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Validation of the Overseer Cropping Model for Estimating Nitrate Leaching Losses in Precision Agriculture

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Abstract

The Overseer model is widely used in New Zealand as a precision-agriculture-related tool for estimating nitrate (NO_3^-) leaching losses in agricultural systems. This study evaluated the accuracy of the Overseer model in predicting nitrate (NO_3^-) leaching through a two-year lysimeter experiment conducted at Woodhaven Gardens, New Zealand, under beetroot and pak choi cultivation. Seven distinct nitrogen (N) fertilizer treatments were applied to assess model performance. In year 1, Overseer overestimated NO_3^- leaching by an average of 45.2 kg N/ha (15.7%), and in year 2, the model overestimated by 35.2 kg N/ha (43.5%). A sensitivity analysis highlighted soil texture, impeded layer depth and crop residue incorporation as key drivers of leaching variability, underscoring the need for improved model calibration. Overseer performed reasonably well under lysimeter conditions, with a strong linear relationship (Pearson's correlation coefficient r = 0.89, $p < 0.0001$) between measured and predicted values and explaining 77% of the variance ($R^2 = 0.77$) in the observed data. The model predicted a baseline leaching loss of 39.4 kg N/ha/year even when measured losses were zero. Overseer demonstrates moderate reliability in predicting NO_3^- leaching under vegetable cropping systems but exhibits notable limitations in handling crop-specific N dynamics, soil hydrology, and fertilizer timing.

Keywords: controlled release fertilizer; leaching; lysimeter; Overseer; nitrate

1. Introduction

Vegetable cropping systems in New Zealand are recognized as a significant source of nitrate (NO_3^-) leaching, largely due to the high nitrogen (N) fertilizer inputs and rapid mineralization of crop residues. These practices often leave substantial amounts of mineral N in the soil, which are susceptible to leaching during periods of high rainfall, posing risks to groundwater quality [1]. In recent decades, increasing awareness of NO_3^- leaching from intensive cropping systems has prompted growers to adopt more sustainable nutrient management practices. This shift is driven by both economic imperatives, such as input efficiency and environmental concerns, particularly the protection of groundwater and surface water quality. Accurate quantification of NO_3^- leaching losses remains a significant challenge due to the complex and dynamic nature of N transformations within the soil–plant–water–atmosphere continuum. These transformations are influenced by soil type, climate variability, crop species, and management practices, making direct measurement

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both costly and impractical at scale. As a result, simulation models have emerged as essential tools for estimating nutrient losses and informing precision agriculture strategies [2,3].

Among these tools, the Overseer model, developed by AgResearch in New Zealand, has gained widespread use as a decision-support and regulatory instrument. In the context of precision agriculture, Overseer provides a framework for integrating site-specific soil, climate, and management data to optimize nutrient use efficiency while minimizing environmental losses. By simulating alternative fertilizer regimes and crop rotations, the model enables growers to evaluate management scenarios before implementation, thereby supporting evidence-based decisions that balance productivity with sustainability. This functionality positions Overseer not only as a regulatory tool but also as a practical decision-support system for precision nutrient management in diverse farming systems.

Overseer estimates long-term average nutrient flows and losses from agricultural systems, including nitrate leaching, phosphorus runoff, and greenhouse gas emissions [4,5]. Its strength lies in its calibration to New Zealand conditions, underpinned by decades of empirical data from pastoral systems. The model's nutrient budget framework enables users to simulate farm-specific scenarios and evaluate the environmental impact of different management strategies. Recent evaluations have reinforced Overseer's utility in estimating N losses under pastoral systems, while also highlighting the challenges of extending its application to cropping systems. Overseer's N leaching estimates from grazed pastures showed strong correlation with experimental data, though performance varied across cropping scenarios due to limited calibration datasets [6]. Studies emphasized the importance of refining N leaching estimates for greenhouse gas inventories, noting that model outputs must be interpreted with caution when applied to non-pastoral land uses [7]. These findings underscore the need for ongoing validation and scenario-based testing to ensure robust predictions across diverse farming systems. Furthermore, the model's modular structure and integration of climate, soil, and management inputs make it a valuable tool for scenario analysis and policy development in nutrient management [8].

While Overseer's pastoral module is well validated, its cropping module has undergone recent updates to accommodate a broader range of plant types, including deeper-rooted species and vegetable crops [9]. These enhancements aim to improve the model's sensitivity to soil depth, climate inputs, and fertilizer regimes. However, a key challenge remains because Overseer's reliance on "long-term average" nutrient budgeting contrasts with the highly dynamic nature of vegetable production systems, where short rotation lengths, rapid changes in soil mineral N, and frequent cultivation events drive large temporal fluctuations in NO_3^- leaching risk. Recent studies have highlighted the importance of validating simulation outputs against empirical data to model reliability in diverse cropping contexts. For example, NO_3^--N leaching losses quantified under intensive vegetable rotations in the Lower North Island reveal substantial leaching during fallow periods and under excessive fertilizer regimes [10]. Their findings underscore the need for calibrated models that reflect site-specific dynamics and fertilizer practices. Bridging this gap requires assessing whether a long-term average modelling framework can adequately capture the short-term variability characteristic of vegetable systems, or whether systematic biases emerge when the model is applied outside its original pastoral calibration domain.

Refined leaching estimates are crucial in improving national greenhouse gas inventories and nutrient loss assessments, particularly for cropping systems that deviate from pastoral systems [7]. These insights align with broader efforts to enhance N use efficiency and reduce diffuse pollution from agriculture [11]. Therefore, this study aimed to investigate the application of the Overseer cropping module as a precision-agriculture-related tool for estimating NO_3^- leaching losses in commercial vegetable systems. Specifically, it evaluates the model's predictive accuracy under varying fertilizer management scenarios by comparing simulated outputs with empirical data from lysimeter trials. By examining how a long-term average model performs under the rapid nutrient turnover typical of vegetable production, this study contributes to the understanding of the model's suitability and limitations in supporting nutrient management decisions in high-intensity horticultural systems. Such validation is critical for building confidence in the model's use beyond pastoral systems and for supporting growers in meeting regulatory requirements and sustainability goals.

2. Materials and Methods

2.1. Site Description and Soil

A lysimeter experiment was conducted at Woodhaven Gardens in Levin, New Zealand, an area with an average annual rainfall of 1181 mm and temperatures ranging from 6.5 °C to 21 °C. The soil profile shows textural variation from loamy to clay loam within the top 60 cm (Table S1). Total carbon and N percentages were highest in the upper 20 cm, with available N content between 8.4 and 53.6 kg N/ha. Bulk density ranged from 1.11 to 1.64 g/cm^3. The upper 20 cm had good hydraulic conductivity, while a flow barrier at 50 cm had very low conductivity ranging from 0.3 mm/h to negligible levels. The agricultural land in this region supports intensive vegetable production, such as beetroot, pak choi, lettuce, broccoli, cabbage, and onion.

2.2. Lysimeter Design, and Arrangement

The lysimeters were constructed using plastic bins (Aotearoa NZ Made Ltd., Palmerston North, New Zealand) with a depth of 60 cm and an internal diameter of 40 cm. Installation followed the protocol and methodology described by [12]. In summary, the constructed lysimeters were placed into a prepared field trench, and the soil within each lysimeter was refilled to match the surrounding field's surface level. The area outside each lysimeter was backfilled with soil to ensure uniformity with the surrounding field surface (Figure S1). The physical and chemical properties of the soil at the trial site were analyzed in five replicates to a depth of 60 cm prior to the installation of the lysimeters (Table S1).

2.3. Experimental Design, Planting, and N Fertilizer Treatments

The experiment was conducted using a randomized complete block design (RCBD) with seven N fertilizer treatments in five replicates, resulting in a total of 35 lysimeters (Figure S2). Basal application of 300 kg/ha of Nitrophoska Blue (12% N) was applied to each lysimeter (excluding the control) prior to the application of mineral N fertilizers. Beetroot (*Beta vulgaris*) seeds were sown as the first trial crop, and after thinning, five plants per lysimeter were maintained for growth. Nitrogen fertilizer treatments in year 1 included water-soluble Calcium Ammonium Nitrate (CAN, 27% N) and N-Control 75 (44% N), applied at varying rates to establish seven treatment groups, as detailed in Table 1. The N application rates of 81 kg N/ha (equivalent to 300 kg/ha of CAN) and 79.2 kg N/ha (equivalent to 180 kg/ha of N-Control 75) reflected the standard grower practices for beetroot cultivation at Woodhaven Gardens. An intensive application rate of 162 kg N/ha was also tested using CAN. The planned harvest at 12 weeks after planting was not conducted due to coronavirus lockdown. As a result, all beetroots harvested from the lysimeters exceeded acceptable size and weight specifications and were determined to be unrepresentative of marketable produce. Consequently, the entire field harvest was incorporated back into the soil by the grower. To maintain consistency with the field's crop and soil management practices, the beetroots harvested from the lysimeters were also incorporated into the soil.

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Table 1. Simulation scenarios used in Overseer to predict NO_3^- leaching losses in year 1 and year 2.

Scenario	Symbol	Fertilizer Treatment/Simulation Scenarios in Year 1	Fertilizer Treatment/Simulation Scenarios in Year 2
1	CTRL	No N application	No N application
2	CRF 1	N-Control 75 of 79.2 kg N/ha	N-Control 75 of 48.6 kg N/ha
3	CRF 2	Two splits of N-Control 75 of 79.2 kg N/ha	Two splits of N-Control 75 of 48.6 kg N/ha
4	STD 1	CAN of 81 kg N/ha	CAN of 48.6 kg N/ha
5	STD 2	Four splits of CAN 81 kg N/ha	Four splits of CAN 48.6 kg N/ha
6	EXC 1	CAN of 162 kg N/ha	CAN of 97.2 kg N/ha
7	EXC 2	Two splits of CAN of 162 kg N/ha	Two splits of CAN of 97.2 kg N/ha

An additional N input of 36 kg N/ha of Nitrophoska was included in scenarios 2, 3, 4, 5, 6 and 7 for year 1. Scenarios 2, 4 and 6 were treated as single applications. CAN refers to Calcium Ammonium Nitrate.

In the 2nd year, pak choi (*Brassica rapa* var. *chinensis*) was sown as the second trial crop on the lysimeters. The N fertilizer treatments used in year 2 were water-soluble Calcium Ammonium Nitrate (CAN) and N-Control 75 (CRF) at different application rates to formulate seven treatments (Table 1). The treatment rates of 180 kg/ha of CAN and 110.45 kg/ha of CRF were selected based on the growers' regular practice for pak choi at Woodhaven Gardens. The application rate of 360 kg/ha of CAN represents an intensive application rate. Pak choi plants meeting marketable standards were harvested from the lysimeters. Following the harvest, Italian ryegrass (*Lolium multiflorum*) seeds were sown as a fallow cover crop in the lysimeters.

2.4. Total Nitrogen Uptake Determination

Beetroot, pak choi and ryegrass plants from the lysimeters were sampled by removing all plants at harvest in both years. The total fresh weight of the harvested plant material was recorded in the field. Subsamples of approximately 150 g were taken for oven drying at 65 °C for a minimum of five days. Once dried, the samples were ground using a Foss Cyclotech mill (ThermoFisher Scientific, Waltham, MA, USA) and passed through a 0.25 mm sieve. The total nitrogen (N) uptake by the plants was determined by digesting 0.1 g of subsample from each treatment using the micro-Kjeldahl digestion method. The total N concentration was then analyzed using a Technicon Autoanalyzer. The total N uptake of the plants was estimated as the product of dry matter yield and plant N concentration (%).

2.5. Measurement and Modelling of Nitrate Leaching Losses from the Lysimeters

Nitrate leaching losses were measured from lysimeter drainage in twelve sampling events in year 1 and eight events in year 2. Drainage water samples were collected after each significant rainfall event (greater than 20 mm). The samples were analyzed for NO_3^--N using a Technicon Autoanalyzer, Series 2 [13]. The latest version of Overseer at the time of the experiments (Version 6.4.2) was utilized to estimate NO_3^- leaching losses. This model was chosen due to its calibration for various farming systems under New Zealand conditions. Additionally, Overseer calibrations have predominantly focused on NO_3^- leaching below the root zone (approximately 0.4 to 0.6 m), using lysimeters [14].

2.5.1. Overview of Overseer Model

It is an empirical model and readily, available data from existing farms can be used to calculate nutrient budgets at a farm scale level [4,15]. Overseer consists of separate sub-models for pastoral, cropping and horticulture enterprises. The model calculates NO_3^- leaching losses as a difference between the sum of input and the sum of N in yield. It produces long-term annual averages, assuming constant inputs and production from year to year for a given site. The model requires climate inputs, soil characteristics, animal type (where relevant), crop type, and management aspects including fertilizer or irrigation inputs. It runs on a monthly time step using long-term average climate rather than daily climate inputs, with crop yields pre-defined by the user, and does not consider the losses of ammoniac or organic N from the field, limiting its focus to NO_3^- losses only. The relative NO_3^- leaching losses vary with soil group and soil drainage characteristics [9].

2.5.2. Input Data Requirements of the Model for Lysimeter Simulations

(i) Soil data

Each simulation was based on 1 ha of block with silt loam over clay, which was considered as well drained to resemble lysimeter conditions. Details about soil parameters were obtained from laboratory analysis. Key soil input data values and soil conditions defined in Overseer simulations are given in Table 2.

Table 2. Key soil profile information used in Overseer for simulating NO_3^- leaching.

Input Data	Depth (cm)	Conditions/Values Defined
Impeded layer depth	-	No barrier (free draining)
Drainage class	-	Well-drained
Topsoil texture	0–10	Loam
Bulk density (kg/m^3)	0–10	1221
Saturated hydraulic conductivity (mm/day)	10–60	1740
Topsoil C%	0–10	2.1
Sand%	0–10	29.0
Clay%	0–10	21.0
Clay%	10–60	38.5
Olsen P (µg/g)	10–60	39.1
K (g/kg)	10–60	0.37
Ca (g/kg)	10–60	14.7
Mg (g/kg)	10–60	0.9
Na (g/kg)	10–60	0.3

(ii) Weather data

Overseer used constant values of 1126 mm, 13.3 °C, and 831 mm for rainfall, temperature, and ET respectively, based on the location of the experimental site, as the database has been designed to ignore year-to-year climate variation. Data on average temperature, rainfall, and potential evapotranspiration for each block were used by the model using 30-year average climate data for the location. Overseer used regional seasonality to extrapolate the annual average to monthly or daily values.

(iii) Crop data

Crop management data pertaining to beetroot cultivation in year 1 and pak choi cultivation in year 2 were used. These data as required by the model were obtained from direct field measurements (Table 3). Ryegrass growth was simulated on lysimeters after the harvest of pak choi in year 2 as a removal of soil residual N. However, the simulation scenarios in year 1 did not have grass growth on lysimeters, as the ryegrass did not germinate in lysimeters in year 1.

(iv) Input data on N additions

Input data related to N fertilization information for the simulation site included type, timing, amounts and dates and rate of fertilization. The incorporated crop materials in year 1 were treated as organic fertilizer with user-defined amounts and N concentrations of these inputs (Table 4).

Table 3. Crop management data used in the Overseer for beetroot and pak choi cultivation.

Input Data	Beetroot	Pak Choi
Maximum rooting depth (cm)	20	20
Date sown	16 January, year 1	14 January, year 2
Date harvested	27 April, year 1	6 April, year 2
Postharvest residue management	Harvest material and residue retained	Harvest material removed; Residues retained
Month ryegrass sown	July and September, year 1	July, year 2
Month ryegrass harvested	-	1 cut October, year 2 2 cut November, year 2

2.5.3. Nitrate Leaching Simulations

The fertilizer treatments applied to beetroot in year 1 and pak choi in year 2 were used as different scenarios to run through Overseer. Overseer-predicted NO_3^- leaching estimates were compared with lysimeter-measured NO_3^- leaching losses for the years year 1 and year 2 at Woodhaven Gardens in Levin. The simulation utilized the Block, Soil, Pasture/Crops, and Fertilizer modules. Each treatment was simulated individually with a block area of 1.0 ha to assess the significance of NO_3^- loss variations. The simulated NO_3^- leaching from Overseer was compared with measured values obtained from lysimeter studies. All simulations represented a free-draining lower boundary. The specific scenarios modeled in Overseer are detailed in Table 1.

Table 4. Key management information used in the Overseer model for beetroot and pak choi cropping in year 1 and year 2.

No.	Input Variables		Simulation Scenarios						
			CTRL	**CRF 1**	**CRF 2**	**STD 1**	**STD 2**	**EXC 1**	**EXC 2**
			Beetroot (year 1)						
1.	Soil residual N (kg N/ha)		32	32	32	32	32	32	32
2.	Fresh yield (t/ha)		64	70	69	65	73	70	65
3.	Month and amount of fertilizer application (kg N/ha) (including Nitrophoska)		0	January, 115.2	January, March 115.2	January, 117.0	January, February 117.0	January, 198.0	January, 198.0
4.	Amount of incorporated harvest material, dry matter (DM) and N concentration								
	(a) Beetroots	Amount (kg)	63,632	70,208	68,560	65,112	72,620	69,888	65,024
		DM%	18	14	14	16	17	16	15
		N%	3.3	3.5	2.7	3.0	3.4	2.7	3.5
	(b) Beetroot leaves	Amount (kg)	33,696	34,544	34,080	35,776	38,928	32,496	36,736
		DM%	11	11	11	11	11	12	11
		N%	2.5	2.8	2.6	2.7	2.7	2.5	2.9
			Pak choi (year 2)						
1.	Soil residual N (kg N/ha)		92.2	110.4	97.4	80.9	120	84.2	94.4
2.	Fresh yield (t/ha)		102	117	112	111	114	130	124
3.	Amount of harvest material incorporated		0	0	0	0	0	0	0
4.	Month and amount of fertilizer application (kg N/ha)		0	January, 48	January, March 48	January, 49	January, March 48	January, 97	January, March 98

2.6. Error Analysis of Overseer

2.6.1. Mean Difference (M_d)

The mean difference of each scenario was estimated to determine the average deviation of the measured values from the predicted values for each treatment. A *t* test was used to check the null hypothesis that $M_d = 0$. A small, non-significant M_d was used to test the accuracy of the model prediction. The positive and negative signs of the M_d were treated so that on average the model underestimated or overestimated the values, respectively.

$$M_d = \frac{\sum_{i=1}^{n}(M_i - S_i)}{n} \quad (1)$$

2.6.2. Root Mean Square Error (RMSE)

The RMSE was determined as a measure of the deviation of the predicted values from the measured values. Lower values of RMSE imply higher simulation accuracy.

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(M_i - S_i)^2\right]^{0.5} \quad (2)$$

2.6.3. Percent of Relative Error (Er%)

Relative error measures the average tendency of the simulated losses to be larger or smaller than their measured counterparts [16].

$$Er\% = \sum\left(\frac{M_i - S_i}{M_i}\right)\left(\frac{100}{n}\right) \quad (3)$$

where S_i is the model Overseer simulated loss, M_i is the corresponding measured loss, and n is the number of observations.

2.6.4. Regression Equation

A linear regression equation was derived from the relationship between simulated and measured data. Overseer's predictive capacity was evaluated using the coefficient of determination (R^2), correlation coefficient (r), and a 1:1 relationship (intercept = 0, slope = 1.0) as the degree of association between the measured and simulated losses. A *t*-test ($p < 0.05$) was used to assess whether the intercept differed significantly from zero and the slope from one.

2.7. Sensitivity Analysis

In addition to the simulations based on the lysimeter experiment, a set of hypothetical scenarios was included in the sensitivity analysis to explore how Overseer responds to changes in key input assumptions. These scenarios were not intended to represent the actual experimental conditions but were performed to examine the model's behaviour under alternative management or soil-profile settings. This approach was done to assess how sensitive Overseer's leaching predictions are to variations in input parameters and to identify which factors have the greatest influence on model outputs. It was conducted by varying one variable at a time, and the relative changes in the output were evaluated with respect to NO_3^- leaching losses.

2.8. Data Analysis

All statistical analysis were performed using MINITAB [17] (version 19.1.1, State College, PA, USA).

3. Results

3.1. Simulated Annual Water Fluxes

The model was validated for its predictive capacity and precision by comparing Overseer simulated drainage and NO_3^- leaching results against the mean of five replicated lysimeter measurements (Table 5). Precision of the measured losses is dependent on the measured drainage through the lysimeters. Therefore, applying the 95% confidence interval (C.I) criterion indicated that Overseer reasonably simulated annual water drainage fluxes below 60 cm depth for the CTRL, CRF 1, CRF 2, STD 1, and EXC 2 simulation scenarios under the beetroot cropping system in year 1. However, Overseer did not predict the annual water fluxes for the STD 2 and EXC 1 simulations. The simulated drainage fluxes were within the 95% C.I range for all the simulation scenarios in year 2 under pak choi cultivation (Table 5).

Table 5. Measured and Overseer simulated values of cumulative (annual) drainage losses below 60 cm soil depth.

Year	Simulation Scenario	Cumulative Water Drainage (mm)	
		Measured (Mean ± 95% C.I)	Overseer Predicted
Year 1	CTRL	440 ± 183	621
	CRF 1	425 ± 221	621
	CRF 2	641 ± 162	621
	STD 1	490 ± 230	621
	STD 2	439 ± 140	621 †
	EXC 1	466 ± 109	621 †
	EXC 2	410 ± 255	621
Year 2	CTRL	422 ± 368	556
	CRF 1	383 ± 220	529
	CRF 2	559 ± 147	529
	STD 1	482 ± 380	556
	STD 2	522 ± 288	556
	EXC 1	431 ± 265	529
	EXC 2	439 ± 290	529

† Values indicate that simulated values are not within the 95% C.I of the measured values. Overseer predictions are deterministic single values without replication.

The measured drainage values showed substantial lysimeter-to-lysimeter variability, particularly in year 2. The wide 95% confidence intervals observed in several treatments indicate considerable variability in drainage among individual lysimeters. This variability is typical of field-based lysimeter studies, where small differences in soil hydraulic properties and crop growth can lead to divergent drainage responses. The confidence intervals represent the uncertainty around the mean drainage estimate and illustrate the extent to which treatment values overlap.

3.2. Cumulative Nitrate Leaching Losses During Beetroot Cropping

Overseer produced a single deterministic output for each scenario, which is why predicted values appear as single points rather than ranges. The model does not generate replicate level predictions or probabilistic outputs, nor does it quantify uncertainty internally. The simulation results reveal that Overseer consistently overestimated NO_3^- leaching losses across six of the seven treatment scenarios under beetroot cultivation, with the exception of CRF 2, where the model underestimated losses by 32.4% (273 predicted vs. 404.2 measured). The largest overestimation occurred in STD 2, where the model estimated 392 kg N/ha, exceeding the measured value of 302.1 kg N/ha by 89.9 kg N/ha (29.8%). Similarly, EXC 2 showed an overestimation of 69.1 kg N/ha corresponding to 24.1% (356 predicted vs. 286.9 measured), and STD 1 was overestimated by 14.8% (344 vs. 299.6).

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EXC 1 had a moderate overestimation by 13% (313 vs. 277.0), while CRF 1 was overestimated by 9% (326 vs. 299.2). CTRL showed a relatively small overprediction of 5.1 kg N/ha corresponding to 2% (226 predicted vs. 260.9 measured 2%) (Table 6). On average, the model overestimated NO_3^- leaching by 45.2 kg N/ha (15.7%).

Table 6. Comparison of measured and Overseer-simulated NO_3^- leaching losses under beetroot cultivation across fertilizer treatments (kg N/ha).

Treatments	Measured Leaching Losses (kg N/ha)	Overseer Predicted Leaching Losses (kg N/ha)
CTRL	260.9 ± 78.5	266
CRF 1	299.2 ± 55.2	326
CRF 2	404.2 ± 37.5	273
STD 1	299.6 ± 67.3	344
STD 2	302.1 ± 50.2	392
EXC 1	277.0 ± 52.2	313
EXC 2	286.9 ± 73.2	356

Measured leaching losses are mean ± standard error (n = 5). Overseer predictions are deterministic single values without replication.

3.3. Cumulative Nitrate Leaching Losses During Pak Choi Cropping

Overseer predictions of NO_3^- leaching varied across treatments, with both overestimations and underestimations relative to measured values during pak choi cropping. The largest overestimation occurred in STD 2, where Overseer estimated 131 kg N/ha, exceeding the measured value of 78.3 kg N/ha by 67.3% (Table 7). Similarly, STD 1 was overestimated by 34.4% (130 predicted vs. 96.7 measured), and CTRL showed an overestimation of 46.6 kg N/ha corresponding to 63.5% (120 vs. 73.4). EXC 1 was also overestimated by 19.8% (112 vs. 93.4). However, CRF 2 and EXC 2 were underestimated by Overseer. CRF 2 had a measured leaching loss of 111.2 kg N/ha, while the model predicted only 97 kg N/ha, resulting in an underestimation of 14.2 kg N/ha corresponding to 12.8%. EXC 2 showed the largest underprediction, with Overseer estimating 71 kg N/ha compared to a measured value of 95.5 kg N/ha, a difference of 24.5 kg N/ha. CRF 1 was closely predicted, with an overestimation of 24.6 kg N/ha corresponding to 32.2% (101 vs. 76.4). On average, Overseer overestimated NO_3^- leaching by 35.2 kg N/ha (43.5%) during pak choi cultivation.

Table 7. Comparison of measured and Overseer-simulated NO_3^- leaching losses under pak choi cultivation across fertilizer treatments (kg N/ha).

Treatments	Measured Leaching Losses (kg N/ha)	Overseer Predicted Leaching Losses (kg N/ha)
CTRL	73.4 ± 18.4	120
CRF 1	76.4 ± 15.6	101
CRF 2	111.2 ± 22.8	97
STD 1	96.7 ± 29.4	130
STD 2	78.3 ± 16.9	131
EXC 1	93.4 ± 22.1	112
EXC 2	95.5 ± 22.6	71

Measured leaching losses are mean ± standard error (n = 5). Overseer predictions are deterministic single values without replication.

3.4. Crop N Uptake

During beetroot cropping, the greatest underestimation of plant N uptake occurred in STD 2, where the simulated plant N uptake was 308 kg N/ha compared to a measured value of 642.1 kg N/ha, resulting in a 52.0% discrepancy. In contrast, the smallest difference was observed in CRF 2, with a predicted uptake of 300 kg N/ha and a measured value of 359.2 kg N/ha, reflecting a 16.4% underestimation. For the remaining treatments, CTRL (290 vs. 456.7), CRF 1 (303 vs. 504.5), STD 1 (293 vs. 412.5), EXC 1 (303 vs. 392.5), and EXC 2 (292 vs. 460.2), the model consistently underestimated plant N uptake, with varying degrees of discrepancy ranging between approximately 22% and 46% (Figure 1).

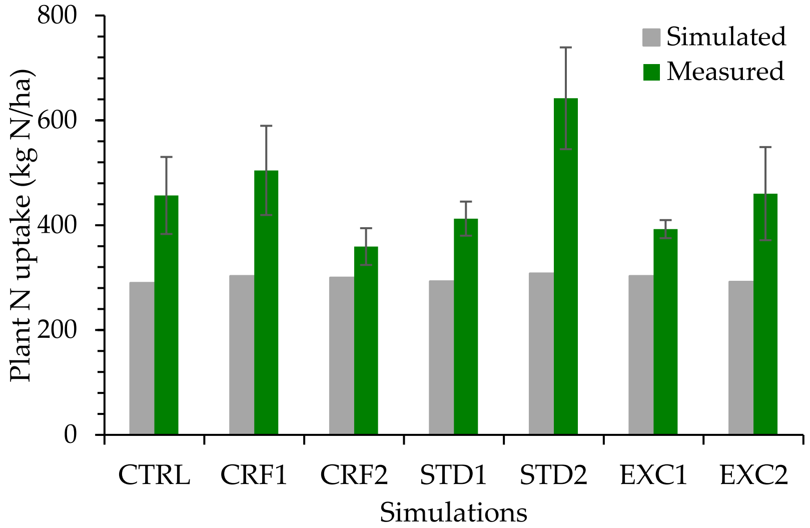

Figure 1. Comparison of Overseer-predicted average beetroot N uptake against measured beetroot N uptake from lysimeters in year 1. Measured values are the mean of five replicates. Overseer predicted N uptakes are deterministic single values without replication.

During pak choi cultivation, the greatest overestimation of plant N uptake occurred in CRF 1, where the simulated value was 520 kg N/ha compared to a measured uptake of 250.03 kg N/ha, resulting in a 107.9% overestimation. In contrast, the smallest discrepancy was observed in EXC 2, with a simulated uptake of 387 kg N/ha and a measured value of 373.91 kg N/ha, reflecting a modest 3.5% overestimation. For the remaining treatments, CTRL (473 vs. 318.5), CRF 2 (504 vs. 461.5), STD 1 (503 vs. 325.67), STD 2 (513 vs. 379.26), and EXC 1 (562 vs. 302.94), the model consistently overestimated plant N uptake, with overestimation ranging from approximately 9% to 85%. (Figure 2).

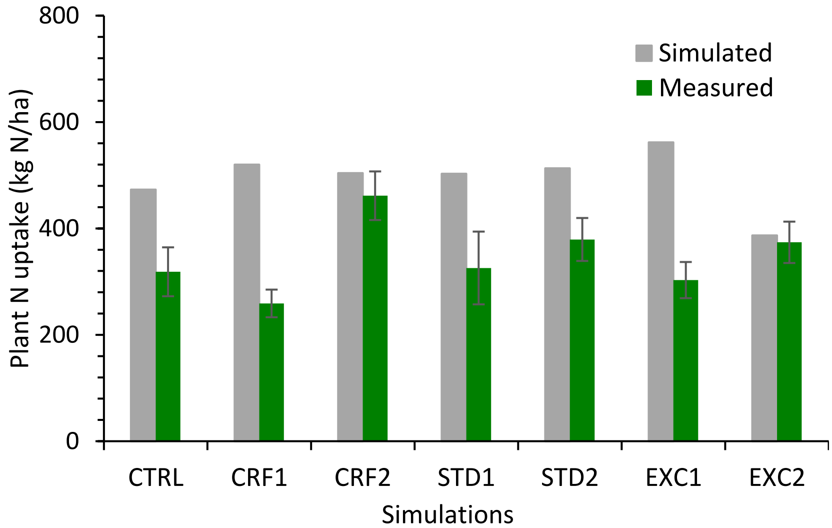

Figure 2. Comparison of Overseer-simulated average pak choi N uptake against measured pak choi N uptake from lysimeters in year 2. Measured values are the mean of five replicates. Overseer predicted N uptakes are deterministic single values without replication.

3.5. Results of the Sensitivity Analysis

Based on the simulation accuracy, the scenario CRF 2 for the year 2 was used to test the sensitivity of different input parameters for their impact on NO_3^- leaching losses. The Overseer output for this scenario shows a leaching loss of 97 kg N/ha against the measured loss of 111.2 kg N/ha. Key input parameters influencing NO_3^- losses included fallow duration, impeded layer depth, soil group, hydraulic conductivity, and crop material incorporation.

3.5.1. Length of Fallow Period

Figure 3 presents a scenario-based sensitivity analysis (rather than additional validation data) designed to evaluate how the Overseer model responds to changes in both fallow duration and planting time. The analysis is anchored to a baseline scenario of 97 kg N/ha of NO_3^- leaching at a 5-month fallow period, which represents the measured lysimeter value used to validate the model. This measured value is shown in Figure 3 as the red-dotted line, indicating the model-predicted loss when fixed input data are applied. Using this baseline as the reference point, two planting-time scenarios such as June and July planting are simulated to assess the model's sensitivity to shifts in crop establishment timing. Across the six-month fallow range, simulating planting one month earlier (June) results in a 4–22% reduction in predicted NO_3^- leaching, with total losses of 75 kg N/ha for June planting compared with 96 kg N/ha for July planting. The simulated leaching trend declines consistently when planting occurs earlier, demonstrating that advancing establishment reduces the duration of bare-soil exposure and therefore lowers N losses. The model also predicts that maintaining grass cover for six months reduces losses to 96 kg N/ha/year. In contrast, leaving lysimeters bare for the same period leads to substantially higher losses of 165 kg N/ha/year. These results suggests that earlier planting consistently mitigates this effect by reducing the duration and intensity of bare-soil N loss.

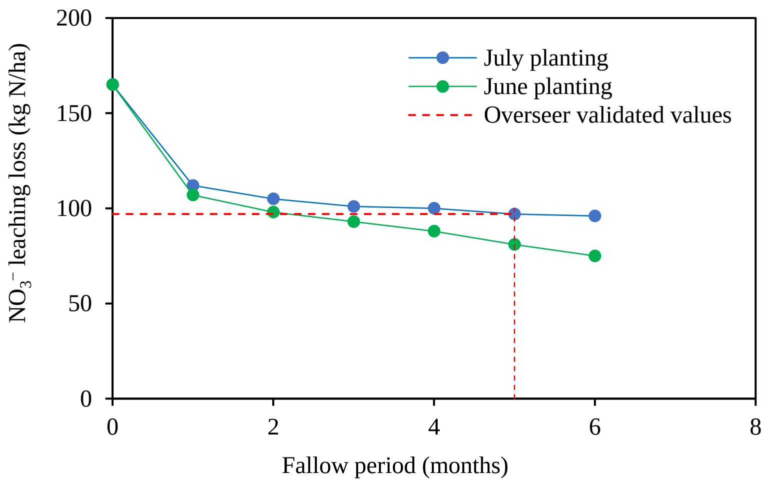

Figure 3. Scenario-based sensitivity analysis of NO_3^- leaching loss (kg N/ha) across planting times. Simulations show that earlier planting (June vs. July) reduces leaching, with the model validated by a 5-month fallow baseline of 97 kg N/ha losses.

3.5.2. Impeded Layer Depth

Model validation for the CRF 2 simulation scenario estimated a NO_3^- leaching loss of 97 kg N/ha under free-draining conditions with no impeded layer. When the impeded layer depth was reduced from 50 cm to 10 cm, NO_3^- losses increased by 12.3% to 108.2% relative to the validated losses (Figure 4). The model was particularly sensitive to depth variations between 10 and 50 cm, indicating, that within this range, lower available water capacity leads to frequent flushing during drainage. However, Overseer showed no sensitivity beyond 60 cm.

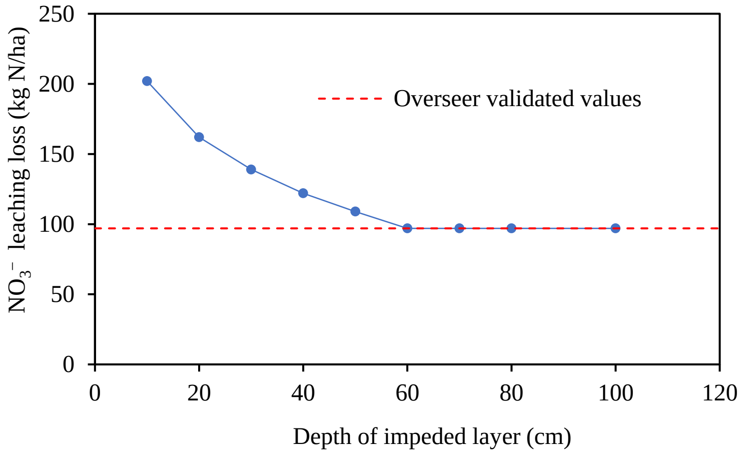

Figure 4. Measured NO_3^- leaching loss (kg N/ha) versus depth of the impeded layer (cm), showing decreasing leaching losses with depth and no Overseer sensitivity beyond 60 cm.

3.5.3. Soil Group and Texture

Overseer predicted a NO_3^- leaching loss of 97 kg N/ha for the CRF 2 scenario in year 2 from a medium-textured, free-draining brown soil. The model predicted a reduction of 15% and 6% in NO_3^- losses for gley and allophanic soils, respectively, while increases of 6%, 23%, 8%, and 1% were observed for melanic, granular, pallic, and recent soils. Soil texture also influenced NO_3^- losses, with a 48% increase in light-textured soils and a 9% rise in heavy-textured soils compared to medium-textured soil (Figure 5). However, changes in drainage class (well, moderately well, imperfect, poor, and very poor) had minimal impact on NO_3^- leaching losses.

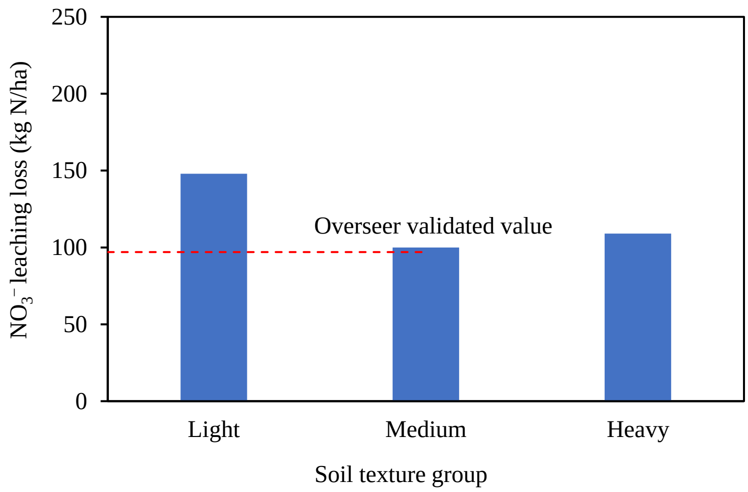

Figure 5. Nitrate leaching response across Light, Medium, and Heavy soil texture groups. Soil textures were grouped using reproducible percentage-based thresholds consistent with S-map and standard texture-triangle classifications: Light (>65% sand, <15% clay), Medium (30–65% sand, 15–35% clay), and Heavy (<30% sand, >35% clay).

3.5.4. Saturated Hydraulic Conductivity

Overseer demonstrated sensitivity to changes in hydraulic conductivity between 1 and 3 mm/day. Nitrate leaching losses increased by 46% when conductivity rose from 1 to 2 mm/day. However, the model did not accept values below 1 mm/day and rounded decimal values (1.1–1.4 mm/day to 1.0 and 1.5–1.9 mm/day to 2.0). Sensitivity was observed only up to 4 mm/day, while values above 3 mm/day resulted in minimal changes in simulated NO_3^- leaching losses (Figure 6).

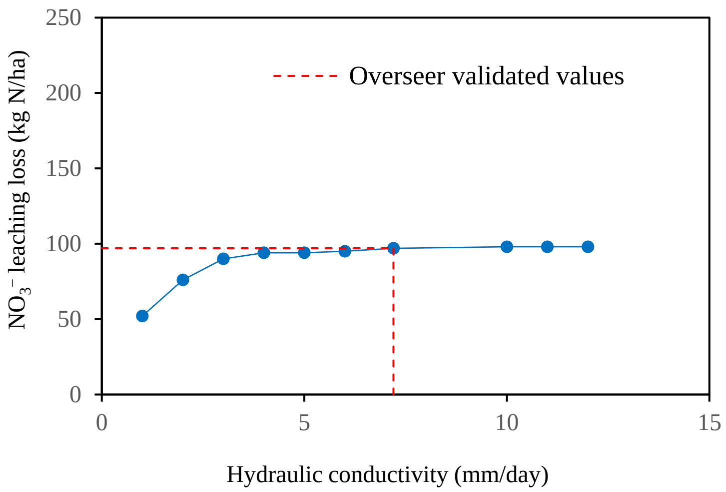

Figure 6. Effect of hydraulic conductivity on simulated nitrate leaching: sensitivity analysis using overseer. Higher conductivity increases predicted leaching, with values stabilizing beyond 3 mm/day; validated scenario intersects at 7.2 mm/day and 100 kg N/ha.

3.5.5. Amount of Incorporated Material

The incorporation of crop residues into the soil had a significant impact on NO_3^- leaching losses. A 50% increase in residue incorporation following harvest resulted in a predicted increase in NO_3^- leaching from 111.5 to 167.3 kg N/ha, representing a 50% rise in losses. Conversely, a 50% reduction in residue incorporation led to a corresponding 50% decrease in NO_3^- leaching losses (Figure 7). Sensitivity analysis of fertilizer type, pH, bulk density, drainage class, soil carbon percentage, and rooting depth had minimal influence on the estimated NO_3^- leaching losses (±20% of the validated values).

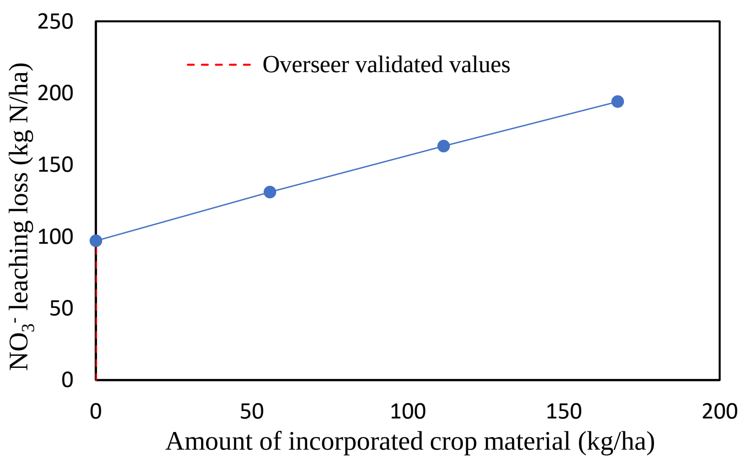

Figure 7. Effect of incorporated crop material on nitrate leaching: sensitivity analysis based on overseer simulation. Simulated leaching losses increase with crop material input, highlighting the model's responsiveness to residue-driven N surplus.

3.6. Evaluation of the Precision of Overseer

In this study, Overseer generally overestimated NO_3^- leaching, as evidenced by negative Md values across most scenarios. The exceptions can be observed in the CRF 2 scenario in year 1 and the STD 2 scenario in year 2, where Md values were statistically significant. Even though the lowest possible value of RMSE should be closer to zero for better simulation accuracy, none of the simulations met this criterion by showing higher RMSE values in both years. The relative error% (Er%) in year 1 remained below 10%, indicating acceptable performance. However, in year 2, simulations such as CTRL and STD 2 exceeded this threshold, with Er% values of −12.7% and −13.4%, respectively (Table 8).

Table 8. Statistical evaluation of Overseer-simulated NO_3^- leaching losses from different scenarios.

Year	Simulations	M_d	RMSE	Er%
Year 1	CTRL	−5.0 ns	157.0	−0.4
	CRF 1	−26.8 ns	113.7	−1.8
	CRF 2	131.1 *	151.0	6.5
	STD 1	−13.3 ns	135.3	−0.9
	STD 2	−53.8 ns	114.0	−3.5
	EXC 1	−66.9 ns	124.1	−4.8
	EXC 2	−105 ns	180.3	−7.3
Year 2	CTRL	−46.6 ns	59.4	−12.7
	CRF 1	24.6 ns	39.8	−6.4
	CRF 2	14.2 ns	47.8	2.5
	STD 1	−33.2 ns	67.6	−6.8
	STD 2	−52.7 *	62.6	−13.4
	EXC 1	−18.5 ns	48.0	−3.9
	EXC 2	24.5 ns	51.5	5.1

Significance * $p < 0.05$ ns—non-significant.

Regression analysis between Overseer-simulated and lysimeter-measured NO_3^- leaching losses revealed a consistent overestimation of 39.4 kg N/ha/year across most scenarios, with data points diverging above the 1:1 line (Figure 8). The regression model yielded an R^2 value of 0.77, indicating that 77% of the variation in measured NO_3^- leaching was explained by the simulated values. Overseer showed good agreement between the measured and the predicted losses across all simulation scenarios in both years. Even though Overseer did not meet the statistical criteria for a few individual simulations, its overall performance in both years resulted in a high positive significant correlation coefficient (r = 0.89, $p < 0.0001$) indicating a good agreement between measured and predicted data. However, the model shows that the slope is significantly different from one ($p < 0.0001$) implying that Overseer did not meet the non-significant slope criteria, implying deviation of data points away from the 1:1 line rather than proportional agreement. A non-significant intercept ($p = 0.21$) indicates that it is not significantly different from 0 and suggests that the overestimated loss of 39.4 kgN/ha was not a significant amount (Table 9).

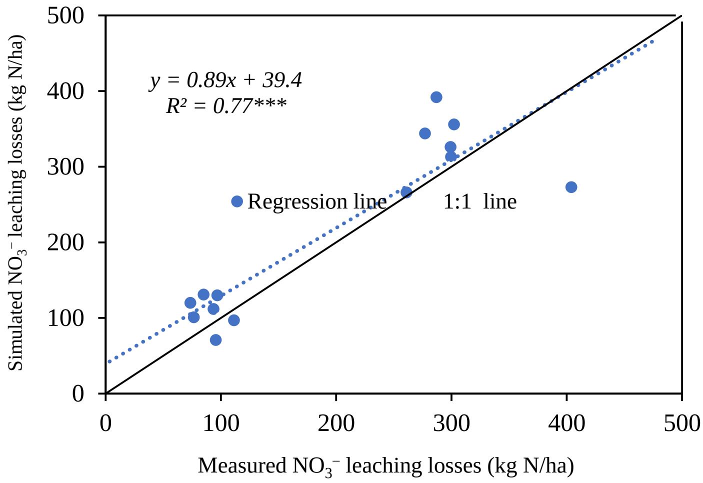

Figure 8. Validation of overall measured and Overseer-simulated NO_3^- leaching losses below 60 cm for the two years from lysimeter studies. The solid line is the 1:1 line. Significance *** $p < 0.001$.

Table 9. Values of the goodness of fit criteria computed for overall performance for Overseer simulated NO_3^- leaching losses.

Statistical Parameter	NO_3^- Leaching Loss (kgN/ha)	*p* Value
Correlation coefficient (r)	0.89	<0.0001
Slope (b)	0.89	<0.0001
Intercept (a)	39.4	0.21

4. Discussion

4.1. Nitrate Leaching Predictions

Overall variability in NO_3^- leaching was found to be associated with the crop N uptake. N uptake is estimated by the monthly crop biomass accumulation and its N content in Overseer. The N content of beetroots and leaves in year 1 was estimated as 3.1% and 2.7%, respectively (Table S2). However, Overseer used a constant value of 1.0% and 1.5% for roots and leaves, respectively [18]. Since N content is a fixed value used by Overseer and cannot be defined by the user, the crop uptakes were underestimated by Overseer during beetroot cultivation. Thus, the simulated higher NO_3^- leaching was due to less crop N uptake (Figure 1).

Another factor to be noted here is that Overseer predicts rapid mineralization of organic matter. Large quantities of crop material were incorporated into the soil during the beetroot cropping cycle. When this was entered in Overseer as organic matter, it estimated higher NO_3^- leaching losses as indicated in the sensitivity analysis (Figure 7). Large overestimation of NO_3^- leaching losses following incorporation of ryegrass in vegetable growing conditions were also reported in the literature [19]. Overall, the average overestimation of 45.2 kg N/ha (15.7%) across year 1 simulations indicate a moderate bias in Overseer's predictions under beetroot cultivation. This aligns with findings from recent evaluations, which rated Overseer's performance in cropping systems as variable, depending on soil type, crop rotation, and fertilizer strategy [20].

The simulation results under pak choi cultivation in year 2 indicate that Overseer predicted comparatively lower NO_3^- leaching losses than in year 1, aligning with the reduced N input applied during that year. This trend reflects the model's sensitivity to input-driven changes in N availability. However, despite the overall reduction, the model still overestimated NO_3^- losses in five of the seven scenarios, with overprediction rates ranging from 19.8% (EXC 1) to 63.5% (CTRL). These discrepancies suggest that while Overseer captures general input trends, its magnitude of prediction may not consistently reflect measured leaching, particularly under low N fertilizer treatments.

Moreover, growth of annual ryegrass was simulated during the fallow period on lysimeters in year 2. Consequently, the crop N uptake was found to be influenced by simulation of five months of fallow period, which resulted in overestimated N uptake in all scenarios (Figure 2). The N contents of pak choi and ryegrass were determined as 3.2% and 2.2%, respectively (Table S2), but Overseer predictions were based on the model's fixed values of 2.6% and 3.7% for pak choi and ryegrass, respectively, which simulated overestimated plant uptake. Hence, relatively greater crop N uptake was found to be associated with lower NO_3^- leaching during pak choi cropping (Table 7). Nitrate leaching losses were also overestimated in a potato–oats–onion rotation where Overseer predicted NO_3^- loss of 220 kg N/ha when the measured losses were 80 to 15 kg N/ha under winter potatos in a similar environment [21]. However, the authors did not provide any explanation for this modelling discrepancy.

Although Overseer generally overpredicted NO_3^- leaching losses across both experimental years, these apparent overestimations were not statistically significant for most treatments based on the mean difference (Md) criterion (Table 8). The only statistically significant deviation occurred for STD 2 in year 2 (−52.7 *), indicating a meaningful difference between measured and modelled leaching for that treatment alone. Consequently, despite the overall tendency for Overseer to overestimate leaching, these differences cannot be interpreted as true statistical overestimations for any treatment other than STD 2 in year 2. Although the overestimations were not statistically significant, they may still influence compliance outcomes and on-farm decision-making, as even non-significant deviations can carry practical consequences for growers. In recognition of this, the present study considered all instances where Overseer overpredicted leaching losses and calculated year-specific, average overestimation values for both year 1 and year 2.

Nitrogen Use Efficiency and N Fate

Nitrogen Use Efficiency (NUE) was generally low in year 1, as most fertilized treatments showed only small increases in predicted N uptake above the control (2–18 kg N/ha) despite substantial fertilizer additions, resulting in large predicted surplus N values (63–160 kg N/ha). This pattern indicates that Overseer assumed poor crop recovery of applied N under beetroot, with much of the fertilizer remaining unused and therefore at higher risk of loss. In year 2, predicted NUE was markedly higher, with several treatments (CRF 1, CRF 2, STD 1, STD 2 and EXC 1) showing strong increases in N uptake (30–89 kg N/ha) relative to the modest fertilizer inputs, leading to very small predicted surpluses (1.6–18.6 kg N/ha). Only EXC 2 showed poor efficiency, with a large surplus (183.2 kg N/ha), indicating substantial unrecovered N and elevated loss potential.

Overseer's predicted surplus N values show how much of the applied fertilizer N the model considers unrecovered by the crop, but the leaching predictions do not always scale proportionally with these surpluses. In year 1, treatments such as EXC 1 (149 kg N/ha) and EXC 2 (160 kg N/ha) had the largest predicted surpluses, yet Overseer predicted moderate leaching losses of (313–356 kg N/ha), which was only slightly above the control (Table 10). Conversely, STD 2, which had a much smaller surplus (63 kg N/ha), was assigned one of the highest leaching losses (392 kg N/ha). This indicates that Overseer does not directly translate surplus N into higher leaching for year 1, but instead, leaching appears to be driven by internal assumptions about drainage behavior and soil profile characteristics rather than treatment-specific N recovery. A similar pattern appears in year 2. Most treatments had small predicted surpluses (1.6–18.6 kg N/ha), yet Overseer still predicted high leaching for STD 1 and STD 2 (130–131 kg N/ha). The most striking mismatch occurred in EXC 2, where Overseer predicted a very large surplus (183.2 kg N/ha) but low leaching (71 kg N/ha), suggesting that the model assumes this surplus remains stored in the soil rather than being lost. Meanwhile, treatments with minimal surpluses (CRF1 at 1.6 kg N/ha) still received moderate leaching predictions.

Framing these results in terms of NUE and N fate is consistent with tracer-based and mechanistic studies showing that management strongly regulates the partitioning of applied N between crop uptake, soil storage, and loss pathways. Classic N^{15} tracer work and conceptual syntheses have demonstrated that synchronizing N supply with crop demand, moderating mineral N pools, and avoiding excess soil NO_3^- are central to reduce leaching while maintaining yield [22–24]. In this context, the above N budget analysis shows that measured plant N uptake and NO_3^- leaching are closely linked across fertilizer strategies. This supports the broader evidence that improving NUE reduces surplus soil NO_3^- pools, lowers loss risk, and maintains productivity.

Table 10. Nitrogen budget summary based on Overseer predictions.

Scenario	Applied N (kg/ha)	Predicted Uptake (kg/ha)	Uptake Above CTRL (kg/ha)	Predicted Leaching (kg/ha)	† Surplus N (kg/ha)
			Year 1		
CTRL	0	290	–	266	–
CRF1	79.2	303	13	326	66.2
CRF2	79.2	300	10	273	69.2
STD1	81	293	3	344	78
STD2	81	308	18	392	63
EXC1	162	303	13	313	149
EXC2	162	292	2	356	160
			Year 2		
CTRL	0	473	–	120	–
CRF1	48.6	520	47	101	1.6
CRF2	48.6	504	31	97	17.6
STD1	48.6	503	30	130	18.6
STD2	48.6	513	40	131	8.6
EXC1	97.2	562	89	112	8.2
EXC2	97.2	387	−86	71	183.2

† Surplus N = (Applied N—(Predicted uptake—Predicted uptake$_{Ctrl}$)).

4.2. Sensitivity of the Model

The sensitivity analysis of the Overseer cropping module underscores the model's responsiveness to key soil and management parameters influencing NO_3^- leaching. Notably, fallow duration and timing emerged as critical factors, with early ryegrass establishment reducing leaching losses (Figure 3). This aligns with previous findings demonstrating that NO_3^- leaching is highly sensitive to crop cover and timing, primarily due to their influence on N uptake and water percolation dynamics [25]. Similarly, the depth of the impeded layer showed strong influence on leaching, particularly within the 10–50 cm range, where reduced water-holding capacity promotes frequent drainage events (Figure 4). These results are consistent with global sensitivity analyses indicating that soil hydraulic properties, especially saturated hydraulic conductivity and water retention, are among the most influential parameters in nitrate transport models [26].

Overseer's sensitivity to the soil texture group further highlights the importance of accurate soil classification in model calibration. Granular and light-textured soils exhibited elevated NO_3^- losses, likely due to their lower retention capacity and higher permeability (Figure 5). However, minimal sensitivity to drainage class and small changes in hydraulic conductivity suggest limitations in the model's granularity for certain soil hydrological traits (Figure 6). The pronounced effect of crop residue incorporation on NO_3^- leaching, up to a 50% variation, emphasizes the role of post-harvest N mineralization in leaching dynamics [27]. These findings collectively suggest that while Overseer captures major leaching drivers, refinement in its treatment of soil hydrology and residue decomposition could enhance predictive accuracy in vegetable cropping systems.

4.3. Evaluation of the Precision of Overseer Under Different Fertilizer Regimes

The mean difference (Md) between measured and simulated NO_3^- leaching losses serves as a critical metric for model validation, with non-significant Md values indicating acceptable simulation accuracy. However, the majority of these differences were statistically non-significant, suggesting that the model's predictions were not significantly ($p < 0.05$) different from empirical measurements. This aligns with findings noting that while Overseer tends to overpredict N losses under certain conditions, its long-term averages remain within acceptable bounds for regulatory use [6]. Significant Md values for CRF 1 in year 1 and STD 2 in year 2 highlight the model's limitations under specific fertilizer regimes and crop rotations. These discrepancies may stem from the model's simplified representation of N mineralization, residue decomposition, and soil water dynamics, which are known to vary significantly across cropping systems [28]. The scenario CRF 2 in year 1 involved two equal split applications of N-Control 75 in January and March so that Overseer may have treated these two applications to estimate NO_3^- leaching losses in three monthly steps. The model tended to reduce losses when the time steps increased, and consequently, the predicted loss was 16.2% lower than the single application scenario CRF 1 (Table 6).

The scenario STD 2 with four split applications include three of the split applications being made in January in two-week intervals and the final split application being made in March, in year 1. Overseer, having a monthly time step, considered that the uptake was complete by the time additional fertilizer application was made, treating any extra fertilizer as unused, despite crop growth and N uptake [19]. This shows that the user interface of Overseer's fertilizer module does not reflect the reality of fertilizer applications under vegetable growing conditions. Consequently, STD 2 scenario in year 2 resulted in some uncertainties when simulating frequent fertilizer applications. However, in general, Overseer did not adequately predict the other split application scenarios (CRF 2 and EXC 2), as indicated by their higher Er %. Moreover, the lack of dynamic feedback mechanisms in Overseer, such as real-time crop uptake and rainfall variability, may contribute to its reduced accuracy in scenarios with high temporal variability.

RMSE is a widely accepted metric for assessing model performance, as it quantifies the average magnitude of error between observed and predicted values [29]. The elevated RMSE values suggest that Overseer may not fully capture the N dynamics occurring under lysimeter conditions, particularly in systems with variable soil moisture and fertilizer regimes. While Overseer performs well in pastoral systems, its cropping module yields variable accuracy due to limited calibration datasets and simplified assumptions about soil–plant interactions [6]. This decline in accuracy in Er% may be attributed to the model's limited responsiveness to dynamic soil moisture and fertilizer regimes. Overseer was compared with the SCRUM-APSIM model, and it was found that while long-term averages aligned under benchmark conditions, Overseer struggled to replicate crop-specific N dynamics under varied soil and climate sequences [30].

These findings are also consistent with meta-analyses showing that management can substantially mitigate nitrate leaching while sustaining or even improving yields. It has been reported that improved fertilizer management, optimized irrigation, enhanced-efficiency fertilizers, and cover crops can significantly reduce nitrate leaching, with effect sizes that depend on crop type, climate, and baseline management for irrigated systems [11]. More recent syntheses, including global assessments of nitrate leaching from major cereals and vegetable systems, further highlight the importance of matching N inputs to crop demand and constraining soil nitrate accumulation as key levers for reducing losses. From a modelling perspective, our use of RMSE and related statistics follows established guidance that emphasizes the complementary roles of error metrics such as MAE and RMSE in evaluating model performance and bias [29,31].

4.4. Overall Simulation Performance of Overseer

Regression slope and intercept deviations are useful indicators for refining model structure and improving calibration [32]. The average overprediction of 39.4 kg N/ha/year highlights a systematic bias in the model's cropping module. Although this value was not statistically different from zero, it represents an inherent model bias when measured leaching approaches zero. This baseline offset is important to acknowledge, particularly in regulatory contexts where Overseer outputs are used to assess compliance and allocate nutrient discharge allowances. In systems with low nitrate-N losses, even a non-significant intercept may influence interpretation of modelled values. Accordingly, this baseline error should be considered when evaluating Overseer's predictions for low leaching scenarios.

Despite this, the R^2 value of 0.77 suggests that Overseer captures the general trend of nitrate losses reasonably well, even if absolute values deviate (Figure 8). Strong correlations between Overseer outputs and field measurements have been reported in pastoral systems, but reduced accuracy has been noted in cropping contexts [6]. The consistent divergence above the 1:1 line also raises concerns about the implications of overestimated NO_3^- losses for growers and regulators. Overprediction may lead to unnecessary restrictions or misinformed nutrient budgeting, potentially affecting farm profitability and compliance. This level of correlation coefficient (r) of 0.89 suggests that the model captures the general trend of NO_3^- leaching across diverse scenarios. Theoretically, for a perfect simulation (simulated values should be the same as the measured values), the r value should be 1, the intercept (a) should be 0, and the slope of the regression line (b) should be 1. However, the significant slope of the regression line ($p < 0.0001$) indicates a systematic bias in the magnitude of predictions (Table 9). This deviation from the 1:1 line suggests that while Overseer tracks the direction of change in NO_3^- leaching, it tends to overestimate leaching values. Slope deviations are common in empirical models when applied to systems with complex N dynamics, especially under variable fertilizer regimes and soil textures [28]. The non-significant intercept in this study further supports that the overestimation was not constant across scenarios but rather influenced by specific input sensitivities such as crop type, rooting depth, and residue incorporation. Despite these deviations, the overall agreement between measured and simulated NO_3^- losses supports a moderately successful validation of the Overseer cropping module.

4.5. Uncertainties Associated with the Simulation Scenarios

The accuracy of Overseer simulations for vegetable crops in New Zealand is limited, as only a few crops can be modeled. Beetroot was categorized under root crops in year 1, while pak choi was treated as regular cabbage due to the absence of a suitable category, potentially leading to discrepancies in crop characteristics. Additionally, Overseer used 30-year averaged climate data (1981–2010) instead of actual daily climate data for year 1 and year 2, ignoring interannual variability in rainfall and evapotranspiration. The recorded rainfall and evapotranspiration were 1048.4 mm and 577 mm in year 1 and 1264 mm and 786 mm in year 2, whereas the model used fixed values of 1126 mm and 831 mm, respectively. This omission likely affected NO_3^- loss predictions, as climate variability influences leaching [33]. As a result, the validation reflects Overseer's performance under its intended long-term averaging framework rather than its ability to reproduce year-specific leaching dynamics. This limitation does not indicate a modelling error but highlights the validation outcomes for anomalously wet years such as year 2.

Overseer also did not distinguish between NO_3^- leaching and runoff N, potentially overestimating NO_3^- losses. Furthermore, fertilizer N was assumed to be incorporated within 20 cm, overlooking variations in NO_3^- distribution, as surface soils generally exhibit higher N concentrations than deeper layers. The model extrapolated equations from pastoral systems to horticultural crops, which may have influenced N uptake estimates, potentially leading to discrepancies in leaching predictions [5,9]. Moreover, Overseer defined NO_3^- leaching as percolation below 60 cm, disregarding field soil heterogeneity beyond this depth. Therefore, Overseer's modeling accuracy provides a reliable estimate, and it is attributed to the model's simplifications in crop, soil, and nutrient interactions, which closely resemble lysimeter conditions [34].

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5. Conclusions

The Overseer cropping module demonstrated moderate success in predicting NO_3^- leaching losses under lysimeter conditions, with a generally good agreement between measured and simulated data (r = 0.89, R^2 = 0.77). While most scenarios showed non-significant mean differences, indicating reasonable accuracy, the model tended to overestimate NO_3^- losses in both years, with an average overestimation of 39.4 kg N/ha/year. This baseline bias is important in regulatory contexts, as Overseer outputs are directly applied in regional council compliance assessments and in determining nutrient discharge allocations. This consistent bias highlights the need for improved crop parameterization to ensure better prediction accuracy. It can be concluded that Overseer output may serve as a useful guide, but their limitations and potential biases must be taken into account before applying them in farm management decisions.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/nitrogen7010017/s1, Figure S1: Schematic diagram of a single lysimetric arrange ment for the collection of leachates at Woodhaven Gardens, Levin, New Zealand.; Figure S2: Treatment allocation for the 35 lysimeters in Woodhaven Gardens in Randomized Complete Block Design (RCBD). Each circle shows the lysimeter and treatment identification. Table S1: Baseline soil physical and chemical properties at the experimental site at different depths prior to the commence ment of the experiment.; Table S2. Nitrogen concentration (%) in beetroot leaves, roots, pak choi, and ryegrass under varying N fertilizer treatments.

Author Contributions: (i) R.B.: Conceptualization, investigation, methodology, data collection and analysis, and writing original draft. (ii) M.G.: Methodology, writing—review and editing, funding acquisition and project administration. (iii) P.J.: Methodology, and writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

N	Nitrogen
NO_3^-	Nitrate
M_d	Mean Difference
RMSE	Root Mean Square Error
Er	Error
CAN	Calcium Ammonium Nitrate
CRF	Controlled Release Fertilizer
EXC	Excess
STD	Standard
SCRUM-APSIM	Simple Crop Resource Uptake Model-Agricultural Production Systems sIMulator

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