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Sustainable Vegetable Systems – annual report 2023

Searle B, Michel A, Fraser P, Brown H, Khaembah E, Sharp J, Maley S, Dellow S, van der Weyden J, Arnold N, Sorensen I, Husband E, Waka P, Husheer S

May 2023

Report for:

Potatoes New Zealand
Sustainable Vegetable Systems

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May 2023

This report summarises activity carried out by The New Zealand Institute for Plant and Food Research Limited (PFR) across the different Workstreams in Year 3 of the Sustainable Vegetable Systems (SVS) project.

Workstream 1 – Field experiments:

- Rotation 1 and 2 in Canterbury have been completed. Measurements in Rotation 3 in Hawke's Bay will no longer continue because of the effects of Cyclone Gabrielle; this means some data from the ryegrass crop will not be collected. However, Rotation 4 can continue and has been sown in the final crop of ryegrass; measurements continue.
- Data collection and analysis is ongoing in this Workstream. In this report we summarise soil nitrogen (N) and the N balance of Rotations 1 and 2.
- Reasons for differences in the N balance between the two potato crops in each of Rotations 1 and 2 are evaluated. The N balance and amount of potential environmental N loss (PENL) varied significantly between the two crops even at good management practice N fertiliser rates. This seems partially due to a difference in yield between the two crops and N uptake pattern, but further direct comparison is needed. An implication is that good management practice can have different N balance outcomes, indicating that target values of losses do not reflect the whole system integration of growth, supply, and uptake.
- Suggestions for further research based on preliminary observations from Rotations 1 and 2 are suggested. At a broad level these include:
  - Establish farmer data-driven approach to enhance tool implementation in practice, so that the tool becomes a standard part of management.
  - Address specific science questions around residue decomposition and N supply, as well as practices that may improve N balance outcomes.

Workstream 2 – Regional monitoring:

- A database of crop biomass and N content, and a database of soil N content for each site have been made available to Workstream 2 to develop N budgets for each crop. The data are also available for use in Workstream 3.

Workstream 3 – Modelling:

- Based on discussions with growers, the tool has been implemented with layers. The underlying algorithms are the same – the layers require different levels of data to be entered by the user. The layers are:
    - The first layer, or basic layer – uses standard parameters for most inputs, but users can alter crop type and sowing date and expected yield. The tool provides a fertiliser application rate, timings of applications and a N balance.
    - The second layer or scheduling layer – maintains some standard parameters, but users can input more information such as soil test values and the number of fertiliser side-dressings they want to apply. Users who take soil tests throughout growth can input these values when available to evaluate changes in recommendations.
    - The third layer or advanced layer – places the crop in the context of the previous crop; the supply of N that comes from residues is crop specific rather than using default.
- Additional work has been progressing on improving the parameters of the model and in particular prediction of crop N use and leaching across all the crops in the rotations.
- Work was done to collate a database of crop residue characteristics and crop information to provide information for a 'draft' crop residue model that can be incorporated into the grower facing tool.
- Gaps in knowledge about modelling residue decomposition were evaluated and steps to address them identified.

Workstream 4 – Technology transfer:

- Presentation of the tool on a one-to-one basis have been ongoing and provided guidance in developing the framework and 'layers' approach.
- Articles on soil N movement in Rotations 1 and 2 have been developed.
- Planning continues for roadshows and presentations.

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1 Background

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

The tool being developed is based on a N balance approach – the difference between all the inputs and outputs of a crop system. A benefit of the N balance approach is that it integrates the complex dynamics of N in the crop-soil system and captures the beneficial effects of N additions for achieving crop yield, as well as the potential for losses. A N balance approach has been used to quantify best management for cereals and estimate losses (Tei et al. 2020; Bohman et al. 2021; Tamagno et al. 2022) but this has not yet been applied to a similar extent in vegetables. The SVS programme seeks to fill this gap and is structured into four workstreams to achieve this.

In Workstream 1 in the SVS project (Figure 1) we measure the different components of a crop system in replicated experiments to quantify the N rate effect on the N balance. We have set it up in rotations as the N history of a crop can affect the subsequent crop. There are two key outcomes from the data of Workstream 1:

1. Determine the N balance and its response to applied N fertiliser rates. This is necessary to understand how the overall system is functioning, and what the balance – and potential losses – can be given N management used.
2. Quantify the growth and N uptake curves of different crops. These are integrators of N movement within the system, given interactions of climate. These data will help us understand how the N balance functions given different management conditions and how management options might improve outcomes.

The data obtained in Workstream 1 provide a retrospective view of factors affecting the N balance. However, decisions on fertiliser rate and timing need to be made before the crop goes in the ground and therefore a prospective – forward looking – N balance is needed. The only way to achieve this is by modelling the soil-crop N system, and this is the focus of Workstream 3 (Figure 1). Models of N uptake for different vegetable crops are being developed in this workstream as well as refining a model of nitrate leaching losses based on Workstream 1 data, and a tool to predict N inputs and N balance of crops.

In commercial practice not all the inputs and outputs needed for estimating a N balance can be expected to be collected routinely, as some are difficult and expensive to measure. Because of this a usable and practical tool developed in Workstream 3 will need to calculate the N balance with data easily obtained under commercial situations and be applicable in commercial fields. To provide these data, information is gathered from nine different commercial fields across New Zealand in Workstream 2 (Figure 1). These data will be used for testing the model in Workstream 3 and evaluating assumptions made from data In Workstreams 1 and 3.

Importantly, there needs to be continuous interaction between growers and model developers to ensure that any tool developed is usable, practical and farmer friendly. This is the focus of Workstream 4 (Figure 1), which is facilitating interaction between growers involved in Workstream 2 and those involved in Workstreams 1 and 3 to improve the tool functionality and usability, as well as evaluate outcomes in farmers' fields.

To develop a farmer friendly tool, we need to:

1. Understand the effect of N rates on the N balance, including all inputs and outputs, and from this identify any factors that may affect management of N to maximise yields while preventing high losses.
2. Quantify the growth and N uptake curves of different crops, and use these to evaluate the assumptions of the modelling, including the response curves and parameters to be used.
3. Evaluate the application of the model to predicting results from experimental and commercial data. This includes prediction of yield, N uptake curves, a N balance, and fertiliser recommendations.

In this report we will review progress in each of the workstreams for the last quarter (January to March 2023) and update the annual workplan. We will also report on a preliminary analysis of N balance in Rotations 1 and 2, and implications for management and research gaps that are starting to be identified. Subsequent reports will complete comparison of N balance across all rotations as all data are compiled, and report on assumptions behind modelling, and modelling results.

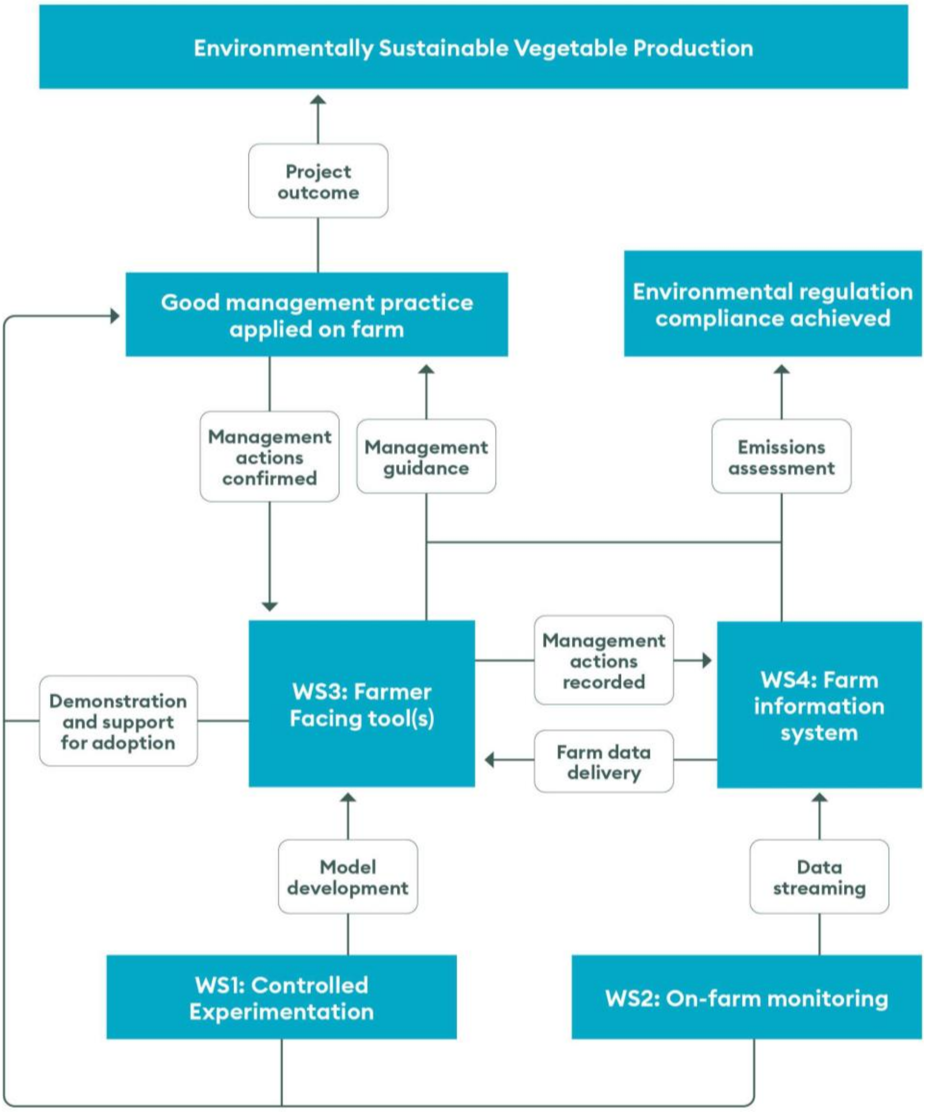


Figure 1. Overview of Sustainable Vegetable Systems (SVS) project, identifying Workstreams 1 to 4 and connections between them.

2 Workstream progress update

2.1 Workstream 1

Details of the experimental design, treatments and measurements are provided in Appendix 1. The experiments consisted of rotations sown at The New Zealand Institute for Plant and Food Research Limited (PFR) farms at Lincoln, Canterbury and Havelock North, Hawke's Bay. This past year saw the final part of Rotations 1 and 2 at the Lincoln site (Figure 2). For both rotations, the final crop was a ryegrass seed crop, which allowed for continued data collection beyond the last vegetable crop from each rotation. Ryegrass seed has been harvested and the crops continue as grass crops (Figure 3).

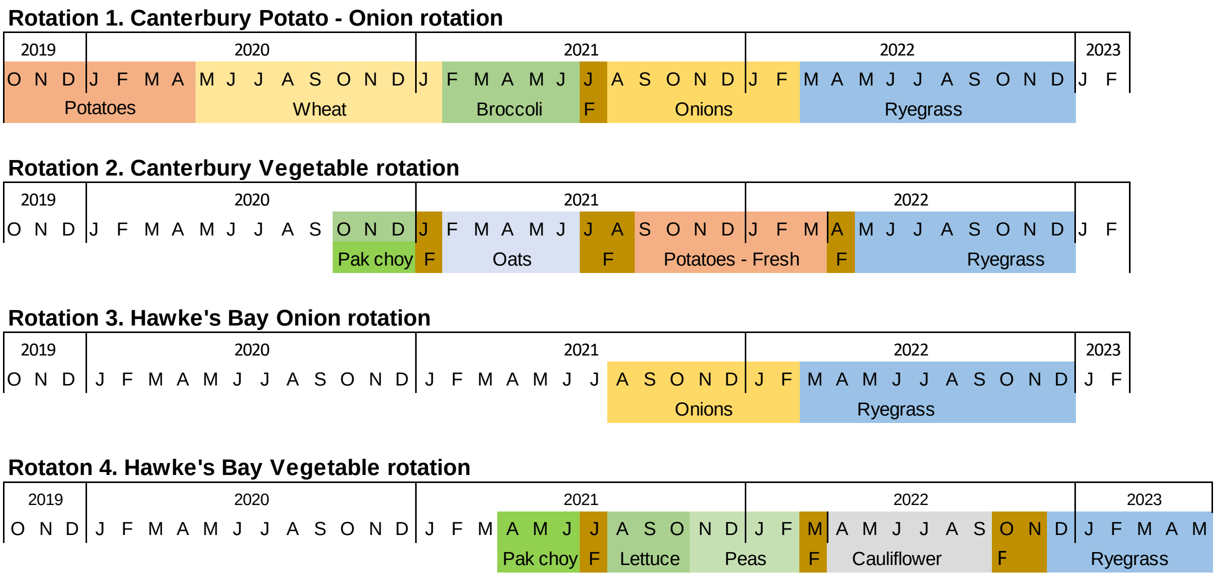


Figure 2. Rotations and crops grown in Workstream 1. Rotations are based on PFR farms at Lincoln and Hawke's Bay.

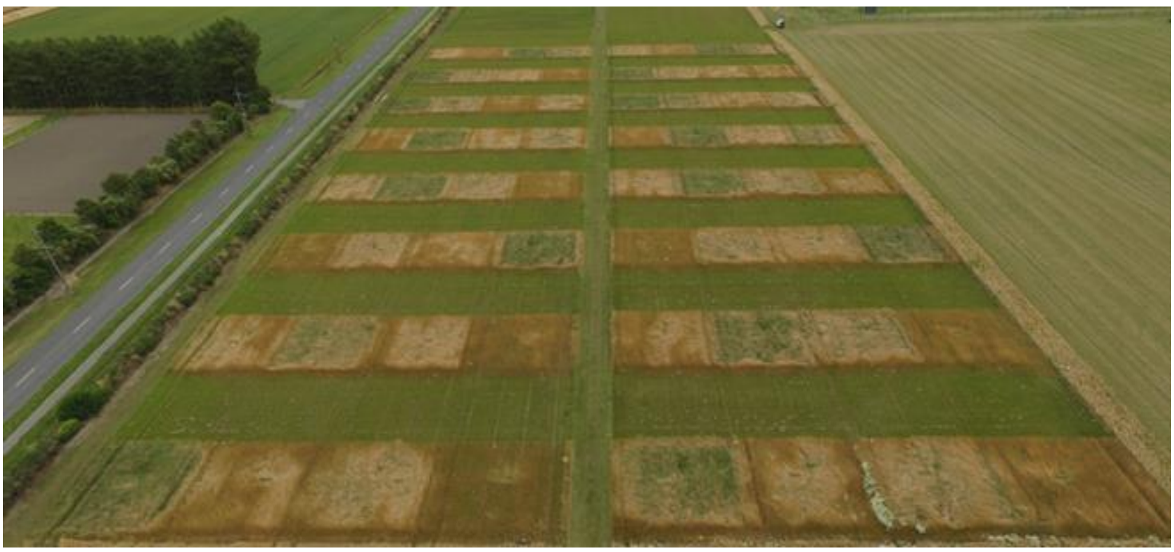


Figure 3. Rotations 1 and 2 grown at PFR Lincoln, showing ryegrass seed crops at harvest.

The final ryegrass crops have been sown in Rotations 3 and 4 at the Hawke's Bay site (Figure 3) Figure 2. For Rotation 3, the ryegrass crop has been taken for hay and the residue incorporated into the soil, and then soil N measurements continue to assess any change due to cultivation and decomposition of the ryegrass. For Rotation 4, the last vegetable crop of the rotation, cauliflower, has been harvested and was followed by a ryegrass crop to end the rotation. This ryegrass crop is still to be taken for hay and the residue incorporated into the soil.

It is important to note the disruptions at the Hawke's Bay site caused by Cyclone Gabrielle in February 2023. There was a total rainfall of 343 mm for the month, which included 229 mm the week the cyclone hit the region. This high rainfall and flooding meant that there was an extremely high likelihood of contamination between plots as well as between the experimental area and the surrounding area.

The effect of the cyclone on the soil N is shown in Figure 4 and Figure 5. In Rotation 3, soil N in the top 60 cm was significantly lower after the cyclone. In contrast, at 120 cm depth there was no significant difference in soil N due to the cyclone, but variability had markedly increased.

In Rotation 4, the amount of mineral-N in the top 60 and 120 cm of the soil profile increased with N treatment, particularly, as expected, in the N4 treatment. In this rotation there have been four crops that have allowed the build-up of this difference in soil N. However, the cyclone significantly reduces the soil N in the top 60 and 120 cm of soil, regardless of N treatment and increases the variability at depth (Figure 5).

The cyclone has disrupted measurements of soil N content to assess the amount of N returned due to decomposition of the ryegrass crop in Rotation 3. The significant reduction in soil N in the top 60 cm with the cyclone, means that we can no longer reliably estimate decomposition returns for the ryegrass crop in Rotation 3. However, we can continue this in Rotation 4, which will have the ryegrass incorporated into the soil in the next 4 weeks.

Figure 4. Effects of Cyclone Gabrielle on the ryegrass crop in Rotation 3 gown at PFR Hawke's Bay. Images show a sump for nitrate leachate collection flooded (left), and the waterlogging after the event (right).

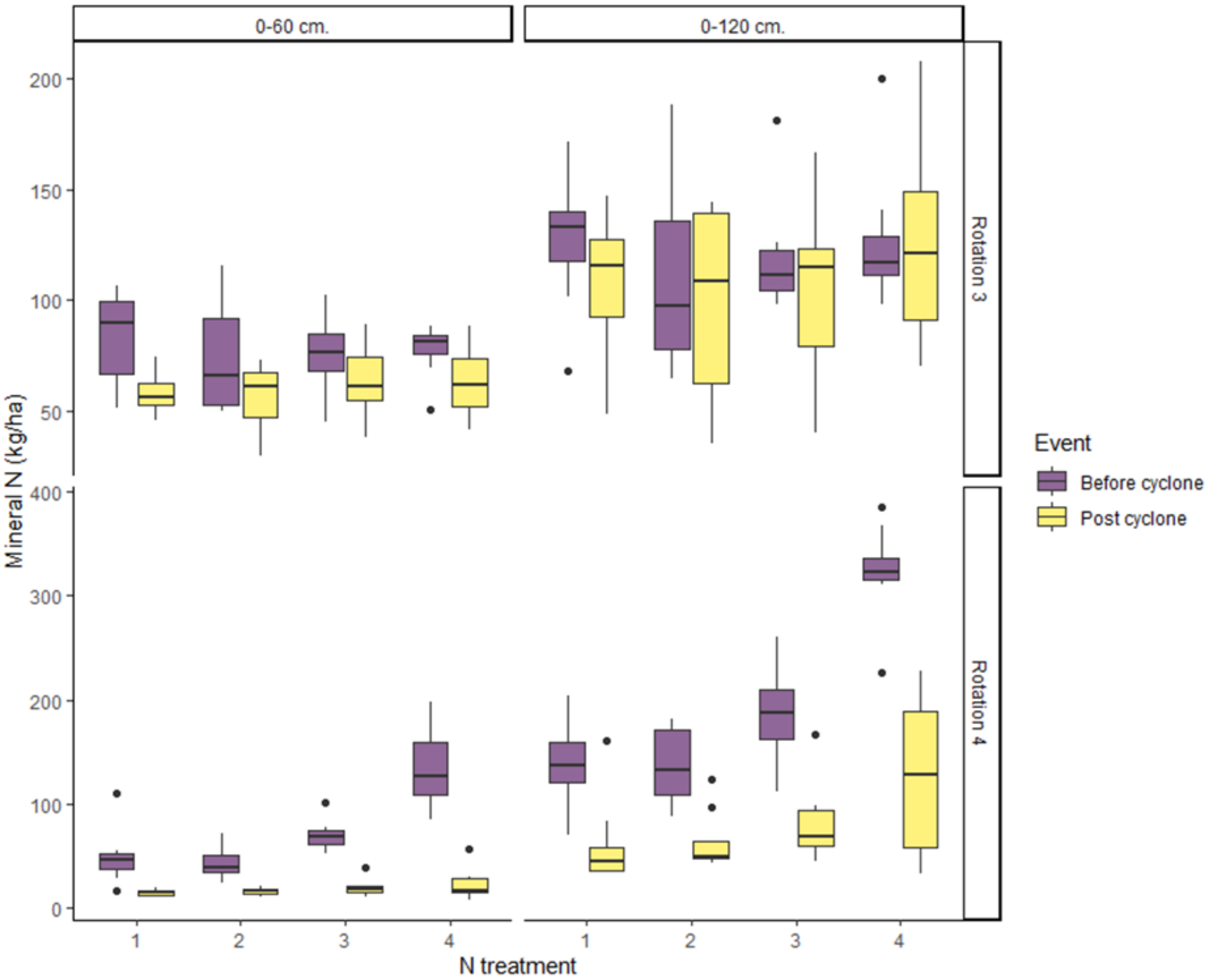


Figure 5. Total soil mineral-nitrogen (N) to depths of 0–60 cm and 0–120 cm for Rotations 3 and 4 at the PFR Hawke's Bay research site, before and after Cyclone Gabrielle on 14 February 2023. Soil samples in Rotation 3 were collected on 1 February and 6 March, and in Rotation 4 collected 23 January and 28 February 2023.

2.2 Workstream 2

- Data have continued to be collected on the regional farms by the regional monitors. The biomass data have been processed by PFR and samples are at the lab for completion of N content analysis.
- A database of crop biomass and N content, and a database of soil N contents for each site is available.
- Data that have been collated are being passed to Workstream 3; modelling analysis will be completed in the next year of work.

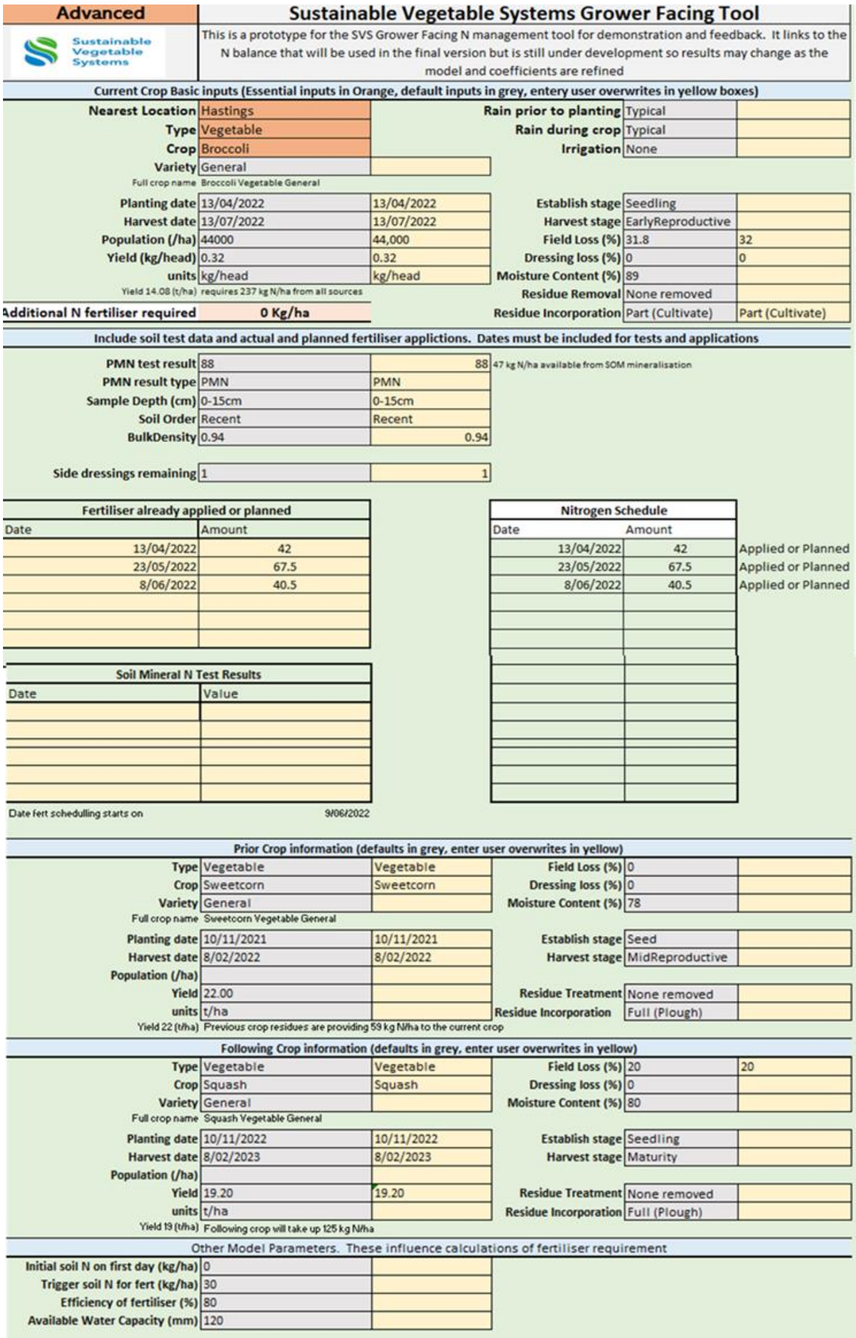
2.3 Workstream 3: Modelling

Model design and implementation

This component of the Workstream is about providing a tool that helps growers implement good management practices and to provide assurance to regulators. A key outcome is to provide a grower-facing tool (GFT) that is usable and practical. There is strong interaction with Workstream 4 to explore case studies with growers to ensure uptake and use of the tool.

Key steps in Year 3 of the project have been:

- A series of workshops were conducted to evaluate the outcome of the prototype and define the desired outcomes and goals of the tool. The focus was on developing a tool that helped growers implement good management, based on a N balance. Additionally, the aim was to provide some direction in the way the tool was coded and developed to ensure it was grower-facing.
- These workshops were followed with a series of one-on-one demonstrations and evaluations with growers to obtain specific feedback on functionality and usability of the tool from a user standpoint. A key outcome was usability and established that different layers of data input for ease of use were crucial to develop interest and confidence in the tool and facilitate technology transfer.
- From this, there was a major effort in coding a second prototype that can be used in discussion with farmers. Details are provided in Searle et al. (2023). The second prototype has been developed with a Microsoft® Excel® interface passing information to and receiving results from the C# code, which are then summarised in Excel. The Excel interface (Figure 6. Image of the advanced layer of the grower facing tool being developed in the SVS programme.) makes it much easier to use and implement. This prototype is being used for testing and early end-user engagement for case studies.
- The tool has different layers for ease of grower access and input. The underlying model structure is the same for each layer; but as layers increase, the amount of information growers can input increases:
    - The first layer, or basic layer – uses standard parameters for most inputs, but users can alter crop type and sowing date and expected yield. The tool provides a fertiliser application rate, timings of applications and a N balance.



Advanced — Sustainable Vegetable Systems Grower Facing Tool

Sustainable Vegetable Systems

This is a prototype for the SVS Grower Facing N management tool for demonstration and feedback. It links to the N balance that will be used in the final version but is still under development so results may change as the model and coefficients are refined

Current Crop Basic inputs (Essential inputs in Orange, default inputs in grey, entery user overwrites in yellow boxes)

Nearest Location	Hastings		Rain prior to planting	Typical	
Type	Vegetable		Rain during crop	Typical	
Crop	Broccoli		Irrigation	None	
Variety	General				
Full crop name	Broccoli Vegetable General				
Planting date	13/04/2022	13/04/2022	Establish stage	Seedling	
Harvest date	13/07/2022	13/07/2022	Harvest stage	EarlyReproductive	
Population (/ha)	44000	44,000	Field Loss (%)	31.8	32
Yield (kg/head)	0.32	0.32	Dressing loss (%)	0	0
units	kg/head	kg/head	Moisture Content (%)	89	
Yield 14.08 (t/ha)	requires 237 kg N/ha from all sources		Residue Removal	None removed	
Additional N fertiliser required	0 Kg/ha		Residue Incorporation	Part (Cultivate)	Part (Cultivate)

Include soil test data and actual and planned fertiliser applictions. Dates must be included for tests and applications

PMN test result	88	88	47 kg N/ha available from SOM mineralisation
PMN result type	PMN	PMN	
Sample Depth (cm)	0-15cm	0-15cm	
Soil Order	Recent	Recent	
BulkDensity	0.94	0.94	
Side dressings remaining	1	1	

Fertiliser already applied or planned

Date	Amount
13/04/2022	42
23/05/2022	67.5
8/06/2022	40.5

Nitrogen Schedule

Date	Amount	
13/04/2022	42	Applied or Planned
23/05/2022	67.5	Applied or Planned
8/06/2022	40.5	Applied or Planned

Soil Mineral N Test Results

Date	Value

Date fert schedulling starts on 9/06/2022

Prior Crop information (defaults in grey, enter user overwrites in yellow)

Type	Vegetable	Vegetable	Field Loss (%)	0	
Crop	Sweetcorn	Sweetcorn	Dressing loss (%)	0	
Variety	General		Moisture Content (%)	78	
Full crop name	Sweetcorn Vegetable General				
Planting date	10/11/2021	10/11/2021	Establish stage	Seed	
Harvest date	8/02/2022	8/02/2022	Harvest stage	MidReproductive	
Population (/ha)					
Yield	22.00		Residue Treatment	None removed	
units	t/ha		Residue Incorporation	Full (Plough)	
Yield 22 (t/ha)	Previous crop residues are providing 59 kg N/ha to the current crop				

Following Crop information (defaults in grey, enter user overwrites in yellow)

Type	Vegetable	Vegetable	Field Loss (%)	20	20
Crop	Squash	Squash	Dressing loss (%)	0	
Variety	General		Moisture Content (%)	80	
Full crop name	Squash Vegetable General				
Planting date	10/11/2022	10/11/2022	Establish stage	Seedling	
Harvest date	8/02/2023	8/02/2023	Harvest stage	Maturity	
Population (/ha)					
Yield	19.20	19.20	Residue Treatment	None removed	
units	t/ha		Residue Incorporation	Full (Plough)	
Yield 19 (t/ha)	Following crop will take up 125 kg N/ha				

Other Model Parameters. These influence calculations of fertiliser requirement

Initial soil N on first day (kg/ha)	0	
Trigger soil N for fert (kg/ha)	30	
Efficiency of fertiliser (%)	80	
Available Water Capacity (mm)	120	

Figure 6. Image of the advanced layer of the grower facing tool being developed in the SVS programme.

- The second layer or scheduling layer – maintains some standard parameters, but users can input more information such as soil test values and the number of fertiliser side-dressings they want to apply. Users who take soil tests throughout growth can input these values when available to evaluate changes in recommendations.
- The third layer or advanced layer – places the crop in the context of the previous crop; the supply of N that comes from residues is crop specific rather than using default values. It also allows the residues from the current crop to be defined, giving indications of N supply from residues to a subsequent crop.

Model development

This component is about improving the development of underlying rules that predict outcomes implemented in the GFT. There are three aspects being focused on in model development:

1. Fitting crop growth and N uptake curves from Workstream 1 data with APSIM-SCRUM. This process helps define parameters used in the tool.
2. Improvement of the soil water movement and N leaching model within APSIM. This is an important part of understanding losses from the system.

Work undertaken in these two steps includes:

- Data from Rotations 1 and 2 are being used within APSIM-SCRUM to estimate the growth curves and N uptake curves for the different crops. This information has been passed on for model design and implementation.
- Data from Rotations 3 and 4 are being quality checked and prepared for analysis with APSIM-SCRUM.
- All the assumptions used in the tool implementation around parameter values are in the process of being evaluated and tested with data from Workstream 1.
- Soil water movement and leaching model has been evaluated with data from Rotation 1 and will be applied to Rotation 2 data. Data from Rotations 3 and 4 are being prepared for model evaluation.

1. Providing a basic crop residue model for incorporation in the SVS tool. The steps include:

- Literature search and data extraction of vegetable residue characteristics. Reasonably exhaustive search of international literature on vegetable crop residue characteristics, including mass, N concentration (by plant organ where available), and other 'quality' characteristics, for model development. Data extracted into database.
- Literature search and data extraction on crop residue decomposition and N supply. Exhaustive search of international literature on crop residue decomposition and N supply (with particular emphasis on vegetable crops), for model development. 229 time series of residue N mineralisation data covering 36 crops/vegetables/forages extracted into database. Within the database other factors are considered including residue addition rate, within crop residue N content, residue placement, residue particle size, soil mineral-N, soil fertility, tillage history, soil temperature and soil moisture. In addition, a suite of 69 other field studies covering 26 crops has been identified as useful for model validation.
- This information was used to contribute to a report on residue characteristics (Sharp et al. 2023).
- A 'draft' model of residue is being developed from the literature data and will be made available for use in the grower facing tool.
- A step plan of work for extending the 'draft' model was developed, identifying knowledge gaps and experimental steps required for obtaining information for model development (Figure 7).

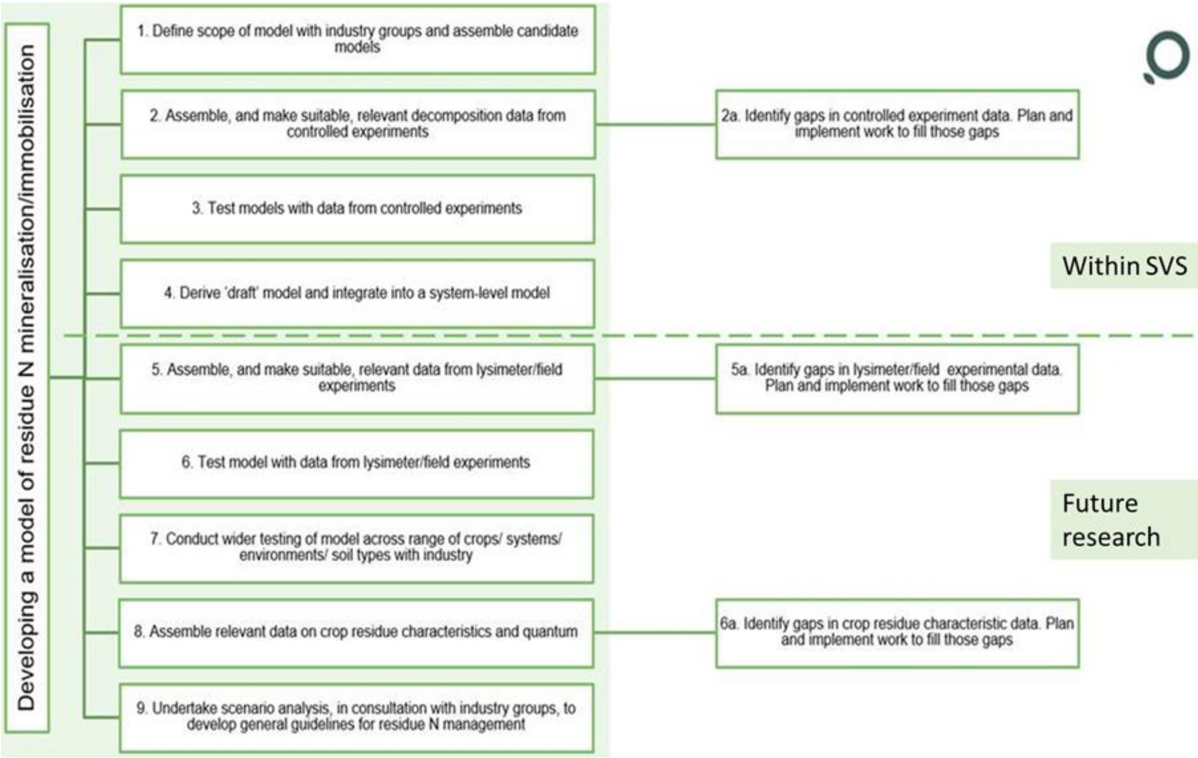


Figure 7. Step plan of developing decomposition model of crop residue N mineralisation and immobilisation with steps in the current SVS project, and steps needed in subsequent research to develop a comprehensive model.

2.4 Workstream 4: Technology transfer

Over the last year:

- Workshops held to discuss model prototype structure and function.
- Individual discussions with growers on tool prototype function and structure.
- Contribution to planning for videos, roadshow and podcast, and continued information sharing.
- Contribution to the NZ Grower article 'Crop residues, fallow periods, and management practices' (Andrew Barber (AgriLink) Trish Fraser and Bruce Searle (PFR)) and 'What is happening in the soil?' (Trish Fraser and Bruce Searle (PFR)).
- Filming for SVS videos was planned but have been delayed because of COVID-19.

3 Preliminary evaluation of N balance – Rotations 1 and 2

The N balance is the difference between all the inputs and outputs of N within the crop-soil system.

As inputs we consider:

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

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

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

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

The outputs considered are:

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

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

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

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

Potential environmental N loss (PENL). This is the amount of N that could be lost during the crop growth period. It is made up of gaseous or leaching losses. Leaching losses are being measured and calculations are underway depending on modelling of soil water movement (see Section 2.3). Gaseous losses are not measured directly but can be estimated from N inputs. Subsequent reports will evaluate the contribution of leaching or gaseous loss. Here we are interested in estimating what the potential environmental N loss (PENL) is given different N rates and crops, and what factors may affect it. The value is estimated as:

PENL = Total N inputs − Total N outputs

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

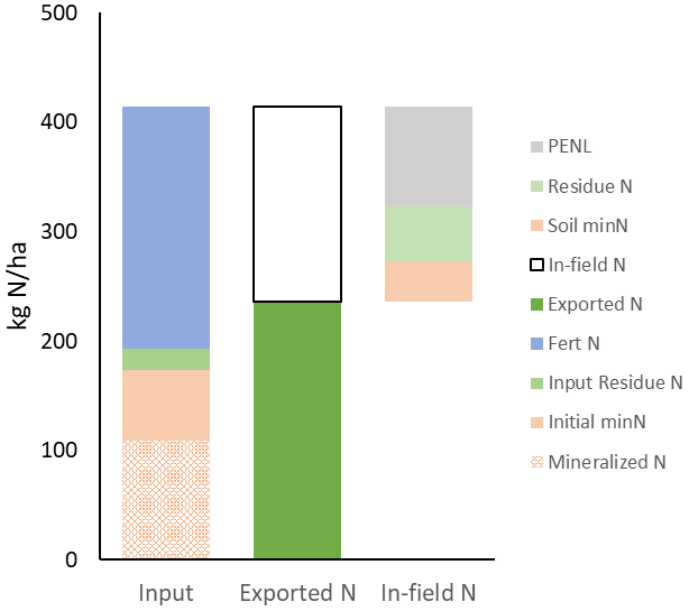


Figure 8. Framework for nitrogen (N) balance calculation.

3.1 Rotation 1

We analysed the N balance for all crops within the rotation except the final ryegrass crop where lab analysis of biomass is still being completed. All the ryegrass crops will be evaluated in a subsequent report.

3.1.1 Soil mineral-N

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

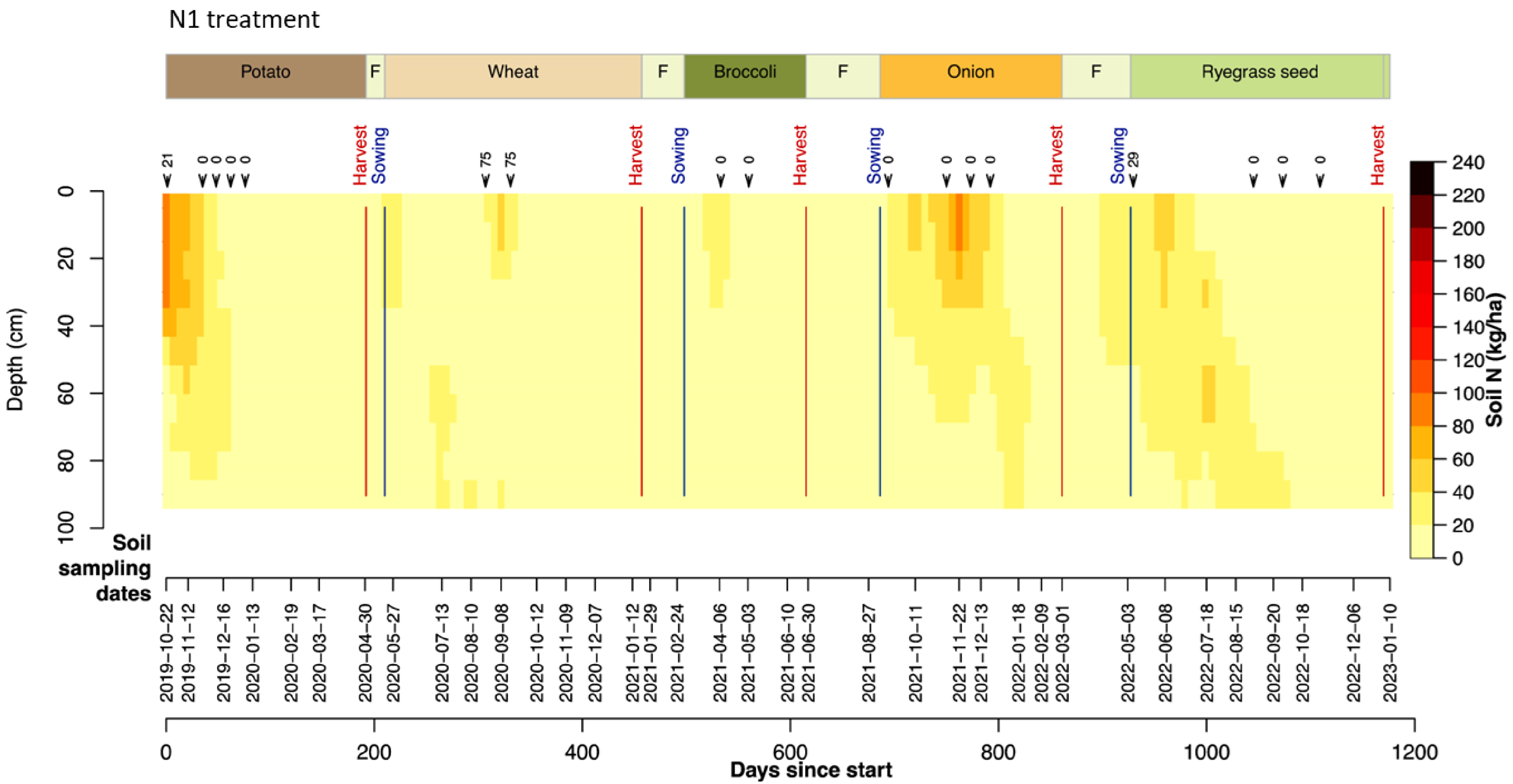


Figure 9. N1 treatment soil nitrate-nitrogen (N) interpolation plot to a soil depth of 90 cm across Rotation 1 sown at PFR, Lincoln, Canterbury. Upper arrows represent N fertiliser application dates and amounts for the different crops in the rotation. The period between harvest and sowing of the subsequent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

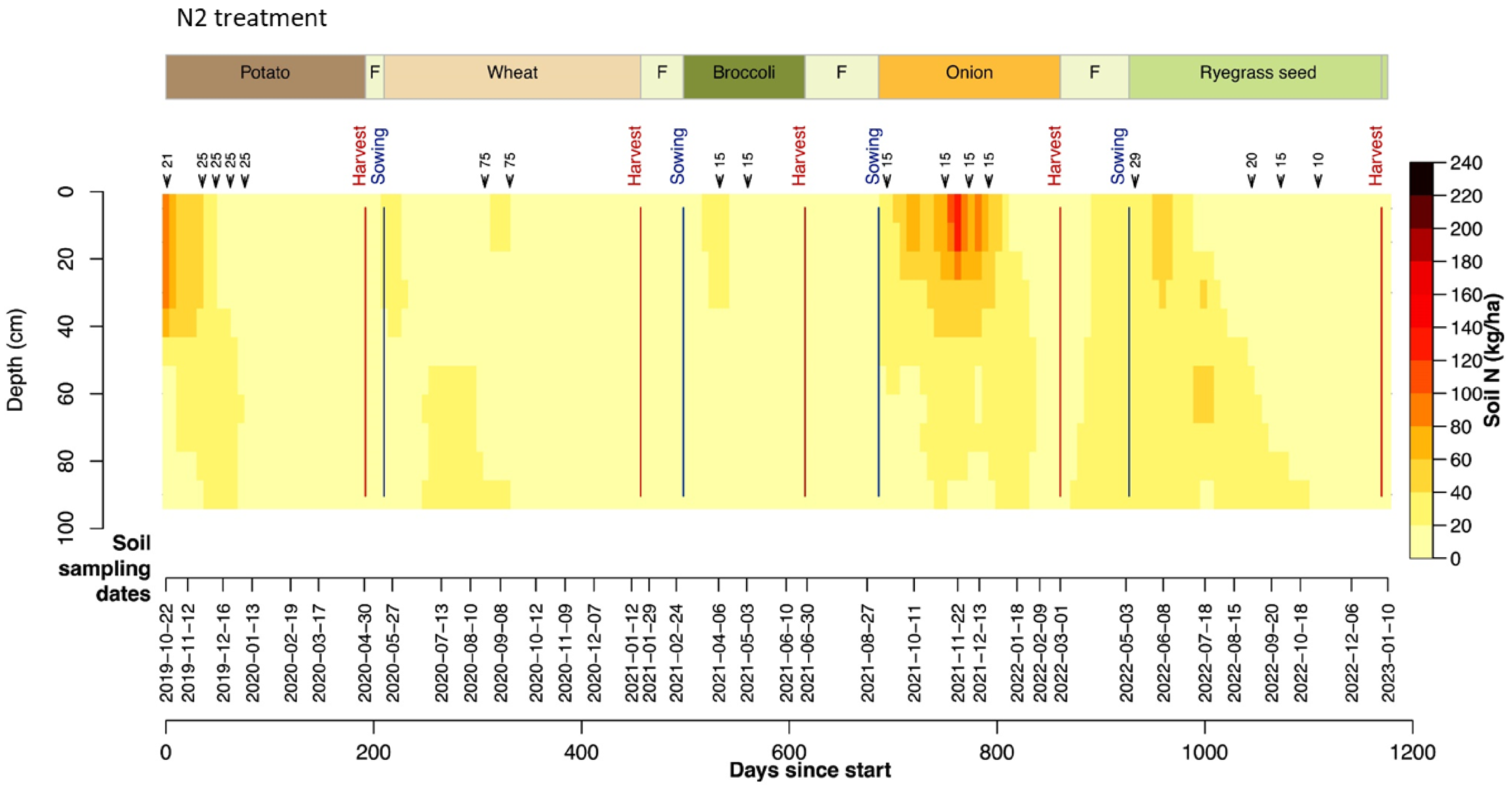


Figure 10. N2 treatment soil nitrate-nitrogen (N) interpolation plot to a soil depth of 90 cm across Rotation 1 sown at PFR, Lincoln, Canterbury. Upper arrows represent N fertiliser application dates and amounts for the different crops in the rotation. The period between harvest and sowing of the subsequent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

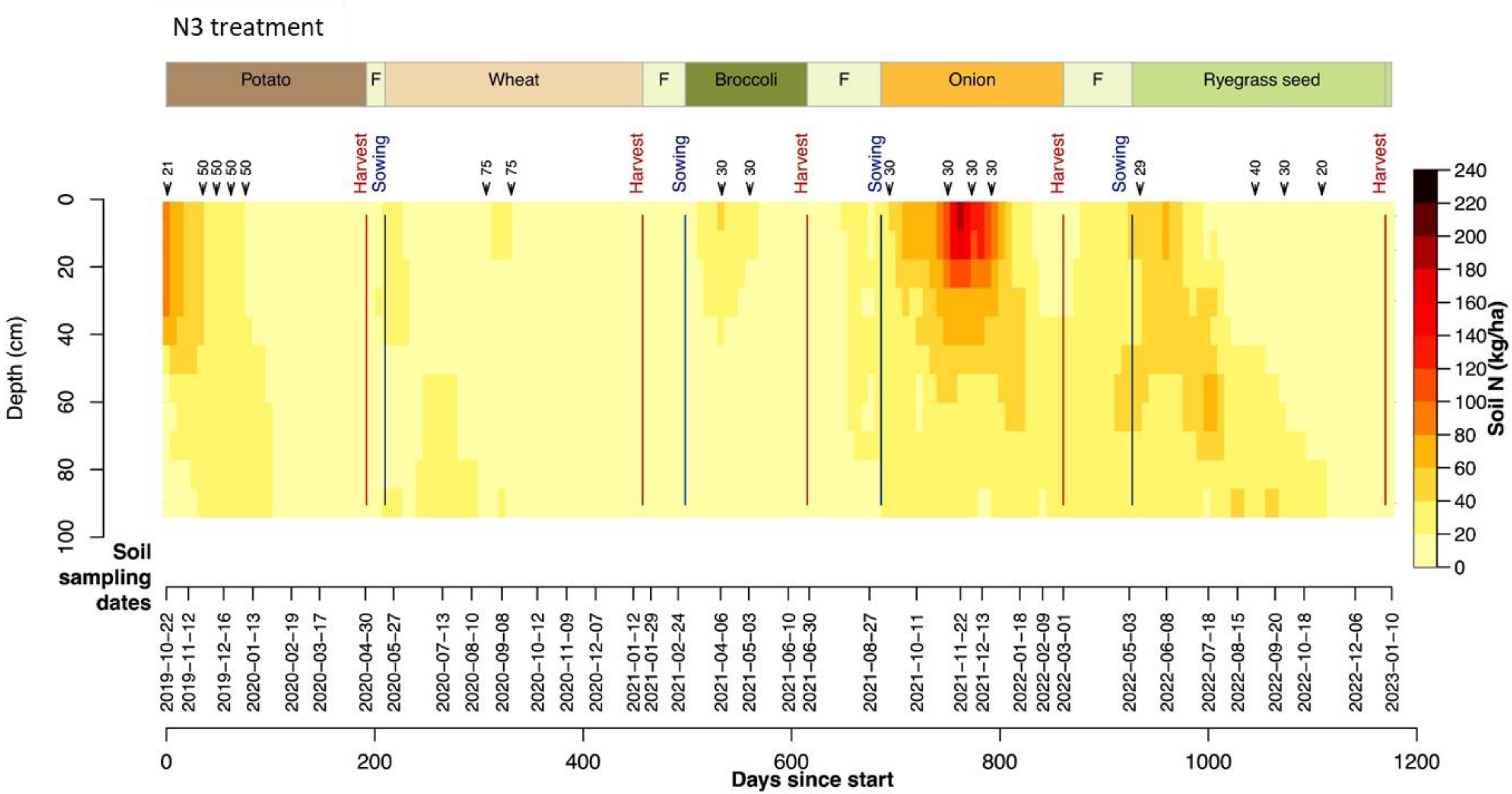


Figure 11. N3 treatment soil nitrate-nitrogen (N) interpolation plot to a soil depth of 90 cm across Rotation 1 sown at PFR, Lincoln, Canterbury. Upper arrows represent N fertiliser application dates and amounts for the different crops in the rotation. The period between harvest and sowing of the subsequent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

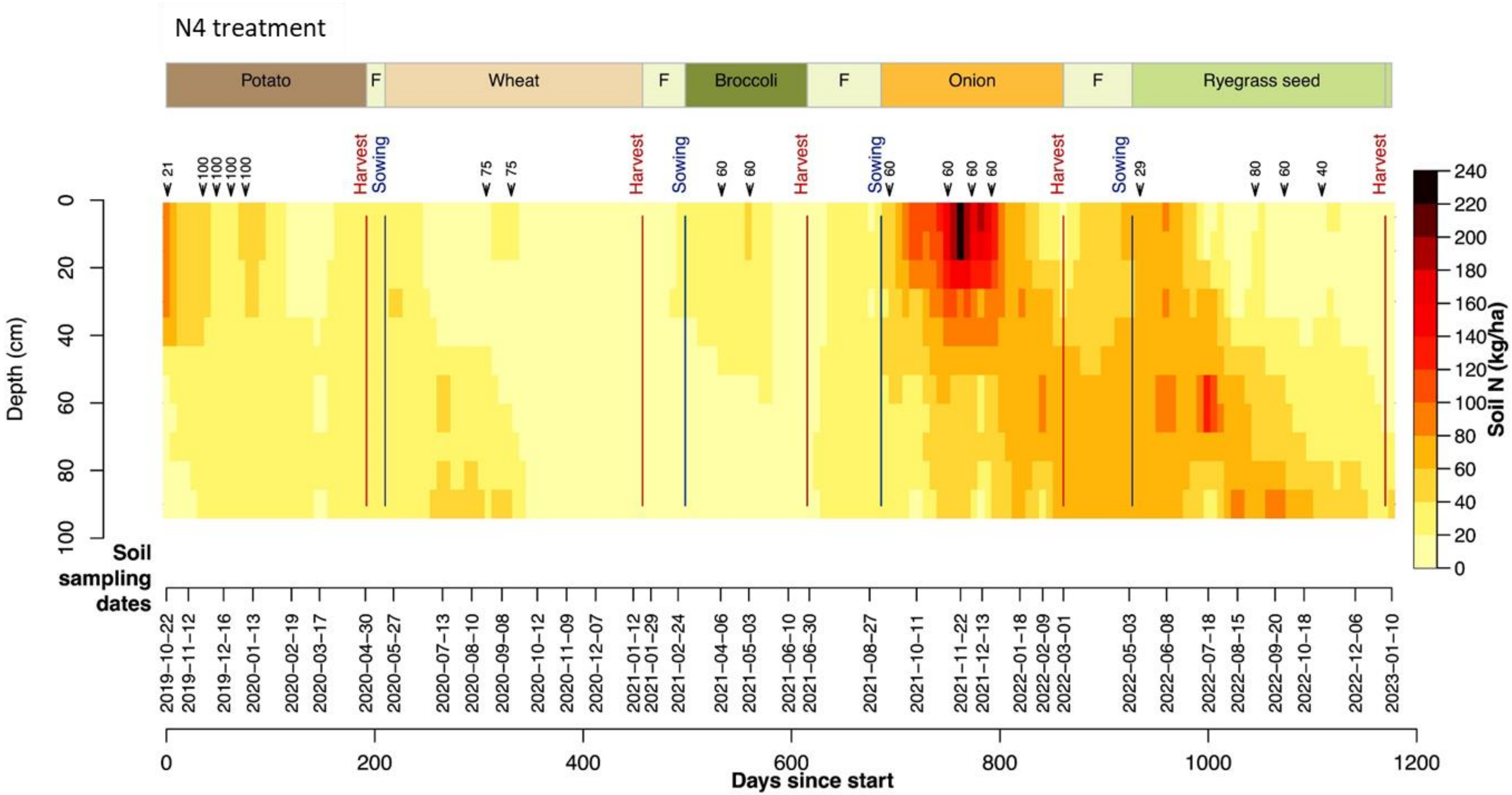


Figure 12. N4 treatment soil nitrate-nitrogen (N) interpolation plot to a soil depth of 90 cm across Rotation 1 sown at PFR, Lincoln, Canterbury. Upper arrows represent N fertiliser application dates and amounts for the different crops in the rotation. The period between harvest and sowing of the subsequent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

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

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

We estimated the N balance for soil mineral-N input and output from 0–30 and 0–60 cm depths and plotted PENL in response to N treatment (Figure 13). We also conducted an analysis of variance (ANOVA via Genstat, VSN International Ltd (2022)) to see if calculating the N balance using N from different soil depths resulted in different PENL outcomes (Table 1). This analysis indicated that irrigation had no effect on the N balance in these crops, and so the data reported focus on N responses.

The results from Figure 13 and Table 1 indicate that:

- PENL increases significantly ($p<0.001$) with N rate in potato, broccoli, and onion, and this is regardless of soil depth used for estimating the contribution of soil mineral-N to inputs and outputs.
- In contrast, PENL decreased significantly ($p<0.01$) with N rate in wheat, from a maximum average PENL of 63.8 kg N/ha with the N2 treatment to 21.8 kg N/ha with the N4 treatment when calculated using soil mineral-N in the top 30 cm of soil. The trend was similar when using the top 60 cm of soil but not significant.
- The depth of soil mineral-N contribution to the N balance calculation had no effect in broccoli regardless of N treatment. In wheat, there was a greater PENL at the N4 treatment when calculated with soil mineral-N to a depth of 60 cm compared with 30 cm depth. In potato, PENL was greater at all N treatments when calculated based on soil mineral-N to a depth of 60 cm.

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

Given that:

- most of the mineral-N is in the top 30 cm (55–88%, depending on stage in Rotation 1),
- and that most of the roots involved in uptake are in the top 30 cm of soil (Kristensen & Thorup-Kristensen 2007),
- and that the PENL response to N rate has the same pattern regardless of depth,

we calculate the N balance with soil N depths to 30 cm. This also has an added advantage of a sampling depth more easily fitted into routine commercial practice.

- There is significant variation in the PENL at each N rate regardless of crop; for example, the range of PENL values at N3 for potato are 98 kg N/ha. There was no significant correlation between variation in PENL and variation in initial mineral-N in the soil (Pearsons r = 0.03, p=0.213).

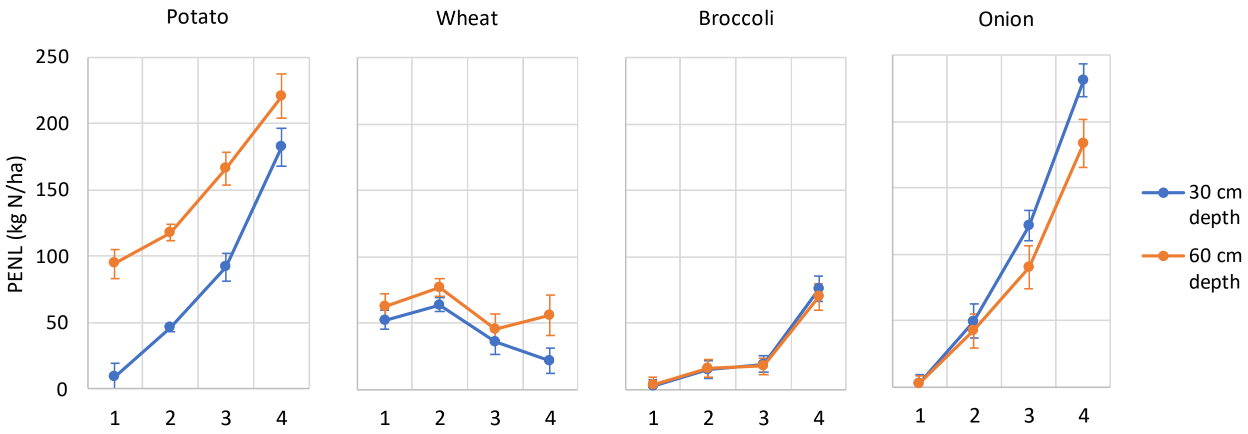


Figure 13. Changes in PENL (Potential Environmental Nitrogen Loss during crop growth) for potato, wheat, broccoli, and onion crops of Rotation 1 at different nitrogen (N) rate treatments. PENL calculated with initial and residual soil mineral-N in the top 30 cm depth and the top 60 cm depth of soil. Error bars are standard errors of the mean.

Table 1. Significance of nitrogen (N) rate at 30 and 60 cm on mean PENL (Potential Environmental Nitrogen Loss during crop growth) for potato, wheat, broccoli and onion crops of Rotation 1, and significance of difference between depths at each N rate. The LSD (p=0.05) is a measure of a significant difference between means at the 5% level and are identified in bold

	PENL estimate from N balance (kg N/ha)							
	Potato		Wheat		Broccoli		Onion	
Soil depth of mineral-N supply (cm)								
	30	60	30	60	30	60	30	60
N rate								
1	**8.4**	**94.1**	52.3	62.7	2.5	4.0	2.9	2.2
2	**45.8**	**117.8**	63.8	77.0	15.3	15.8	49.6	42.3
3	**91.7**	**166.0**	35.8	45.6	18.9	17.4	121.8	90.1
4	**182.1**	**220.7**	**21.6**	**55.9**	76.0	69.8	**231.2**	**183.8**
N sig. (*p*)	<0.001	<0.001	0.01	NS	<0.001	<0.001	<0.001	<0.001
N LSD (*p*=0.05)	32.9	37.9	25.8	35.7	21.8	23.5	32.3	40.7
Depth sig. (*p*) at each N rate								
1	<0.001		NS		NS		NS	
2	<0.001		NS		NS		NS	
3	<0.001		NS		NS		NS	
4	0.026		0.024		NS		0.009	
Depth LSD (*p*=0.05)	33.8	-	29.7	-	21.3	-	34.9	-

The PENL level at the different N rates varies with crop. For instance, at the N3 treatment, PENL of potato is 91.7 and onion 121.8 kg N/ha. These are higher than the PENL of 35.8 and 18.9 kg/ha for wheat and broccoli. These PENL levels are not just a function of applied N fertiliser rate – for instance the N3 fertiliser rate for wheat was 150 kg N/ha and that of onions 120 Kg N/ha – but despite a 30 kg N/ha difference in N rate, there was an 86 kg N/ha difference in PENL. Clearly, there is a crop effect on PENL that may be associated with root depth activity and growth characteristics, or differences in previous crop residue decomposition.

3.1.2 Nitrogen balances

The calculated N balance for each crop is shown in Figures 14–17.

The N remaining in-field is the difference between the total N inputs and that exported in sold product. This in-field N is split into the portion that remains in the soil as mineral-N at harvest, the residue component of the crop, and the remainder which is the PENL. The PENL component can be split into leaching and gaseous losses – this will be explored in subsequent reporting.

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

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

These results indicate that the N balance is a crop-specific result and depends on the way the crop takes up and uses N. The PENL component of the in-field N for onion at the N1 treatment (no fertiliser added) is much higher than that for the broccoli and potato crop. Comparison across a wider range of crops will be needed to corroborate this, and subsequent analysis of N balance in Rotations 3 and 4 will help to contribute to this.

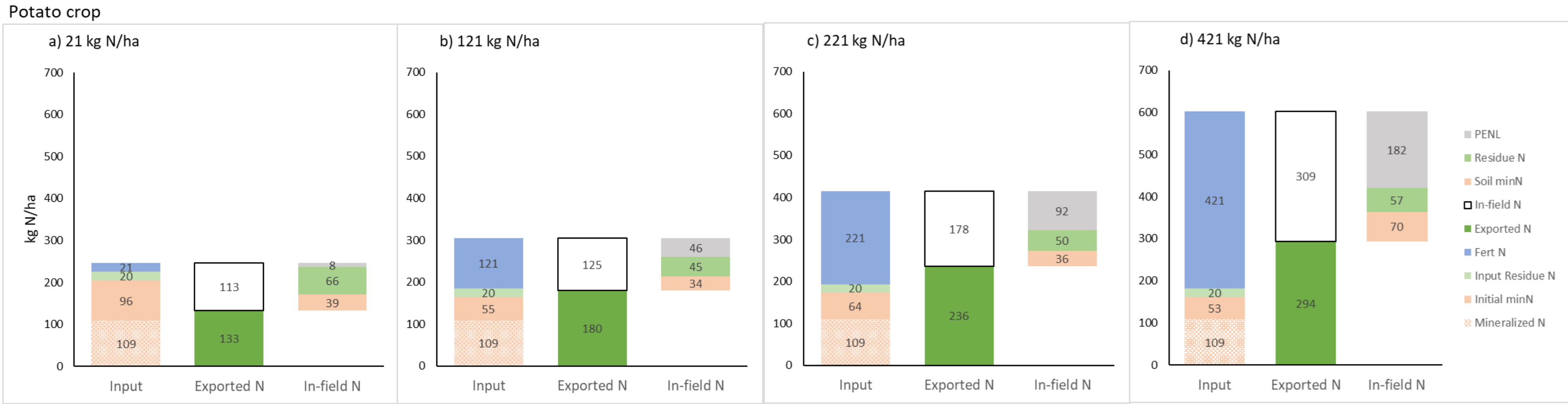


Figure 14. Nitrogen (N) balance of potato crop from Rotation 1 at different N rates. Potato crop was the variety ‘Russet Burbank’ sown on 22 October 2019 at PFR, Lincoln, Canterbury.

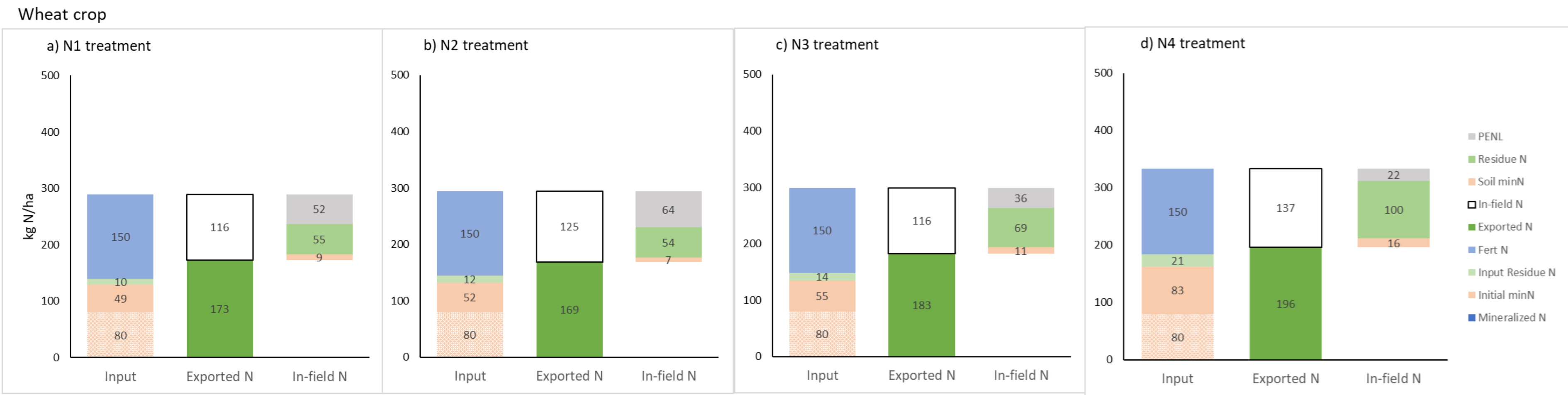


Figure 15. Nitrogen (N) balance of wheat crop from Rotation 1 at different N rates. Wheat crop was the variety ‘Catherine’ sown on 19 May 2020 at PFR, Lincoln, Canterbury.

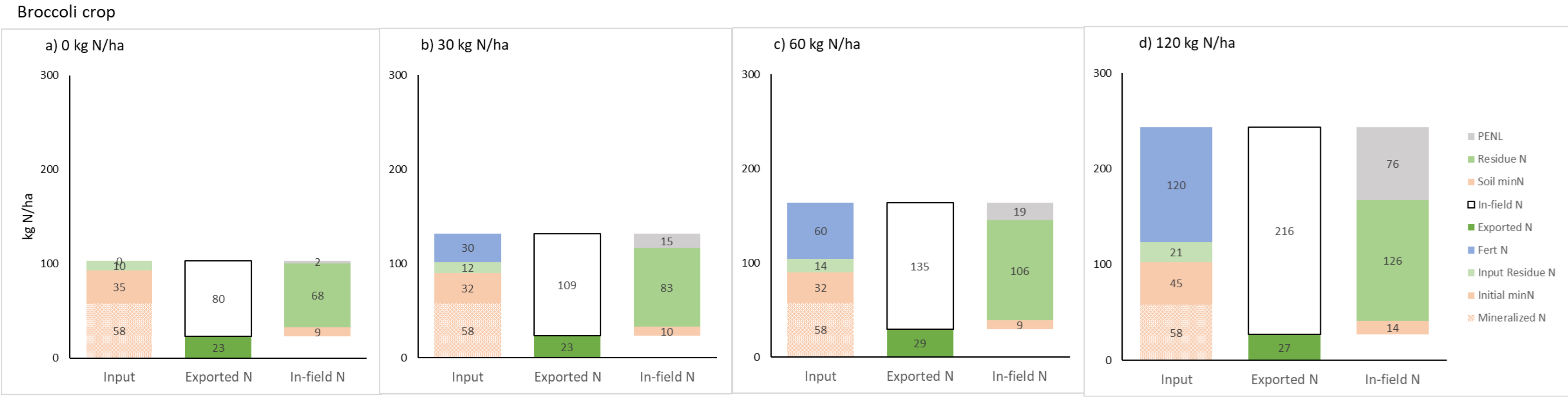


Figure 16. Nitrogen (N) balance of broccoli crop from Rotation1 at different N rates. Broccoli crop was the variety 'Nobel' transplanted on 3 March 2021 at PFR, Lincoln, Canterbury.

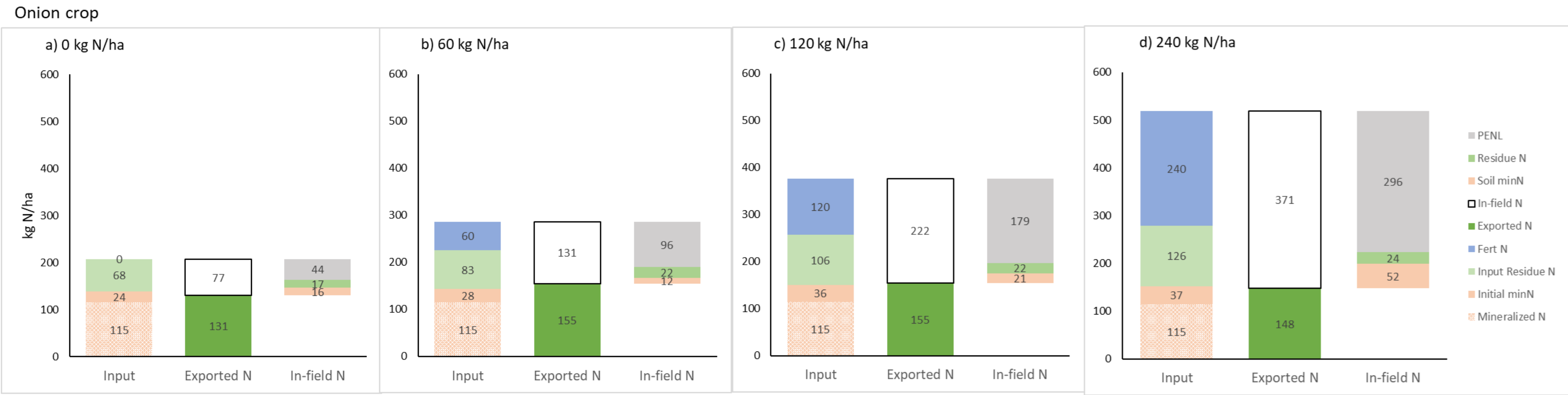


Figure 17. Nitrogen (N) balance of onion crop from Rotation 1 at different N rates crop. Onion crop was the variety 'Tilbury' sown on 7 September 2021 at PFR, Lincoln, Canterbury.

3.2 Rotation 2

3.2.1 Soil mineral-N

The plots of interpolated soil mineral-N to depths of 90 cm for Rotation 2 are shown in Figure 18 to Figure 21. Results show:

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

PENL was estimated using N from the top 30 and 60 cm of soil (
Figure 22 and Table 2). The plots show that there is considerable variation in PENL, and this is more marked when estimated using N in the top 60 cm of soil. There were no significant differences in PENL with N rate when estimated using N from the top 60 cm of soil (Table 2). These results corroborate results from Rotation 1, suggesting that the calculation of N balance using the top 30 cm of soil can provide a useful indicator of the N balance of a crop.

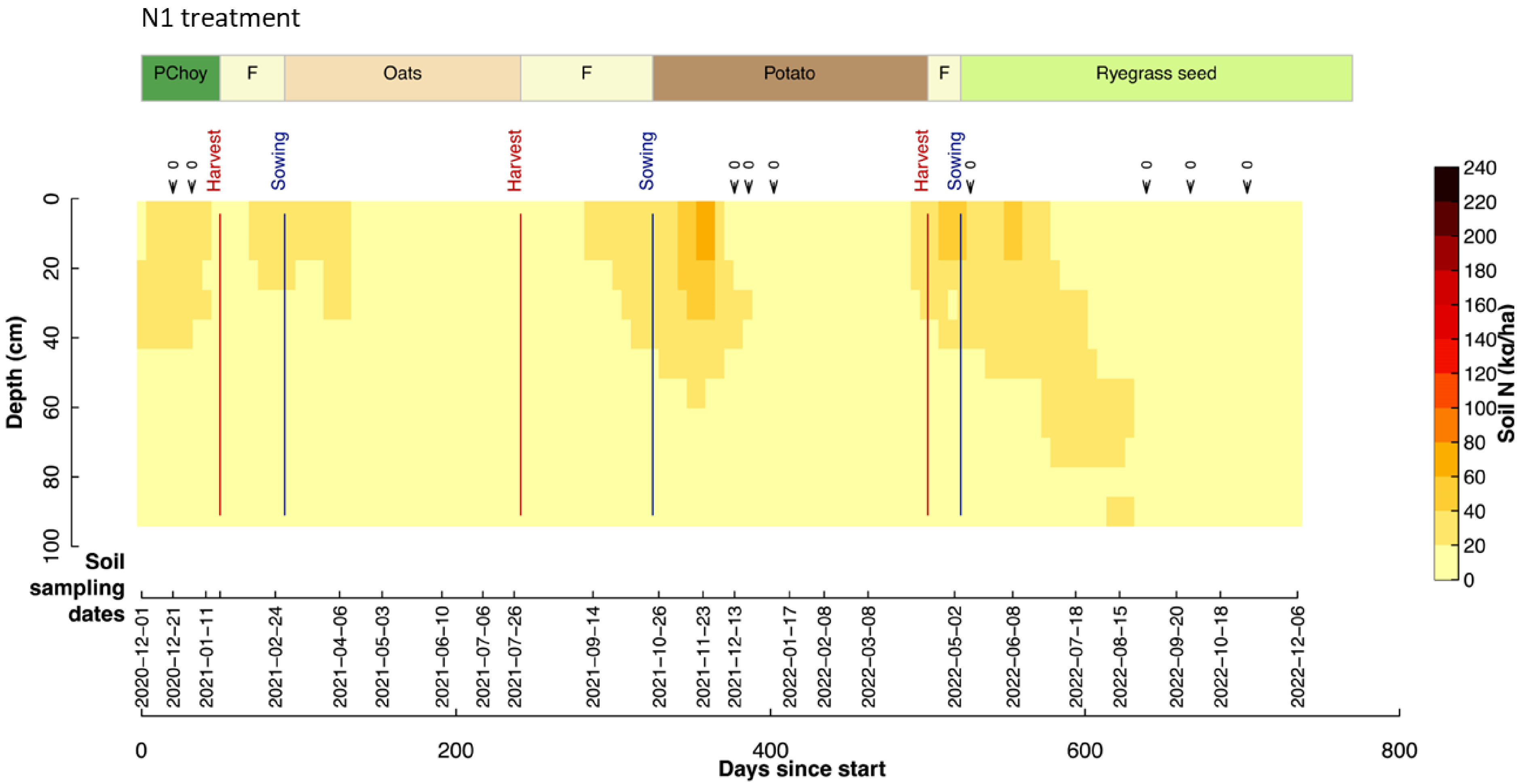


Figure 18. N1 treatment soil nitrate-nitrogen (N) interpolation plot to a soil depth of 90 cm across Rotation 2. Upper arrows represent N fertiliser application dates and amounts for the different crops in the rotation. The period between harvest and sowing of the subsequent crop is fallow period (F).

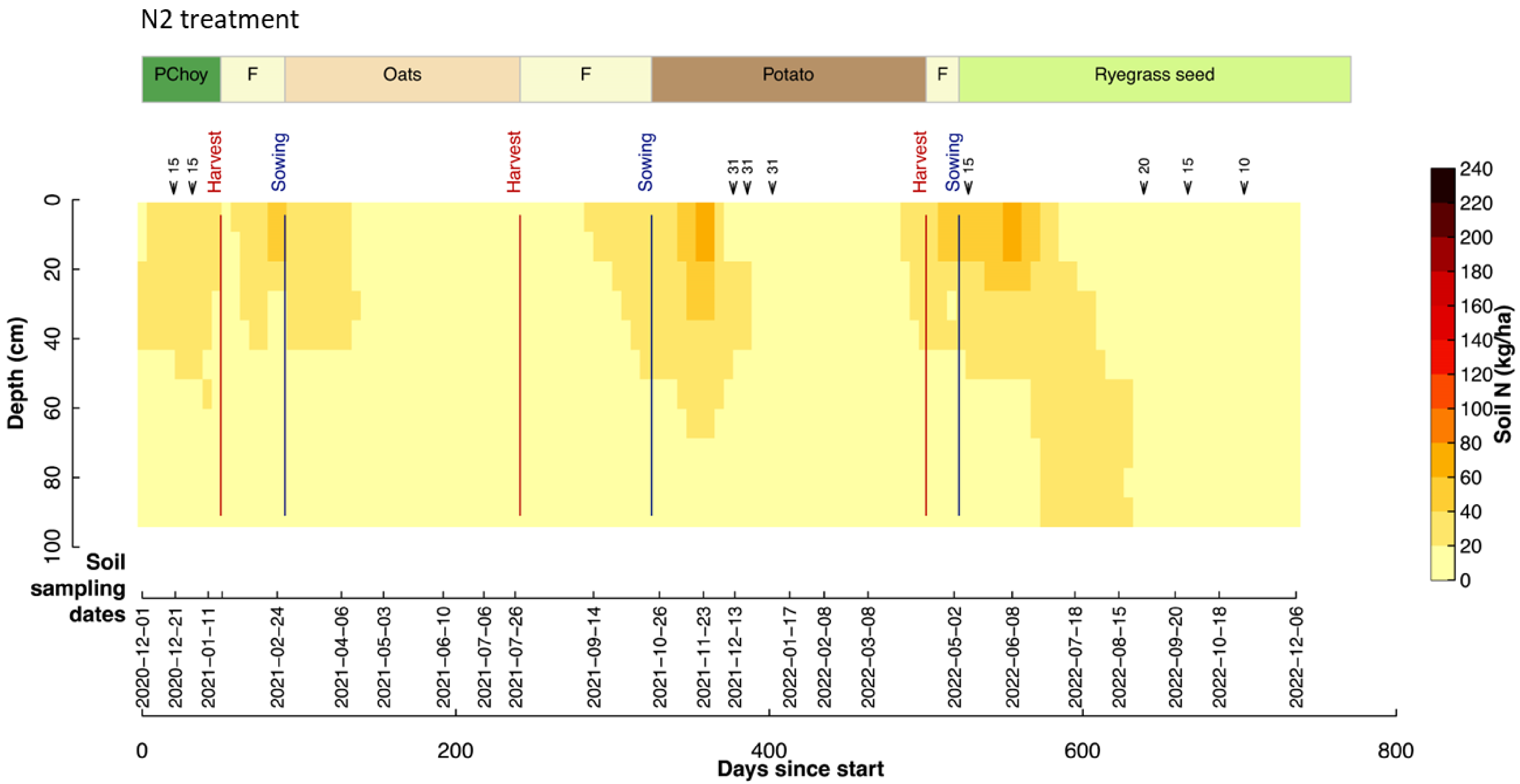


Figure 19. N2 treatment soil nitrate-nitrogen (N) interpolation plot to a soil depth of 90 cm across Rotation 2. Upper arrows represent N fertiliser application dates and amounts for the different crops in the rotation. The period between harvest and sowing of the subsequent crop is fallow period (F).

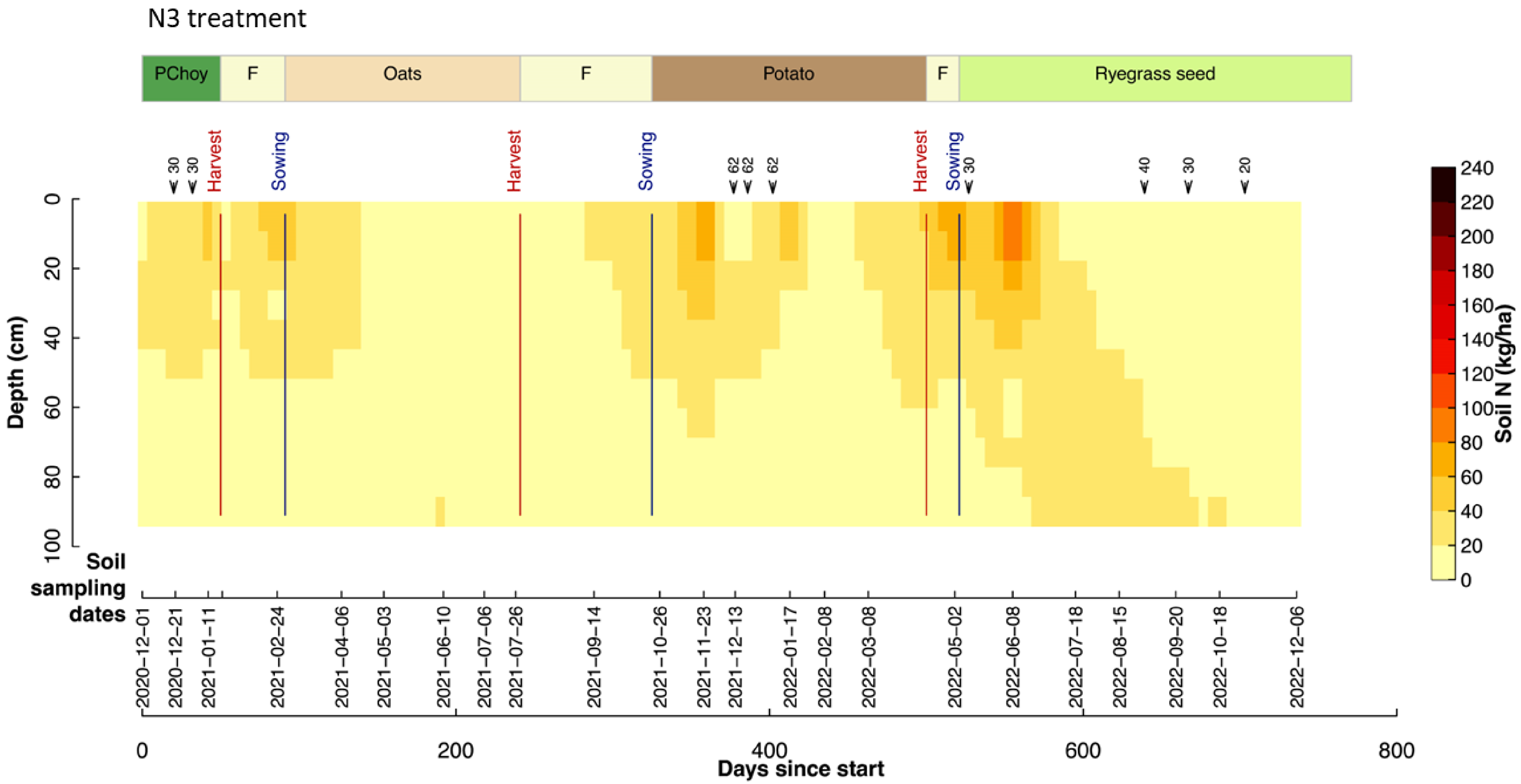


Figure 20. N3 treatment soil nitrate-nitrogen (N) interpolation plot to a soil depth of 90 cm across Rotation 2. Upper arrows represent N fertiliser application dates and amounts for the different crops in the rotation. The period between harvest and sowing of the subsequent crop is fallow period (F).

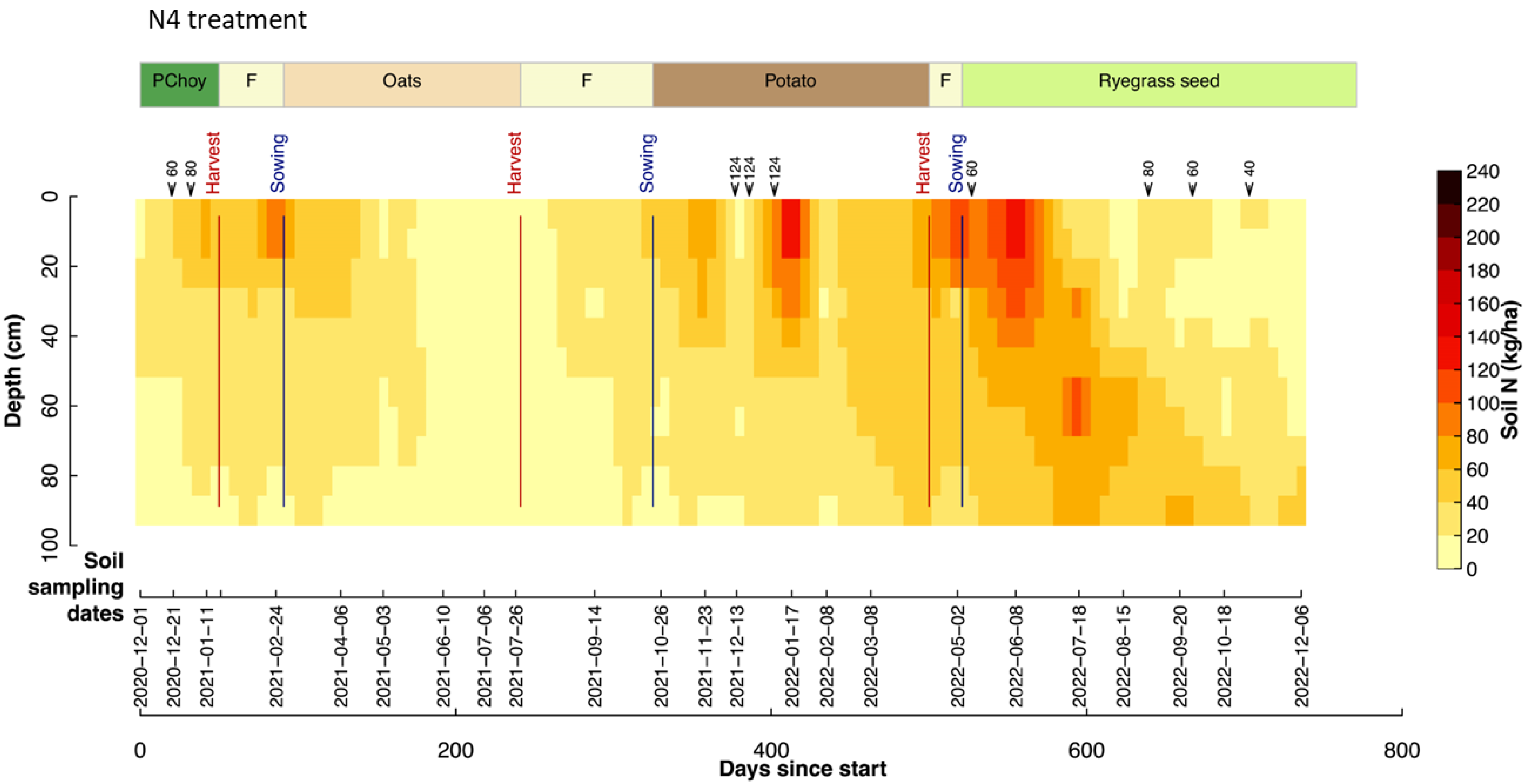


Figure 21. N4 treatment soil nitrate-nitrogen (N) interpolation plot to a soil depth of 90 cm across Rotation 2. Upper arrows represent N fertiliser application dates and amounts for the different crops in the rotation. The period between harvest and sowing of the subsequent crop is fallow period (F).

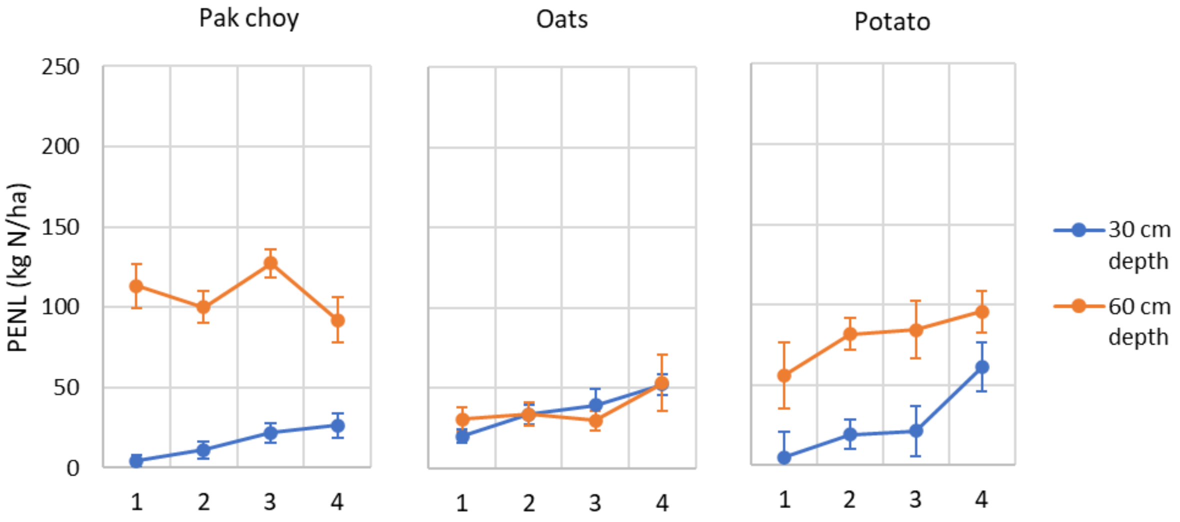


Figure 22. Changes in PENL (Potential Environmental Nitrogen Loss during crop growth) for pak choy, oats, and fresh-market potato crop of Rotation 2 at different nitrogen (N) rate treatments. PENL calculated with initial and residual soil mineral-N in the top 30 cm depth and the top 60 cm depth of soil. Error bars are standard errors of the mean.

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

PENL estimate from N balance (kg N/ha)						
	Pak choy		Oats		Potato	
Soil depth of mineral-N supply (cm.)						
	30	60	30	60	30	60
N rate						
1	4.3	113.4	20.0	30.7	5.3	56.2
2	11.0	100.1	33.7	33.8	19.2	81.8
3	21.8	127.2	39.5	29.9	21.4	84.61
4	26.5	92.1	52.4	53.2	61.2	95.9
N sig. (*p*)	NS	NS	0.05	NS	0.03	NS
N LSD (*p*=0.05)	19.1	35.7	22.7	34.9	42.4	50.2
Depth sig. (*p*) at each N rate						
1	<0.001		NS		0.007	
2	<0.001		NS		0.006	
3	<0.001		NS		0.006	
4	<0.001		NS		NS	
Depth LSD (*p*=0.05)	27.8		28.4		21.3	

3.2.2 Nitrogen balances

The calculated N balances for pak choy, oats and fresh market potatoes are shown in Figure 23 to Figure 25. Some general observations from the N balances are:

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

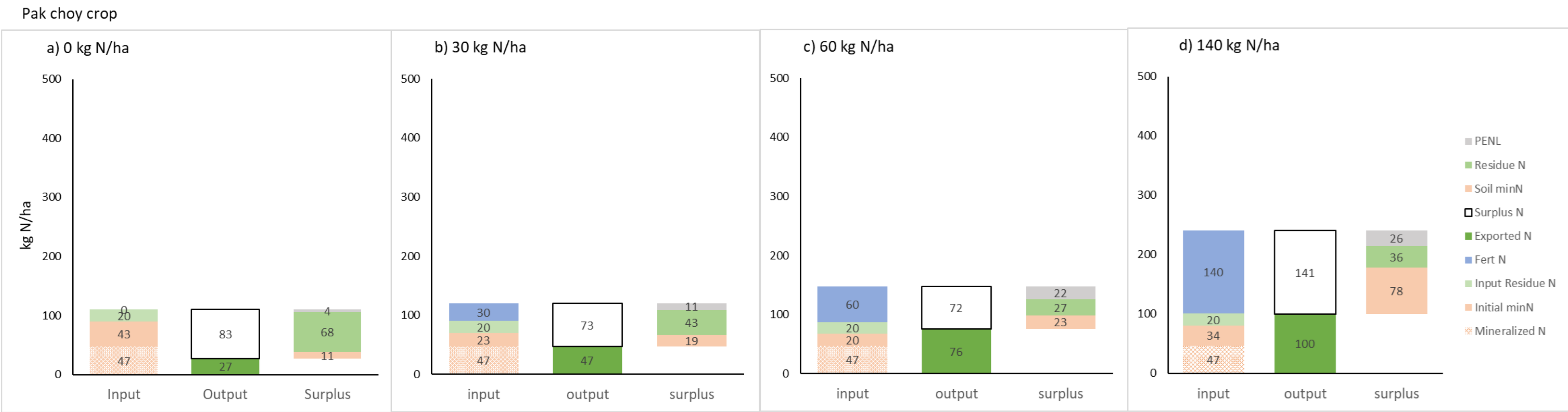


Figure 23. Nitrogen (N) balance of pak choy crop from Rotation 2 at different N rates. Pak choy crop was the variety ‘Shanghai’ sown on 7 December 2020 at PFR, Lincoln, Canterbury.

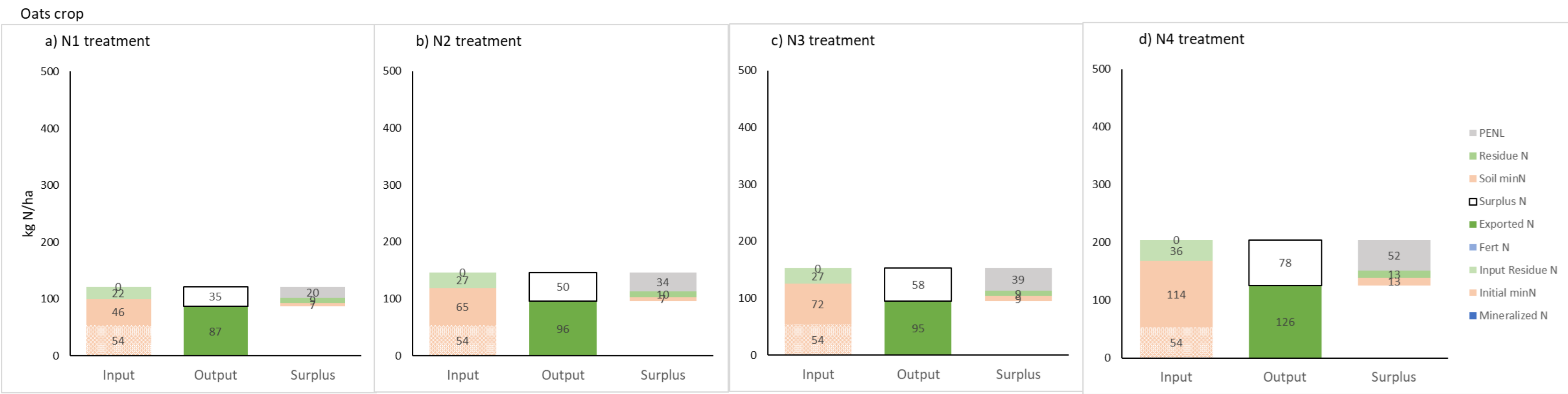


Figure 24. Nitrogen (N) balance of oat crop from Rotation 2 at different N rates. Oat crop was the variety Milton sown on 19 May 2020 at PFR, Lincoln, Canterbury as a catch crop.

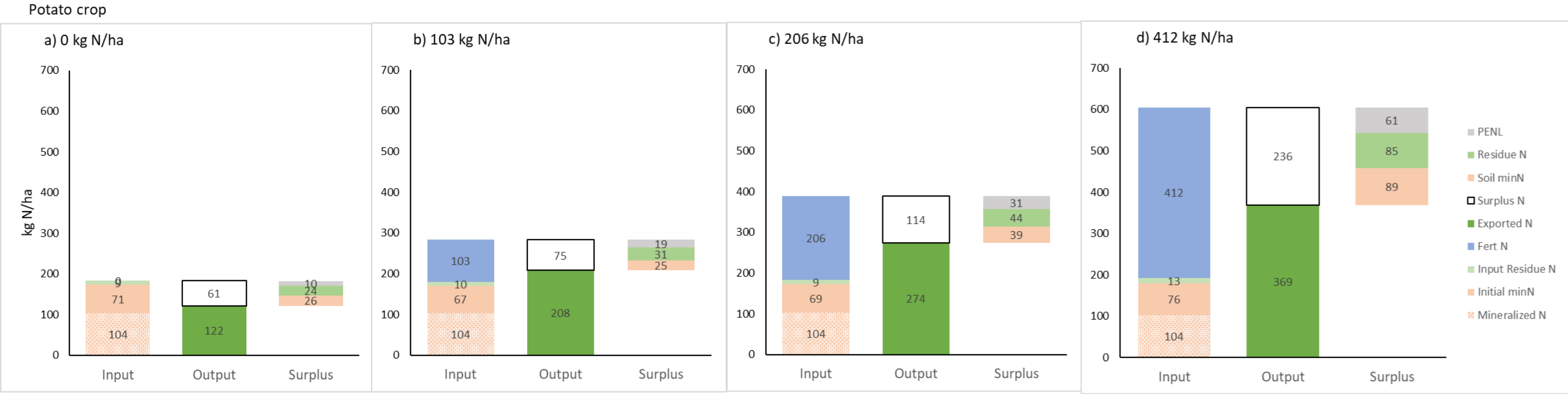


Figure 25. Nitrogen (N) balance of potato crop from Rotation 2 at different N rates. Pak choy crop was the variety 'Agria' sown on 22 October 2021 at PFR, Lincoln, Canterbury.

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

The potato crops in Rotations 1 and 2 were different varieties, grown for different markets and with different N management, and also quite different N balances (Table 3, Figure 14 and Figure 25). There was a much higher potential for losses in Rotation 1 with a PENL of 92 kg N/ha (51% of in-field N) compared with 31 kg N/ha in Rotation 2 (27% of in-field N) at the N3 treatment rate. This is a large difference in the N balance for crops that had good management fertiliser application.

Table 3. Comparison of potato crops in Rotations 1 and 2 with management, yield and Potential Environmental Nitrogen Loss (PENL) of N3 treatment.

Rotation	Variety	Market	Method	N3 treatment					
				Side-dress	Rate (kg N/ha)	Total N input (kg N/ha)	Yield (t/ha)	Exported N (kg N/ha)	PENL (kg N/ha)
1	'Russet Burbank'	Processing	Potato Calculator	Pre-set time	221	414	72	236	92
2	'Agria'	Fresh	SVS Prototype	Checked with nitrate test strip	206	389	81	274	31

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

Differences in the PENL could be due to:

- Differences in side-dress 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. This could be why there was a more even N supply throughout the life of the crop in Rotation 2 (Figure 14).
- 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.

Future work should involve direct comparison, particularly of yield effects and N uptake and use effects on the N balance outcomes.

To understand some of the differences in N balance interactions between the two crops, we evaluated relationships between PENL, yield, and N supply as an initial comparison, using regression and plotting the relationships.

The amount of PENL that occurred was relatively well predicted by fertiliser N rate in Rotation 1 (R^2=82.4, Table 4) but not in Rotation 2 (R^2=22.6, Table 4). Similar responses were observed for total N input and when combined across both rotations did not provide a good indicator of PENL levels (Table 4).

Table 4. Regression parameters and goodness of fit of potential environmental nitrogen loss (PENL) against yield, applied N fertiliser, total N input, and partial N balance (PNB) for potato crops in each of Rotations 1 and 2 and combined across rotations.

Predictor	Intercept	Parameter	R2	p-value
Potato Rotation 1				
Yield	-233.8 (68.6)	4.69 (1.01)	40.0	<0.001
Fertiliser N	-3.95 (8.89)	0.439 (0.036)	82.4	<0.001
Total N input	-91.8 (16.0)	0.449 (0.039)	81.1	<0.001
PNB	92.6 (4.98)	0.720 (0.054)	85.2	<0.001
Potato Rotation 2				
Yield	15.2 (53.6)	0.114 (0.68)	1	0.86
Fertiliser N	-3.5 (11.4)	0.153 (0.048)	22.6	0.003
Total N input	-30.0 (18.3)	0.149 (0.046)	23.2	0.003
PNB	57.1 (7.4)	0.48 (0.07)	57.6	<0.001
Combined across rotations				
Yield	83.5 (52.6)	-0.08 (0.71)	1	0.96
Fertiliser N	-3.54 (9.98)	0.301 (0.041)	45.1	<0.001
Total N input	-58.4 (16.7)	0.297 (0.041)	44.5	<0.001
PNB	80.81 (4.52)	0.670 (0.047)	76.5	<0.001

To consider the yield and N uptake effect within the balance, we also calculated a partial nitrogen balance (PNB) estimated by subtracting applied N from the exported N (which is Yield x N content). PNB can have negative values if the amount of exported N is greater than the applied N fertiliser. Since exported N is a key component of the balance, PNB has been related to PENL in cereal and maize crops (Rozas et al. 2004; Rocha et al. 2020; Tamagno et al. 2022).

The results (Table 4) suggest that PNB is a better estimator of PENL than the applied N or total N input in each rotation and when combined, though still not a strong predictor of PENL in Rotation 2 or across the combined crops.

While there is a poor relationship between yield and PENL (Table 4), plots show there is a unique relationship that is defined by N rate, and at each N rate PENL decreases as yield increases across the both rotations (Figure 26a). We fitted an ellipse to these relationships that contains an estimated 95% of the data to highlight each unique relationship, and these data indicate that PENL is strongly driven by yield and N supply to the crop. The relationship is very similar between yield and PNB (Figure 26b). There is more overlap in PENL with N rate (Figure 26a) whereas the PNB relationships are more clearly defined (Figure 26b).

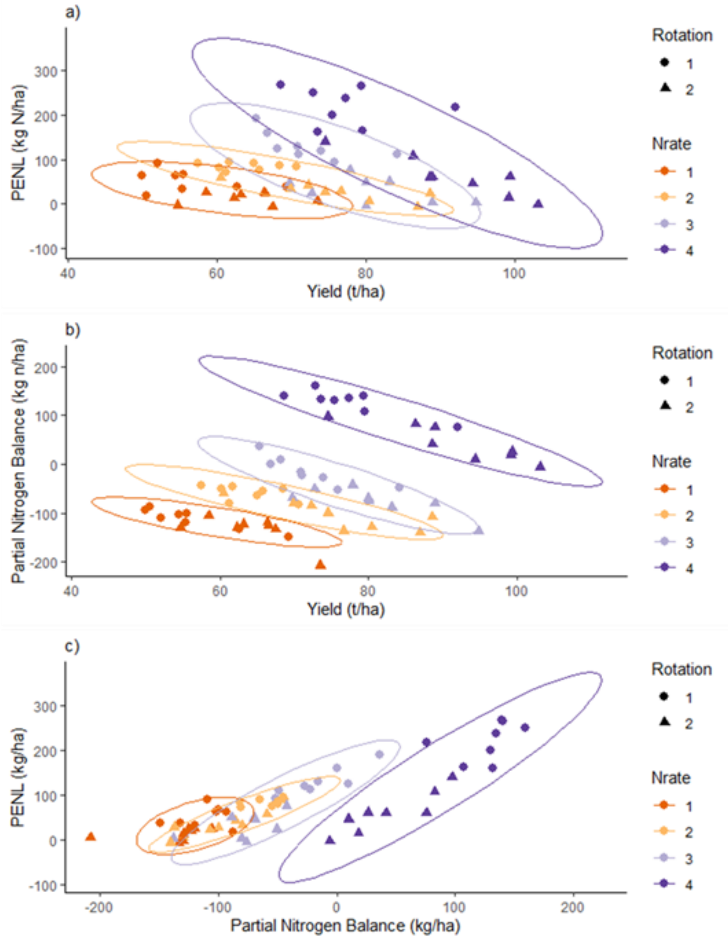


Figure 26. Relationship between a) yield and potential environmental nitrogen loss (PENL), b) yield and partial nitrogen balance (PNB) and c) between PNB and PENL. Ellipses are the 95% confidence intervals for the data of relationships between the parameters for each N rate for potato crops grown in Rotations 1 and 2.

There was a closer relationship between PNB and PENL also defined by N rate (Figure 26c) and by crop (Table 4). So, while combined across all N treatments in both rotations, PNB was not closely correlated with PENL (Table 4), the relationship for N3 treatment was a significant quadratic response (R^2=81.7, p<0.001).

These relationships indicate that yield and N supply are important factors when considering potential N loss from a crop. We explored this by overlaying the yield response with PNB for the N3 treatment (Figure 27). The estimate of PENL for a combination of yield and N had an R^2 of 81%, while for PNB it was 91% for each rotation. Given that at N3, there is a close relationship between PNB and PENL, we opted to overlay the yield response on PNB as an indicator of likely losses. The PNB isolines (with the isoline of PNB=0 in red) show that at a given N input, the isoline depends on yield.

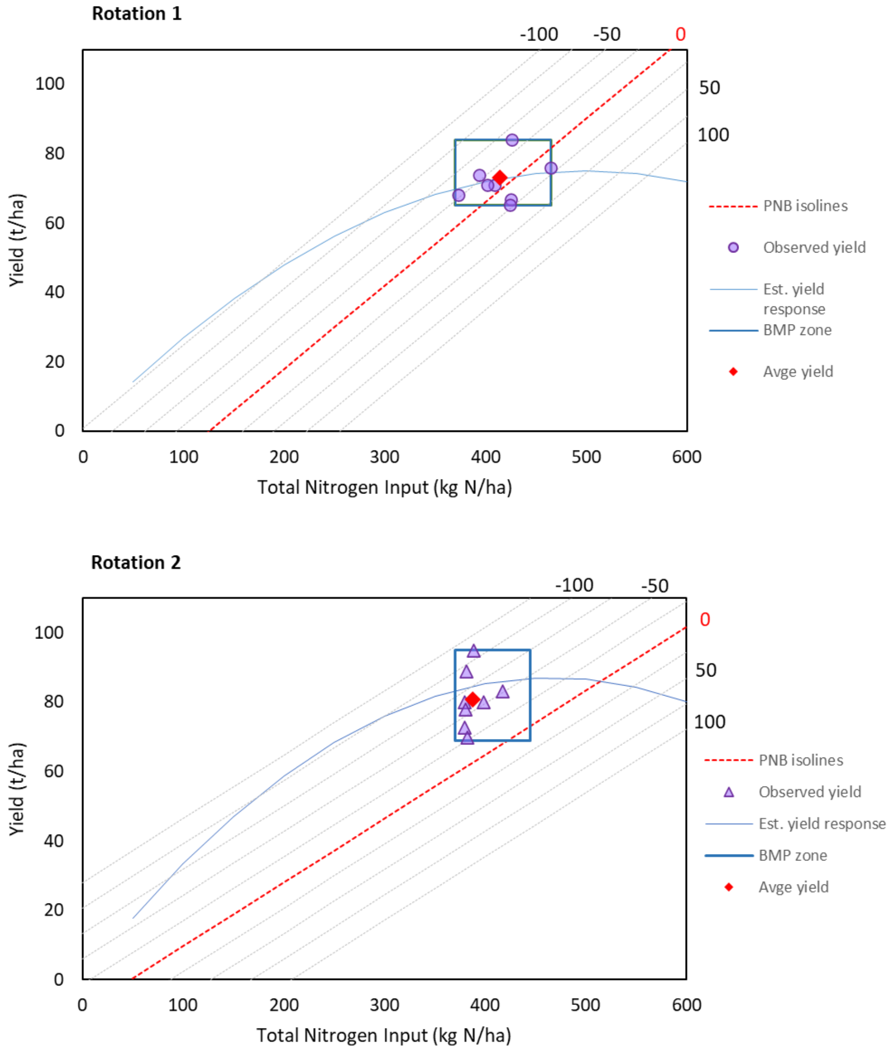


Figure 27. Relationship between yield and total nitrogen (N) input of potato crops in Rotations 1 and 2. Isolines represent the partial N balance (PNB), with the red highlighting when PNB=0 (N fertiliser application = N exported by crop). Data is average and observed yields for the N3 treatment (good management rate) in each rotation. The BMP (Best Management Practice) encompasses the spread of yield and total N input observed for the N3 treatment.

We compared the yield response using total N inputs to highlight the variability present in yield and PNB for each crop and there is a difference between the responses in the two rotations (Figure 27). For Rotation 1, average yield is 72 t/ha (ranges from 65 to 84 t/ha) and PNB averages −15 kg N/ha (ranges from −52 to 36 kg N/ha), In Rotation 2, the average yield is 81 t/ha (range from 70 to 95 t/ha) with an average PNB of −77 kg N/ha (range from −138 to −44 kg N/ha).

It could be assumed that PNB is lower, and hence N losses lower in Rotation 2, due to the higher yield and slightly lower N inputs. To achieve a PNB of −75 kg N/ha in Rotation 1 for the same input would require an average yield of 86 t/ha – higher than the maximum achieved in Rotation 1 and higher than the Rotation 2 average yield. Thus, the improved N balance in Rotation 2 is not due to yield alone, though the greater yield is a contributor.

There could be several reasons for the difference:

- The uptake of N and partitioning differed between the varieties. The 'Agria' crop in Rotation 2 used 71% of all N supplied for the export component. This lowered the amount of in-field N, and the residue component made up 38% of that. In contrast, the 'Russet Burbank' crop of Rotation 1 took up only 57% of total N supplied in the marketable yield, and the residue component only made up 28% of the in-field N component of the balance.
- The N supply to the crop in Rotation 2 was more even – an additional 20 kg N/ha was supplied to the crop in the last side-dressing as soil n content was getting lower than expected. This means that the N supply throughout the life of the crop was not as limited for the Rotation 1 crop (Figure 11 and Figure 20).
- A possible combination of all these conditions.

The analysis reveals several implications that need considering:

- For each N rate, higher yields result in lower PNB and PENL (Figure 26). This means that yield is important in minimising losses. It highlights that yield outcomes should be considered when interpreting N balance outcomes. Seasonal effects (combinations of temperatures, solar radiation, and rainfall) that result in higher yield potential will give a lower potential loss. This means that a target level of loss imposed as an indicator, does not really reflect the realities of the crop–soil system on a seasonal basis.
- There is an overlap in the PENL for treatments N2 and N3 (N2 was half the rate of the N3 treatment) when plotted against yield (Figure 26a) and plotted against PNB (Figure 26c). This suggests that increasing N treatments to non-limiting levels does not necessarily increase losses of N from the system, particularly if yields are maximised for a good management treatment.

There is a significant variation in yield, PENL and PNB at each N rate (see Figure 13,

- Figure 22, Figure 27). The N3 treatment is as close to good management practice as we were able to estimate. At this treatment rate N is not limiting yield, nor is the crop taking up N that is not used for additional growth. This suggests that the relationship between PNB and yield is reflecting the N status of the crop. So, PENL seems to reflect physiological and environmental interactions on growth and N uptake. Again, this indicates that a fixed target loss does not address the system realities and dynamics. A better approach is to define a good management zone of PENL that comprises good input management and crop production.

3.4 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 provides a unique 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 in subsequent research 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

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 should involve one-to-one involvement and interaction, as well as group discussion.
- Develop farm field trials to contribute to use case evaluation that validate the N balance approach and identify key concerns. These would include standard practice compared with use of the tool to validate the use of the N balance approach across a wide range of environments and crops. These data are necessary to ground the tool in commercially relevant situations. It will also help improve the tool parameter values and predictive capacity.

Tool improvement

This is about key science questions that have arisen. This should link very closely with the tool use aspect, so that any improvements are included in the farmer data driven evaluation.

- Specific trials should be conducted to compare outcomes of the N balance where side-dressings are set by calendar dates with side-dressing rates and timings determined based on soil nitrate test strip assessment during growth.
- Specific trials should compare same varieties of selected crops grown in different environmental conditions – to evaluate the yield potential effect on N balance outcomes.
- Specific trials should be conducted to provide the information needed to fine tune a residue model as well as to evaluate its implementation in making decisions on fertiliser management. An approach for this work is described in Figure 7.
- 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 PENL. This has implications for how rotations should be structured for best N management and environmental outcomes.
- Evaluation of any other parameter of the model as identified by grower discussion and use cases.

4 Key highlights and achievements

Workstream 1

- Rotations 1 and 2 (Lincoln) have been completed; these fields have been left in pasture after the ryegrass seed harvest. Rotation 3 was largely completed, but the last two soil samples in fallow soil were affected by Cyclone Gabrielle.
- Rotation 4 will continue with soil N and biomass sampling of the ryegrass crop. This crop had not been turned into fallow before Cyclone Gabrielle, so changes in soil N from tilling and incorporating the residue can be followed.
- Data continue to be gathered and analysed as planned. An approach to interpolate soil mineral-N data over time and depth provides graphs that visualise soil N movement across the rotations. Initial analysis of the N balance from potato crops in Rotations 1 and 2 provide indications that management can reduce potential N losses from the system.

Workstream 2

- We have continued to process samples for biomass and crop N content.
- A database of the results is now available.

Workstream 3

- A significant amount of work has gone into coding and preparing a grower-facing tool. This has been informed by many interactions with technical panels and with discussions with growers.
- A grower-facing tool is ready for use in case studies with growers. While the underlying algorithms are the same, the interface provides three different layers, depending on the amount of data the grower wants to input. These layers also allow users to explore implications of management decisions within their system.
- Options for managing IP have been implemented.
- Work on a preliminary approach to residue decomposition and modelling structure has been conducted.

Workstream 4

- Papers and articles prepared and presented.
- Demonstration of tool use with growers.

5 Collaborations with other programmes

- Real time N-losses – Rural Professional Fund through the National Science Challenge, Our Land and Water, looking at real-time measurement of N losses under vegetable (onion) production in Hawke's Bay. PFR is providing data analysis support.
- Residue incubation – PFR-funded project looking to quantify the rate of decomposition of different vegetable residues and the rate of N release from the residues into the soil. Some residues were obtained from crops in Workstreams 1 and 2. A scientific journal paper is almost ready for submission that incorporates the results of this work.
- Process Vegetable Coefficients – Process Vegetables New Zealand-funded project quantifying some of the coefficients needed for N uptake and use by processed vegetable crops within Overseer.
- Mineralisable N to improve management – a Sustainable Food and Fibre Futures (SFFF) project looking to improve the measurement and prediction of the amount of biologically mineralised N in a field. This pool of N is a key component for understanding crop N requirements, alongside measurements of mineral-N (nitrate and ammonium). PFR leads this project, which includes the Vegetable Research & Innovation Board and Potatoes New Zealand.
- Regenerative Management of NZ Vegetables (SFFF). This project with LeaderBrand is evaluating the use of compost for vegetable production. There is interest in collaboration to ensure a grower-facing tool can incorporate compost as a N source.

6 Annual workplan

Workstream 1

1. **Data analysis completed.**

    - Complete data analysis of rotations, including all crop and soil parameters. Provide information on assumptions of key parameters for model to Workstream 3.
    - Complete leachate analyses. Liaise with work in Workstream 3 to obtain these data for analysis.
    - Prepare information for extension/publication.

Workstream 2

- Continue to work with regional monitors to support data collection, complete N analysis and prepare data for analysis.

- Contribute to analysis of data.

Workstream 3

1. **Model implementation**

    - In collaboration with Workstream 4 continue one-on-one discussion and demonstrations of model.
    - Implement model refinements based on discussions and workshops and make model ready for field testing.
    - Test model with data from Workstreams 1 and 2.
    - Contribute to case studies and use learning to help improve model usability and outputs.

2. **Model development**

    - Complete modelling of N uptake and losses by all crops in the rotations using SCRUM-APSIM ensuring appropriate parameterisation of parameters for different crop types and environmental conditions. These data to inform ongoing tool implementation.
    - Together with Workstream 1 analysis, evaluate assumptions and parameter values used. Information to contribute to model implementation.

Workstream 4

- Contribute to webinars and podcasts as needed.

    - Contribute to planning of themes and topics.
    - Contribute to content planning and presentation.

- Contribute to extension around model implementation in conjunction with activities of model implementation in Workstream 3.

- Contribute to extension with articles and manuscripts. Liaise with wider Workstream 4 team to define articles to be published. Papers to include:

    - Nitrogen use efficiency of different crops and rotations.
    - Nitrogen balance as a management tool to improve N use efficiency and reduce losses.
    - Consider publishing a data paper – to make all data from SVS available internationally.

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Appendix 1. Workstream 1 experimental approach

Overview

There are four different rotations within this programme of work consisting of different crops chosen together with growers and agronomists (also known as the Technical Panel) to represent key crops where information was most needed. These rotations 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) and details of crops and sowing dates are shown in Tables A1-A4.

Experimental design and treatments

Each rotation consists of four rates of nitrogen (N) fertiliser and two rates of irrigation, replicated four times. This results in a total of 32 plots in each rotation (128 plots in total across all four rotations). Each experiment is set as a split-plot design, with irrigation rate as the main plot and N rate as the sub-plot. The aim of the irrigation treatments is to provide an irrigation rate at which yield is not compromised. For this, irrigation is applied to ensure that soil moisture deficit does not trigger yield reduction, and this depends on crop type. The I1 treatment aims to ensure that there is little to no drainage, and so irrigation is applied to replace lost water to a deficit of 15–20 mm below field capacity. This also accommodates for potential rainfall events during the season. The I2 treatment ensures that additional irrigation is applied, so that the deficit sits close to field capacity and thus increases the likelihood of drainage.

The N fertiliser rates vary from crop to crop (Tables A1–A4) and depend on the supply from soil mineral N and mineralisable N, which are measured at planting. One aim is to ensure that the N3 treatment reflects what is considered as a good management rate. This rate is determined by consulting literature and tools (e.g., Potato Calculator, Nutrient Management Handbook for Vegetables) that provide good N management fertiliser rates, and the final rate is confirmed in discussion with the Technical Panel, made up of agronomists and growers. The number and timing of side-dressings are also confirmed with the Technical Panel. In some cases, where soil N supply is sufficient that very low rates of additional fertiliser are needed, the aim of the N treatments is to have enough spread of N to provide useful data on N uptake and losses from the system for modelling purposes. Each N treatment plot stays consistent across the duration of the rotation – hence a N3 plot will consistently receive the N3 treatment rate for all crops, except for catch crops that received no applied N fertiliser.

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

* N applied at planting

Table A2.. Rotation 2 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
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 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
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 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
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	50:50 mix of ‘Asset’ and ‘Tama’ ryegrass					
Fertiliser rate (kg N/ha)						
Side dressings						

Data collection and analysis

Crop biomass is sampled monthly following the date of crop sowing. Sample area is 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 is doubled in size; biomass collected at this stage is partitioned into above ground canopy, marketable and residue components. After recording fresh and dry weights, samples are sent to the laboratory for analysis of N content. Preliminary yield data is summarised in Appendix 1. From these data, the total amount of N taken up by the crop, and the amount in marketable yield and crop residue can be calculated. These are all important parts of the N flow within a crop system.

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

Additional samples are collected prior to planting from the 0–15 cm depth for basic nutrient analysis to help determine the need for additional nutrients such as phosphorus (P) and potassium (K). Prior to planting, soil samples from 0–15 and 15–30 cm depths are also collected and analysed for soil mineralisable N (using the PMN test), and the results are used to calculate the amount of N that could potentially become available during the season. Values for some of the crops have now been calculated (e.g., broccoli in Rotation 1 and pak-choy in Rotation 2), but the remainder are still being calculated and the algorithms are being implemented in the SFFF “Mineralisable N to improve N management”.

Soil bulk density was measured at intervals to a depth of 150 cm at the start of each rotation, and is measured once during crop growth to a depth of 0–15 and 15–30 cm. These values are used to convert mineral N concentrations to kg N/ha in the soil.

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

Appendix 2. Measured yield of marketable produce for Workstream 1

Rotation 1 at Lincoln

Table. A5. Range of measured marketable produce yields for the potato (t/ha fresh tuber), wheat (t/ha grain at 14% moisture), broccoli (t/ha fresh head), onion (t/ha bulbs) and ryegrass seed (kg/ha seed at 14% moisture) crops grown at Lincoln for rotation 1 in Workstream m1. Means given in brackets.

Nitrogen rate	Potato (processed) 'Russet Burbank'	Wheat 'Catherine'	Broccoli 'Nobel'	Onion 'Tilbury'	Ryegrass seed 'Nui'
N1	50.0–69.3 (56.3)	9.2–10.9 (9.9)	2.7–8.5 (5.5)	70.7–83.3 (77.0)	701.8–2559.6 (1503.9)
N2	57.4–70.7 (63.8)	8.9–10.3 (9.6)	1.1–12.3 (5.2)	63.6–105.6 (90.9)	1509.0–2852.6 (2257.6)
N3	65.3–84.2 (72.0)	9.1–10.1 (9.6)	2.7–11.3 (6.1)	69.9–99.0 (83.7)	1030.2–2584.5 (1968.4)
N4	68.6–92.0 (77.3)	8.0–10.1 (9.4)	3.4–7.9 (5.5)	51.2–88.0 (72.5)	563.6–2474.7 (1413.1)

Rotation 2 at Lincoln

Table A6. Rnge of measured marketable produce yields (t/ha) for the pak choy (fresh biomass) and oats (green chop silage) crops grown at Lincoln for rotation 2 in Workstream 1. Means given in brackets.

Nitrogen rate	Pak choy 'Shangai'	Oats 'Milton'	Potato (fresh) 'Agria'	Ryegrass seed 'Nui'
N1	24.4–45.5 (36.1)	33.0–41.6 (38.0)	54.8–67.5 (62.8)	753.1–1722.2 (1188.8)
N2	19.9–45.7 (35.3)	34.0–43.1 (38.3)	60.5–88.6 (76.2)	1654.0–2604.8 (2047.7)
N3	33.7–48.1 (41.2)	22.0–38.3 (34.3)	69.7–94.8 (80.9)	1675.3–2713.2 (2306.7)
N4	30.9–54.3 (43.1)	33.0–47.8 (39.5)	74.6–103.1 (91.8)	1462.0–2756.4 (1930.1)

Rotation 3 at Hawke's Bay

Table A7. Range of measured marketable produce yields (t/ha) for the pak choy (fresh biomass), and oats (green chop silage) crops grown at Lincoln for rotation 2 in Workstream 1. Means given in brackets.

Nitrogen rate	Onions 'Tilbury'	Annual forage ryegrass 'Asset' and 'Tama' mix
N1	24.4–45.5 (36.1)	753.1–1722.2 (1188.8)
N2	19.9–45.7 (35.3)	1654.0–2604.8 (2047.7)
N3	33.7–48.1 (41.2)	1675.3–2713.2 (2306.7)
N4	30.9–54.3 (43.1)	1462.0–2756.4 (1930.1)

Table A8. Range of measured marketable produce yields (t/ha) for the pak choy (fresh biomass) and oats (green chop silage) crops grown at Lincoln for rotation 2 in Workstream 1. Means given in brackets.

Nitrogen rate	Pak choy 'Shanghai'	Lettuce 'Contessa'	Peas (fresh) 'Ashton'	Cauliflower 'Casper'	Forage Ryegrass 'Winter Star II'
N1	24.4–45.5 (36.1)	33.0–41.6 (38.0)	54.8–67.5 (62.8)		753.1–1722.2 (1188.8)
N2	19.9–45.7 (35.3)	34.0–43.1 (38.3)	60.5–88.6 (76.2)		1654.0–2604.8 (2047.7)
N3	33.7–48.1 (41.2)	22.0–38.3 (34.3)	69.7–94.8 (80.9)		1675.3–2713.2 (2306.7)
N4	30.9–54.3 (43.1)	33.0–47.8 (39.5)	74.6–103.1 (91.8)		1462.0–2756.4 (1930.1)

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