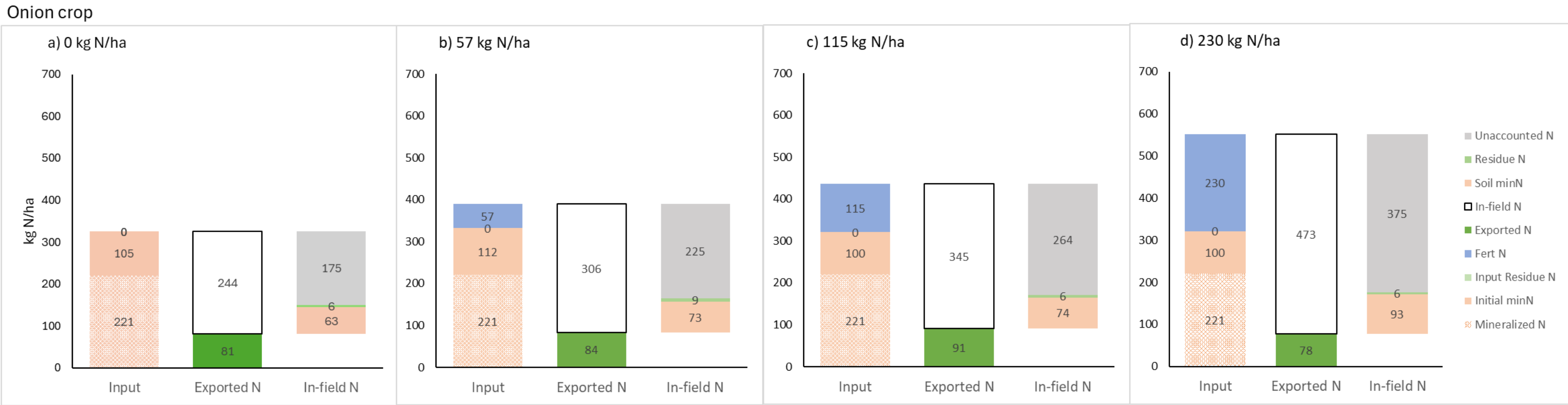

Figure A43. Nitrogen (N) balance graphs for onion crop of Rotation 3.

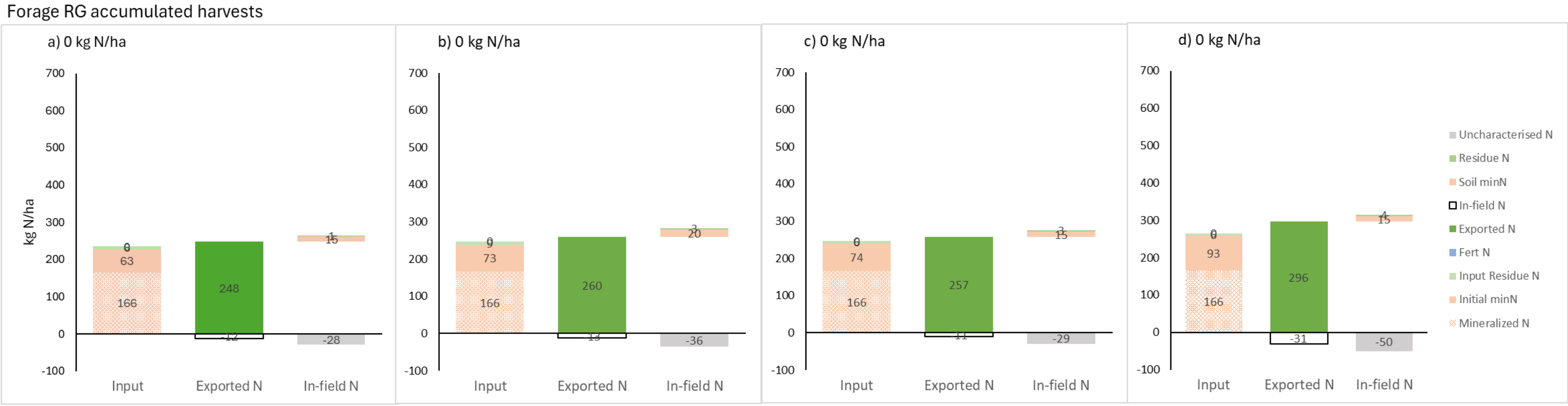

Figure A44. Nitrogen (N) balance graphs for ryegrass forage crop accumulated across all harvests of Rotation 3.

Rotation 4

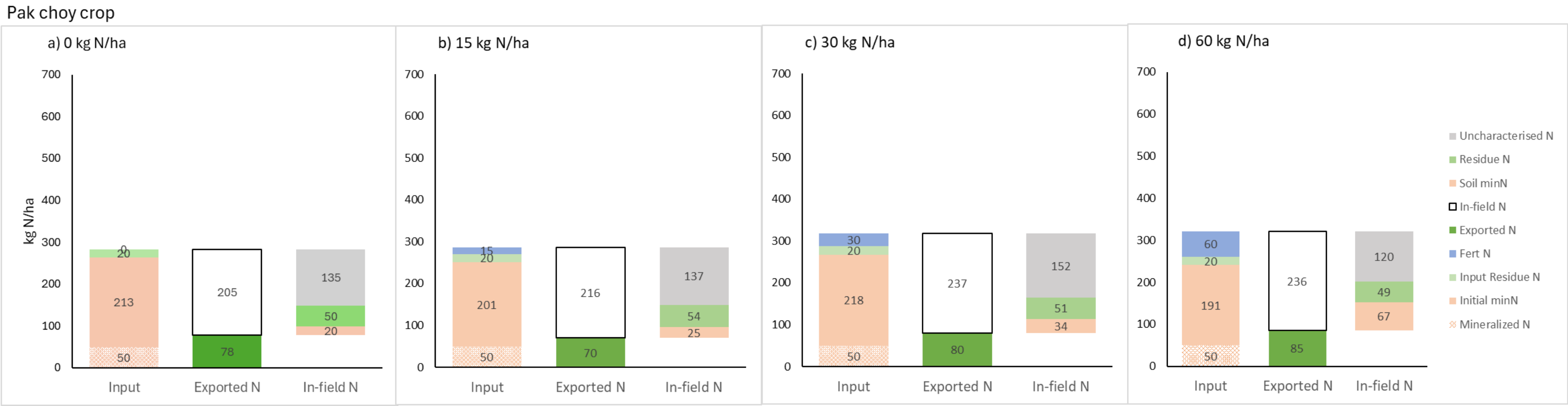

Figure A45. Nitrogen (N) balance graphs for pak choy crop of Rotation 4.

Lettuce crop

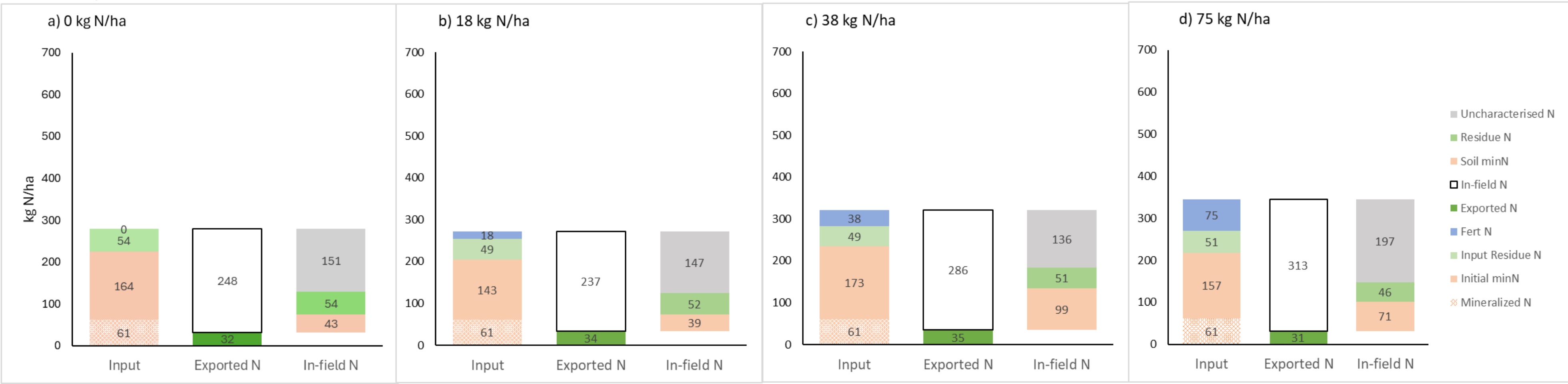

Figure A46. Nitrogen (N) balance graphs for lettuce crop of Rotation 4.

Pea crop

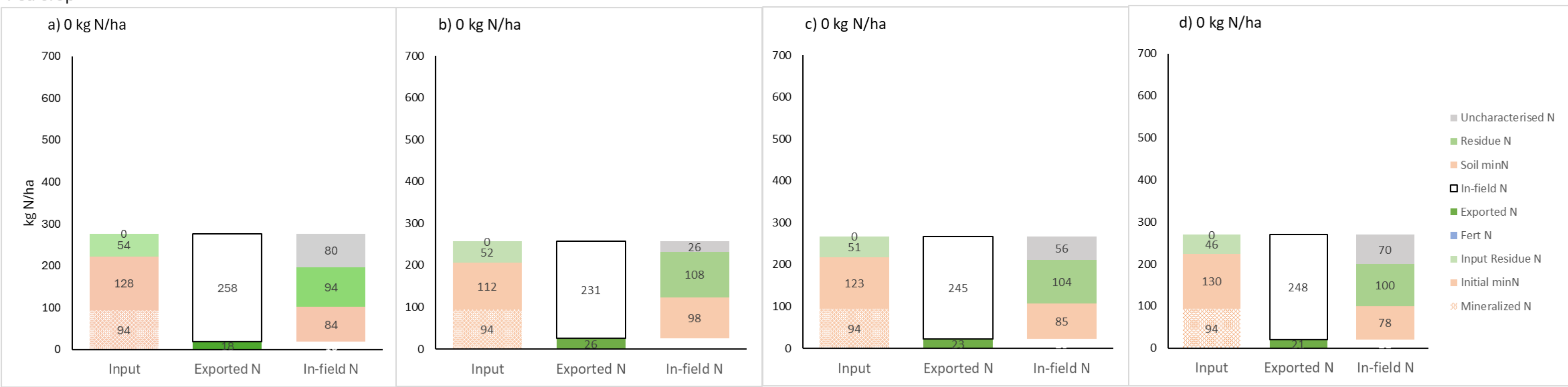

Figure A47. Nitrogen (N) balance graphs for pea crop of Rotation 4.

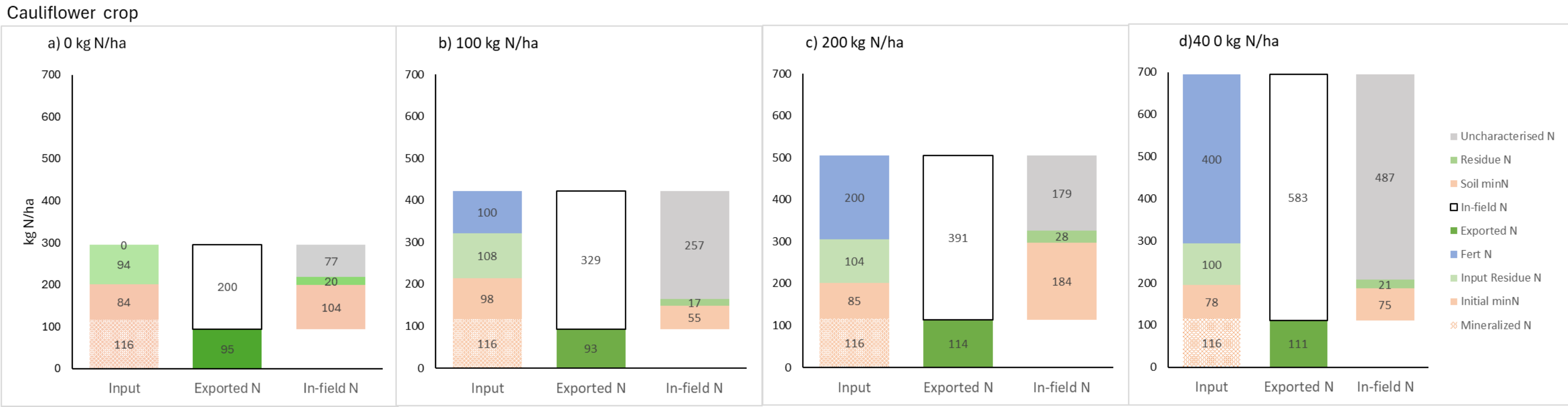

Figure A48. Nitrogen (N) balance graphs for cauliflower crop of Rotation 4.

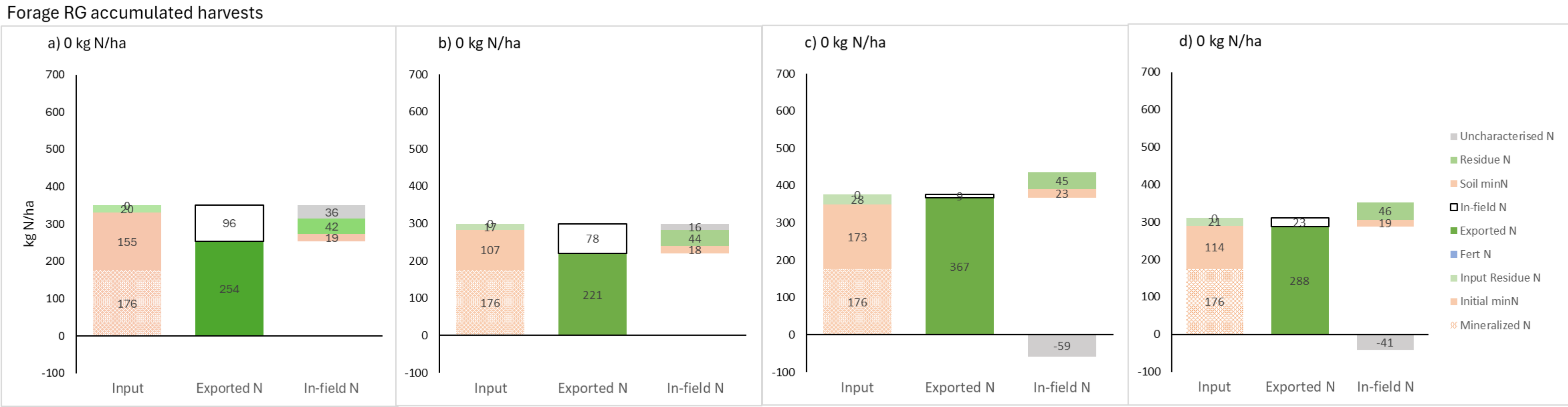

Figure A49. Nitrogen (N) balance graphs for ryegrass forage crop accumulated across all harvests of Rotation 4.

Appendix 8. Model fitting of Workstream 2

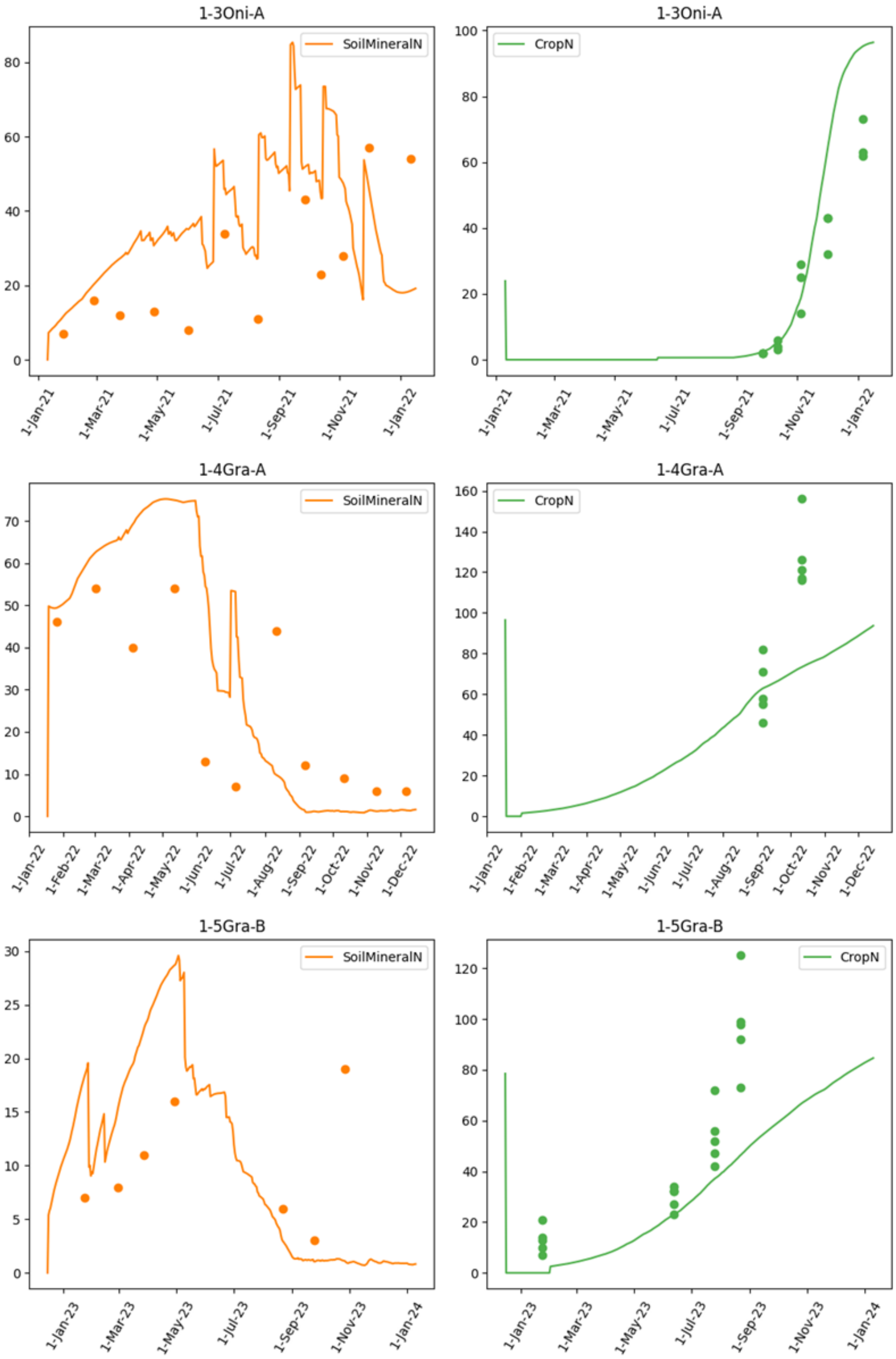

Figure A50. Site 1. The model over predicted in the nitrogen (N) uptake in the onion crop by about 20 kg/ha but then appeared to under predict the N uptake in the two following grass crops. The grass crops were not fertilised, and the model predicted low soil N contents toward the end of each crop which could be due to an over prediction of N loss or and under prediction of N from soil mineralisation. Plots on the left are soil mineral N levels, plots on the right are crop N uptake. Lines indicate predicted values and dots indicate measured values. Colours red, orange, green and blue represent N treatments N0, N1, N2, and N3 respectively. Units are in kg N/ha.

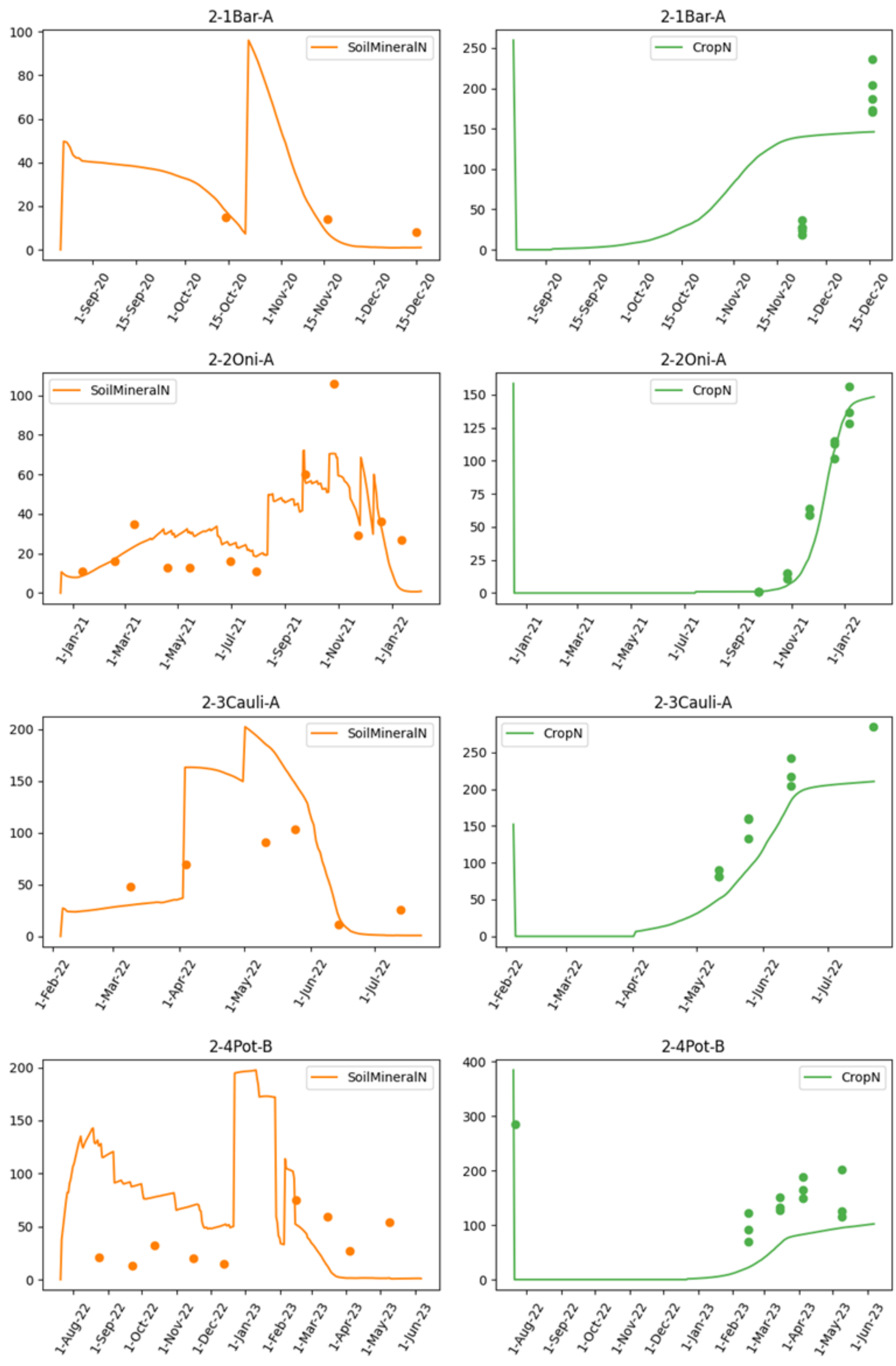

Figure A51 Site 2. There was good agreement at this site except for the cauliflower and potato crop nitrogen (N) uptake was under predicted by about 50kg/ha. In both cases we see a flattening off of the N uptake curve which means uptake was constrained by lack of N supply in the soil. This could be due to an under prediction of N entering the system from mineralisation or an over prediction of N losses leaving the system. Plots on the left are soil mineral N levels, plots on the right are crop N uptake. Lines indicate predicted values and dots indicate measured values. Units are in kg N/ha.

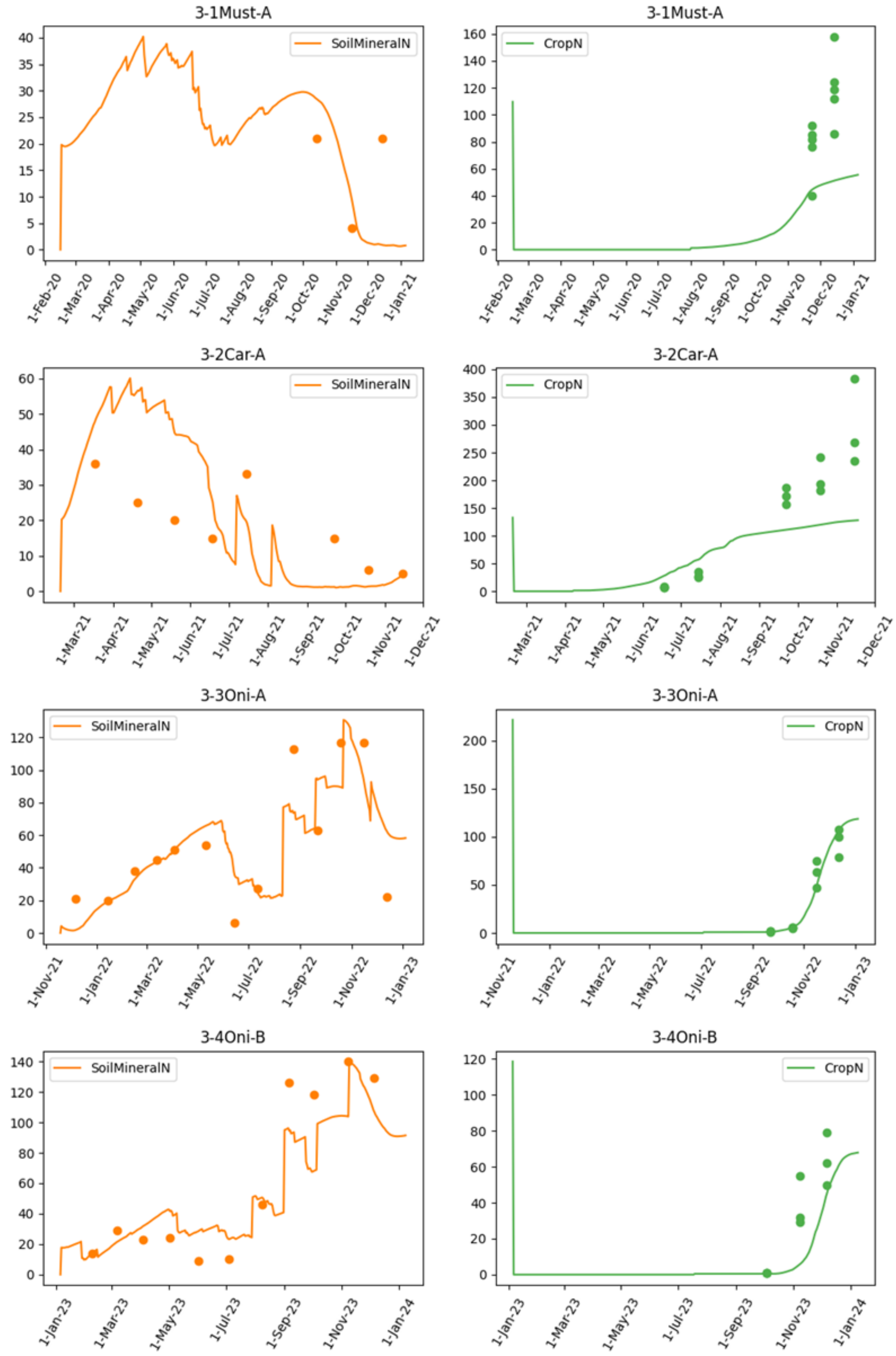

Figure A52. Site 3. The model performed well for the two onion crops measured at this location but under predicted nitrogen (N) uptake for the mustard and carrot crops due to lack of N in the soil. This could be due to an under prediction of inputs from mineralisation or an over prediction of losses. Plots on the left are soil mineral N levels, plots on the right are crop N uptake. Lines indicate predicted values and dots indicate measured values. Units are in kg N/ha.

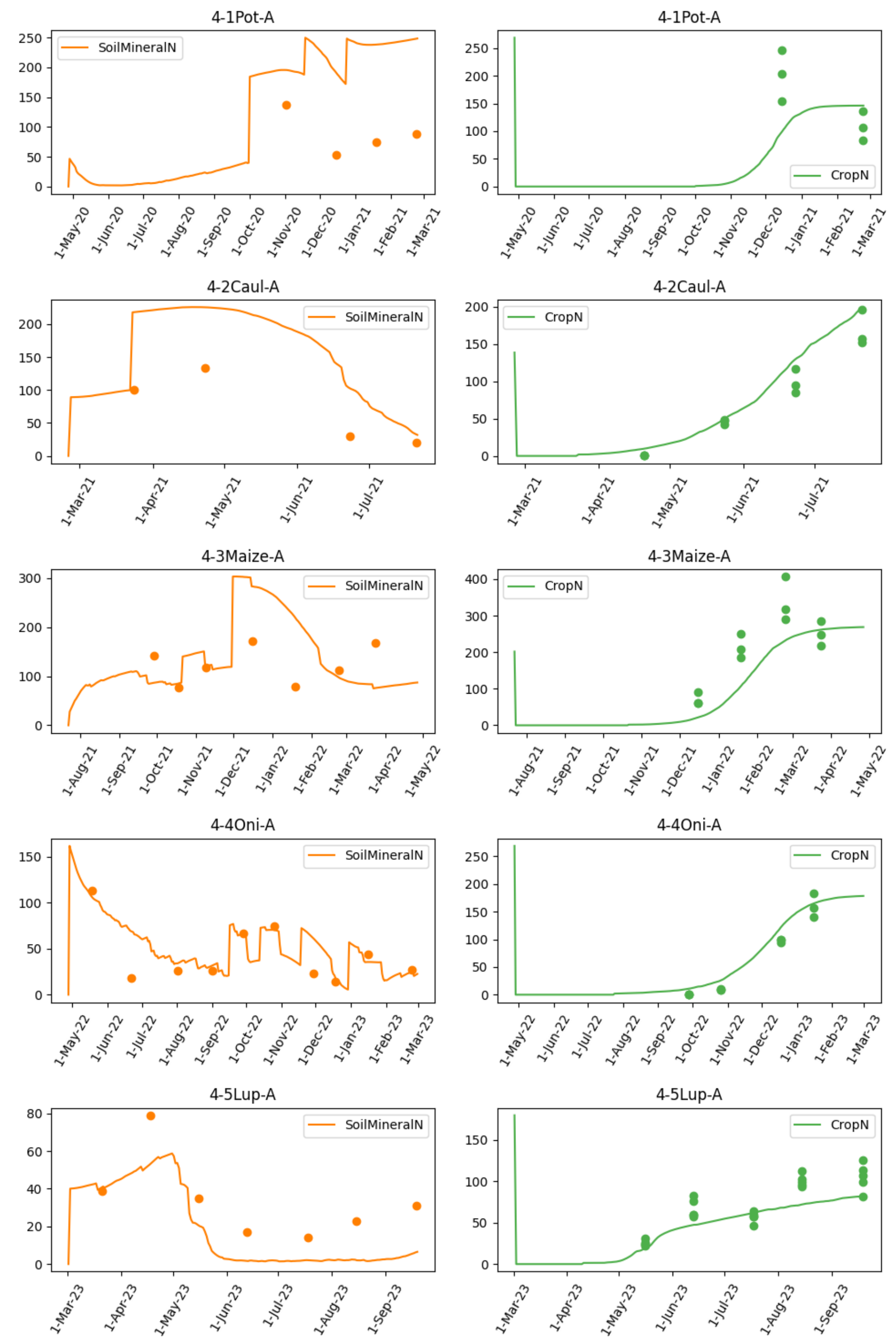

Figure A53. Site 4. The model performed well at this location. Plots on the left are soil mineral N levels, plots on the right are crop N uptake. Lines indicate predicted values and dots indicate measured values. Units are in kg N/ha.

Figure A54. Site 5. The model performed well at this location except for an over prediction of early nitrogen (N) uptake by the first potato crop and an under prediction of early N uptake by the grass crop. We are unclear what caused the under prediction in the potato crop but the observed pattern of uptake is not consistent with other potato crops measured so there may have been a problem with the sampling protocol. The grass crop was continuously grazed and it was not possible to configure the model to represent this in a realistic way. Plots on the left are soil mineral N levels, plots on the right are crop N uptake. Lines indicate predicted values and dots indicate measured values. Units are in kg N/ha.

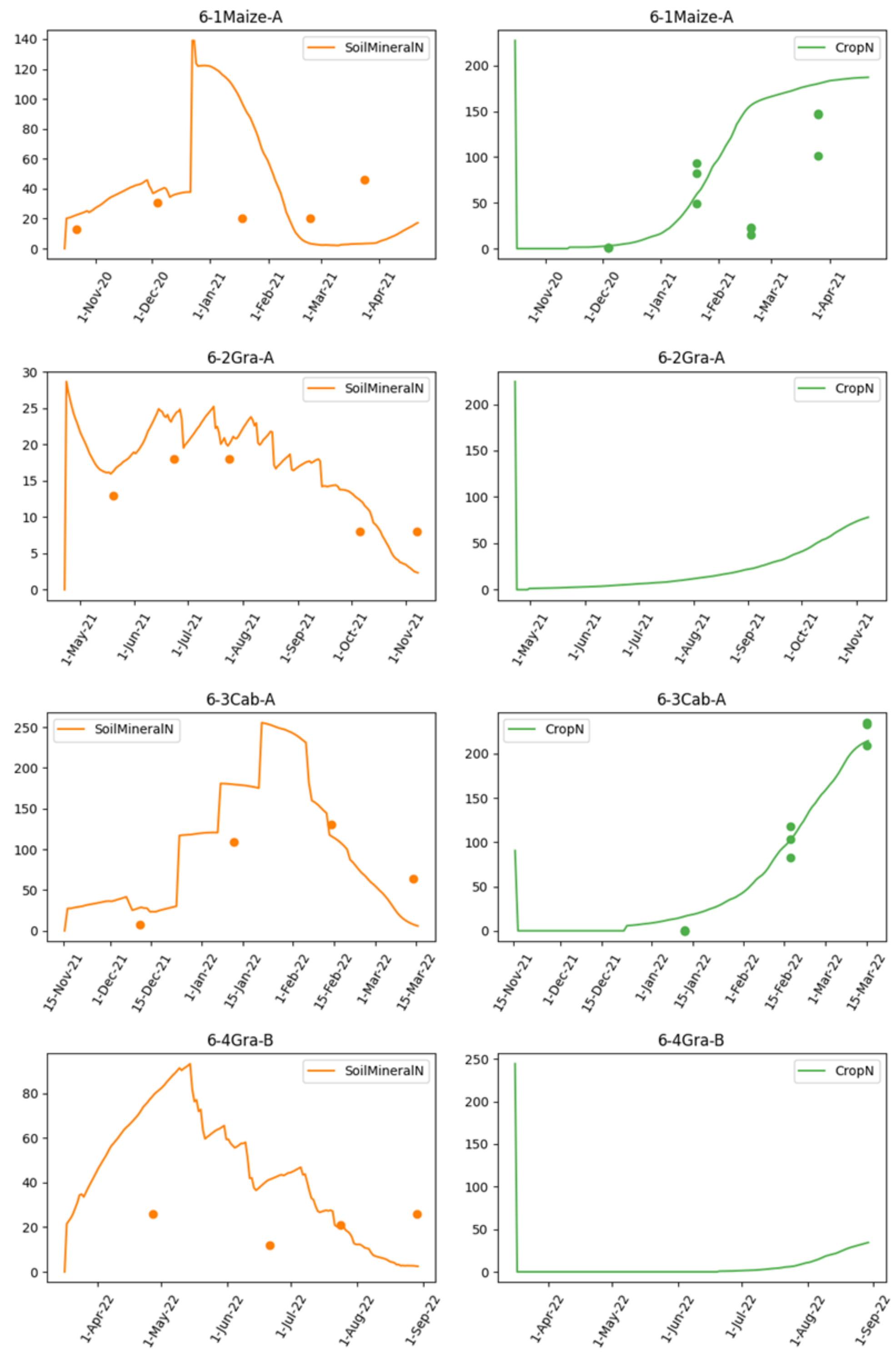

Figure A55. Site 6. There was good agreement for the cabbage and grass crops although no measurements were collected for N uptake from the grass crop. There appeared to be an over prediction of nitrogen (N) uptake for the maize crop but there is some uncertainty about the observations later in this crop. Plots on the left are soil mineral N levels, plots on the right are crop N uptake. Lines indicate predicted values and dots indicate measured values. Units are in kg N/ha.

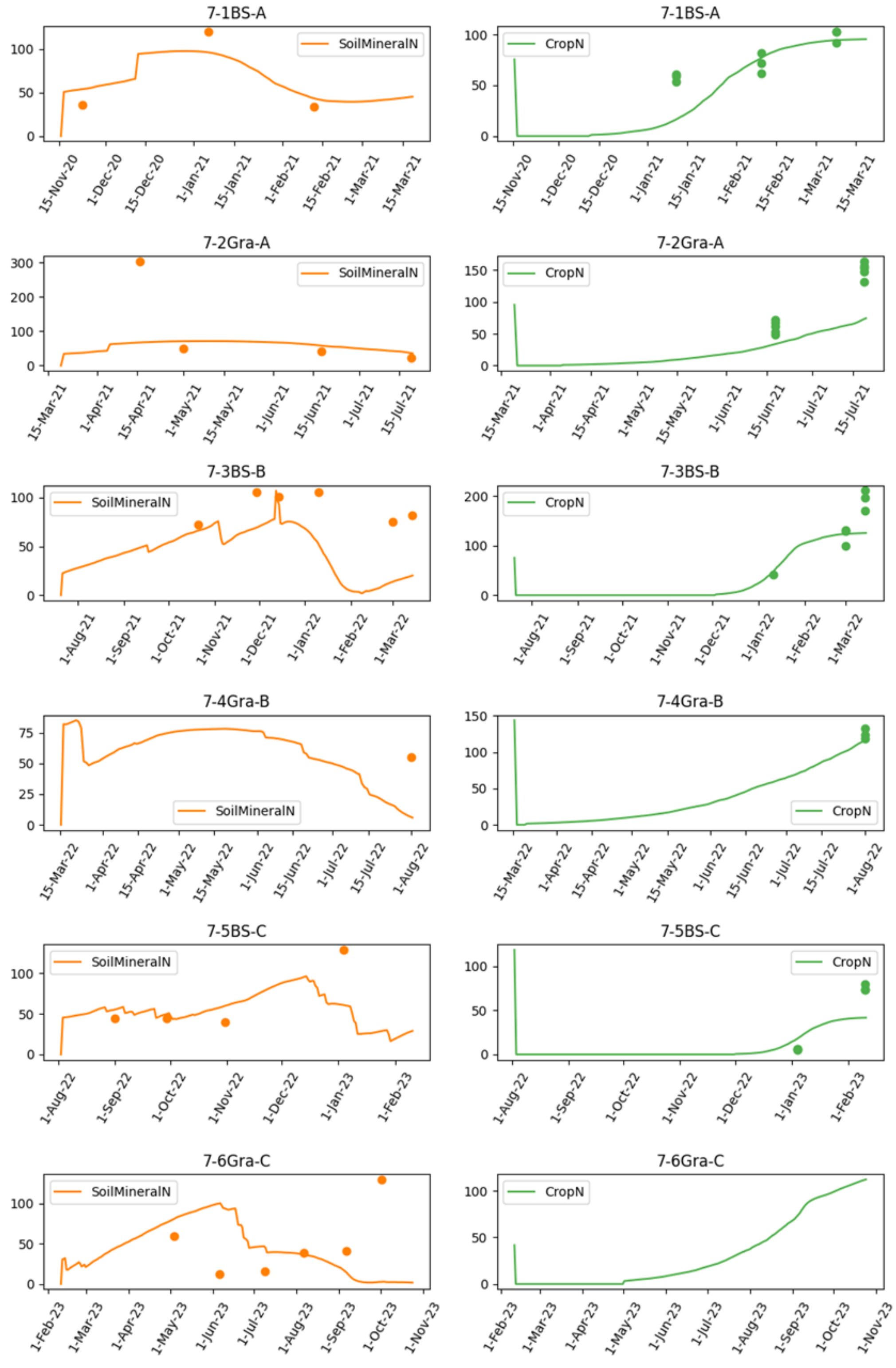

Figure A56. Site 7. We have an incomplete record of fertiliser nitrogen (N) inputs for this location, so it is not possible to make judgement on the performance of the model. Plots on the left are soil mineral N levels, plots on the right are crop N uptake. Lines indicate predicted values and dots indicate measured values. Units are in kg.

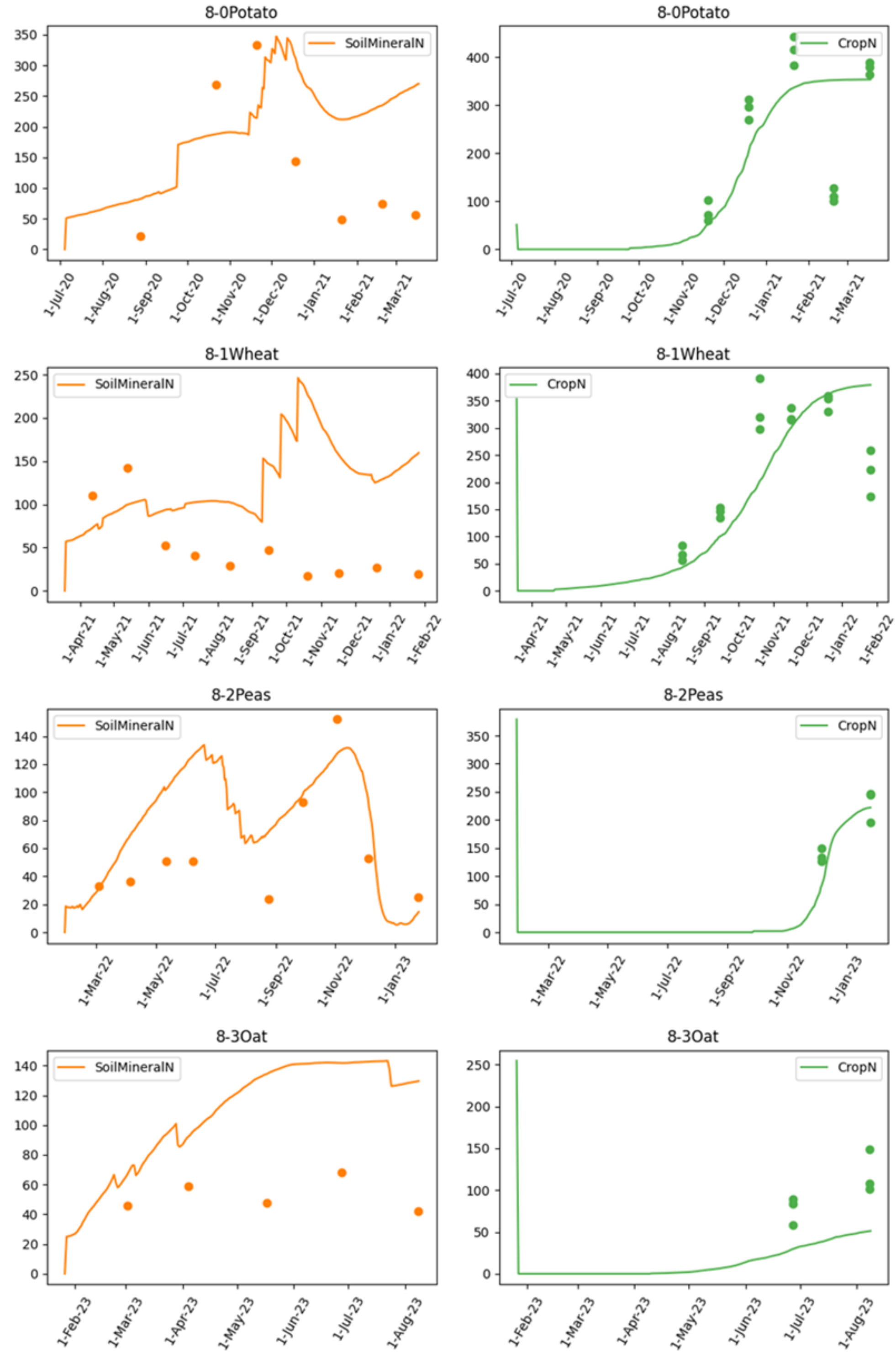

Figure A57. Site 8. The model gave good predictions of crop nitrogen (N) uptake at this location except for the oat crop which N uptake was underestimated. This is due to the model not accounting for luxury N uptake in this crop which has been explained earlier. There was a general tendency to over predict soil N which may be due to an over prediction of N mineralisation or and under prediction of losses. Plots on the left are soil mineral N levels, plots on the right are crop N uptake. Lines indicate predicted values and dots indicate measured values. Units are in kg N/ha.

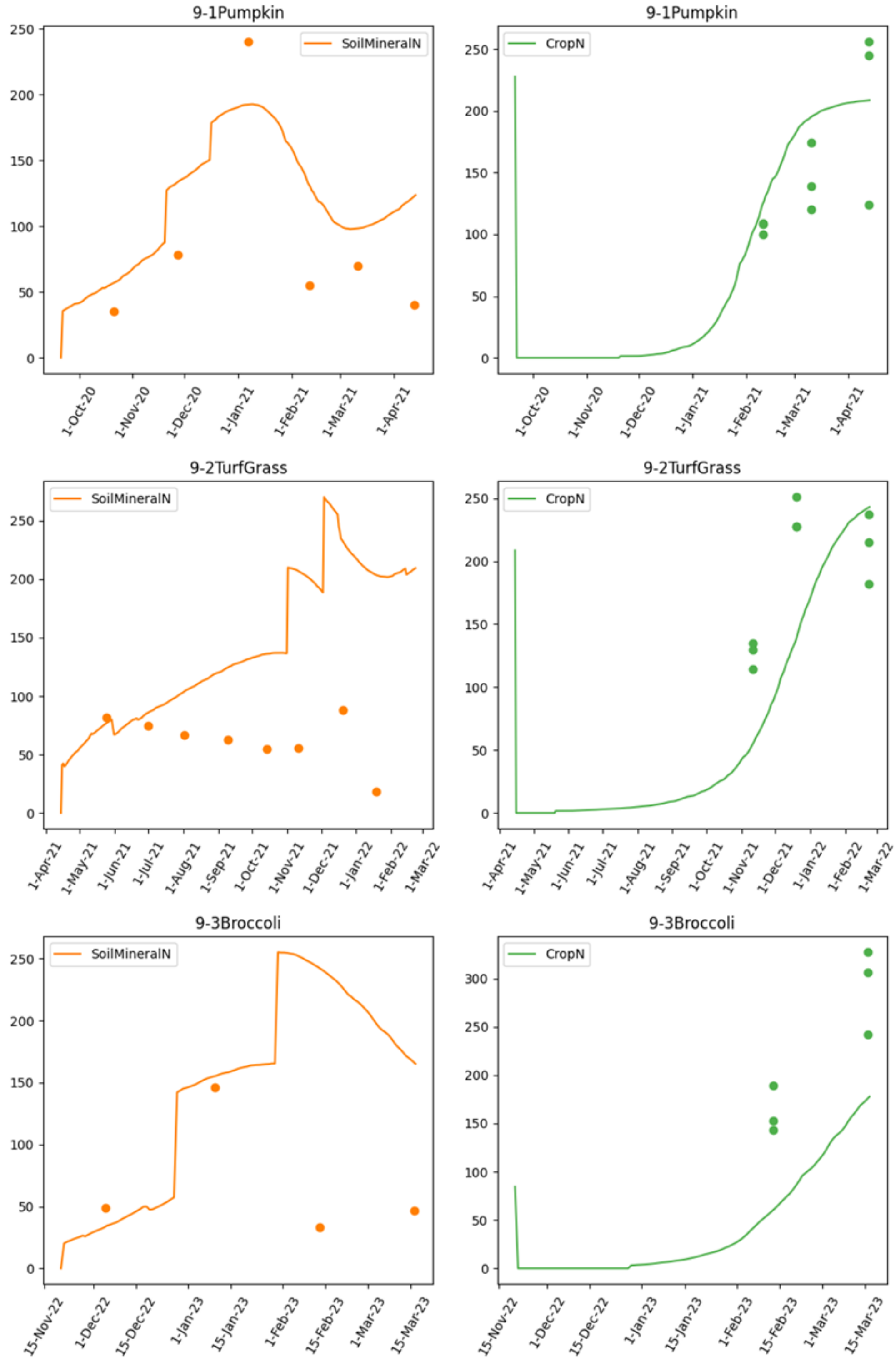

Figure A58. Site 9. The model gave an under prediction of nitrogen (N) uptake by broccoli at this location which could be due to an incorrect yield being used in the model configuration or incorrect coefficients for harvest index or N content in the model. There was also a tendency to over predict soil N which may be due to an overprediction of mineralisation or under prediction of losses. Plots on the left are soil mineral N levels, plots on the right are crop N uptake. Lines indicate predicted values and dots indicate measured values. Units are in kg N/ha.

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