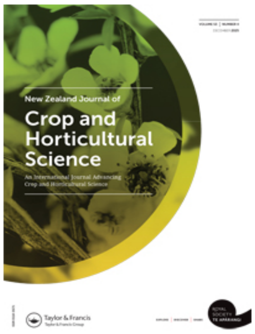

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RESEARCH ARTICLE

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Quantification of nitrate-N losses under intensive vegetable production systems in New Zealand

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ABSTRACT

Nitrogen leaching under intensive vegetable production is a major concern in New Zealand, yet measurements remain scarce. The main aim of this study was to quantify the amount of nitrate-N leached from representative soils and vegetable crops of the Lower North Island of New Zealand.

Nitrate-N concentrations in soil and drainage losses were measured from 2020 to 2022 at two vegetable crop sites. One site had a potato-fallow rotation with six N fertiliser treatments: control, standard practice, split liquid, controlled release, good practice, and excess fertiliser. The second site, a lysimeter study, evaluated a beetroot-Pak choi rotation under similar treatments, including a reduced rate and chicken manure.

High nitrate-N concentrations were observed in topsoil (9.3–18.3 mg kg^{-1}), subsoil (7.3–9.6 mg kg^{-1}), and drainage water (33.8–61.9 mg L^{-1}), with leaching losses reaching 225 kg N ha^{-1}, particularly during fallow periods. Alternative fertiliser strategies reduced soil nitrate-N but did not consistently maintain or increase yields. Excess fertilisation did not significantly increase potato yields but greatly increased nitrate-N losses.

This study provides essential data on soil nitrate-N concentration and leaching from intensive vegetable farms.

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KEYWORDS
Nitrate-N losses; vegetable farming; diffuse pollution; water quality; crop rotations

Introduction

As losses from agricultural fields are often of the order of 50% of applied nutrients, agriculture has been identified as the main diffuse source of the nutrients that degrade aquifers and water bodies (Fageria and Baligar 2005; Stewart and Lal 2017; Wang and Li 2019). Increasing nitrogen (N) use efficiency and mitigating N losses have become key challenges to modern agriculture (Quemada et al. 2013). Therefore, farmers need practices that, simultaneously, maintain or increase food production, and protect water quality. This is particularly the case for vegetable production systems, where often

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large amounts of N fertiliser are applied and can lead to large losses of N to the receiving water (Agneessens et al. 2014).

Vegetable production constitutes only about 0.3% of the utilised agricultural area in New Zealand (Horticulture New Zealand and Plant and Food Research 2020; Stats NZ 2021). However, market gardens are important to the New Zealand's economy, and in particular to the Horowhenua district in the Manawatu-Whanganui region (Infometrics 2021). Horowhenua, and specifically the Arawhata catchment, has been identified as one of the key areas of vegetable crop production in New Zealand, particularly for broccoli, cauliflower, cabbage, and carrots (Horticulture New Zealand 2017). Businesses associated with outdoor vegetable production are one of the main employers in the region (Infometrics 2021).

Lake Horowhenua, a 290-hectares shallow coastal lake located downstream the Arawhata catchment, is fed by several small tributaries, but most notably by the Arawhata stream. Currently, Lake Horowhenua is one of the most degraded lakes in New Zealand. Land Air Water Aotearoa (2022) reported a mean total N concentration of 3.5 g N m^{-3} in 2021, well above the national bottom line (0.8 g N m^{-3}) (Ministry for the Environment and New Zealand Government 2022). In 2010, Lake Horowhenua had the seventh worst water quality out of 112 surveyed lakes in New Zealand, and it is frequently closed to the public because of the presence of cyanobacteria (Horizons Regional Council 2017). There is much debate about what is exactly affecting today's water quality in the lake, but the most likely cause is land use intensification surrounding the Arawhata stream (Gibbs 2011; Horizons Regional Council 2017).

Vegetable cropping is considered to be one of the land-uses responsible for most of the nitrate-N leaching losses to the environment in the area (Clothier et al. 2007). Zemek et al. (2020) characterised nitrate-N leaching losses of 40 different green vegetables species, indicating that broccoli, cauliflower and cabbage, – the most commonly grown crops in Horowhenua – have a very high leaching potential. The vulnerability of vegetable systems to nitrate-N leaching has been attributed to the use of large amounts of N fertiliser, low N use efficiency, and large amounts of residual N left in the soil after harvest (Di and Cameron 2002). Moreover, residues of vegetable crops often have low C:N ratios which result in rapid N mineralisation and accumulation in the soil (De Neve and Hofman 1998; Chaves et al. 2007).

Several practices have been suggested help to reduce nitrate-N leaching from vegetable production systems. Three important suggested practices are: (1) optimising the timing of N fertiliser applications to meet plant N demand, (2) using catch crops to capture residual N, and (3) managing crop residues adequately (Zemek et al. 2020). Other in-field practices have also shown promising results in decreasing N losses, such as the use of controlled release fertilisers (Quemada et al. 2013), fertilisers that release small and steady amounts of N in time, and the use of liquid fertiliser (Holland 2014; The Ohio State Digital Ag Team 2018).

There has been very little research into nutrient leaching under intensive vegetable crop production in New Zealand (Norris et al. 2017; Thompson 2022; Thompson et al. 2022). Existing research is limited in terms of a robust quantification of nutrient losses and its critical flow pathways in vegetable crop production systems of New Zealand. Increased understanding of leaching rates under vegetable systems is essential to assist central Government and Regional Councils to make realistic and effective policy decisions, and to identify and evaluate the impact of mitigation practices on N leaching.

Due to the constraints associated with direct measurements of nitrate-N leaching, field-scale models, such as the Agricultural Production Systems sIMulator (APSIM) model (Holzworth et al. 2018), are useful to simulate nitrate-N losses under a range of cropping patterns and the effects of improved management. However, these models require field observations for their development and robust calibration.

Hence, the aims of this study are:

(1) To quantify the amount of nitrate-N leached from representative soils and vegetable crops of the Lower North Island of New Zealand.
(2) To assess the ability of selected in-field strategies related to N fertiliser management to reduce nitrate-N leaching from intensive vegetable farming in representative soils and vegetable crops of the Lower North Island of New Zealand.

Materials and methods

Experimental sites

Two research sites were established in the Arawhata catchment, in the Manawatu-Whanganui region. The trials were conducted between December 2019 and February 2022. Potatoes were grown at the experimental site located in the middle section of the catchment ('Potatoes site') while green vegetables were grown at the other side in the lower section of the catchment ('Green vegetables site').

The climate in the catchment is temperate (Garr and Fitzharris 1991). The 30-year average annual rainfall is 1163 mm (Chappell 2015). Monthly rainfall during the experimental period is indicated in Figure 1. Annual rainfall in the catchment was 1056 and

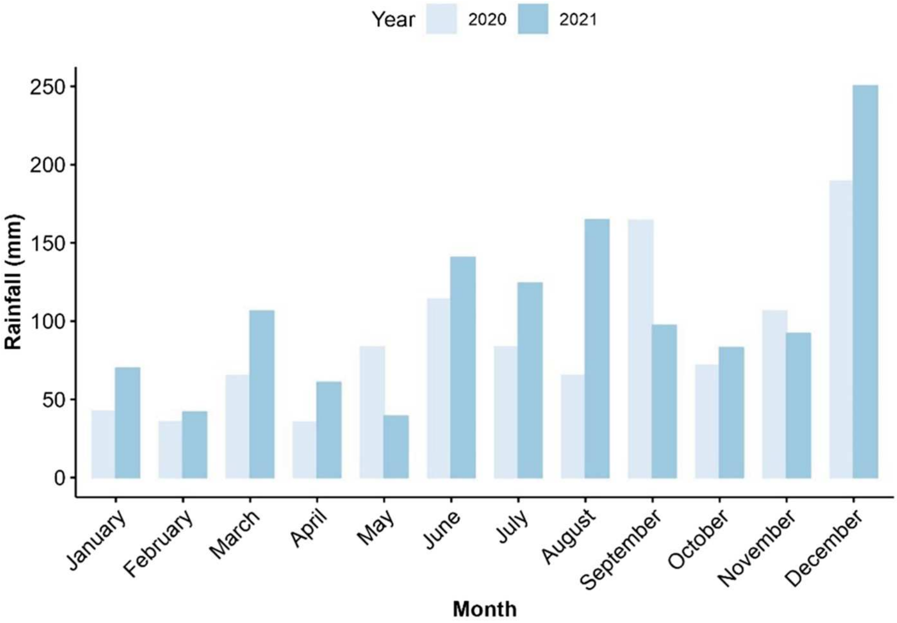

Figure 1. Monthly rainfall during the trial period (covering two years) in the Arawhata catchment.

Table 1. Cultivation practices at each site for the study period.

Practice/Site	Potatoes site	Green vegetables site
Typical crop rotation	Potatoes (2 years)-Onions (2 years)-Ryegrass (4–5 months)	Beetroot – ryegrass – Pak choi – ryegrass – cabbage/broccoli – maize – lettuce
Crops during the study[a]	Potatoes (2 years)	Beetroot – fallow – Pak choi – ryegrass
Irrigation	Boom sprayer, as needed (between 30–60 mm approximately)	No
Tillage	Mouldboard ploughing and bed building at sowing. Mounding up at ~5 weeks from sowing	Rotary hoe and bed building at sowing

[a]Crop rotation during the study period.

1270 mm for 2020 and 2021, respectively. Complementary irrigation is occasionally applied by some growers to obtain greater yields.

The soils are developed in up to a metre of silty loess over greywacke gravels. The most common soils are Allophanic Brown Soils, Brown Soils and Perch-gley Pallic Soils (Landcare Research 2018).

At the Green vegetables site, the soil is Shannon silt loam which has imperfect drainage. The soil at the potatoes site is Waitohu silty clay loam, which has better drainage than the Shannon series (moderately well drained). Both soils become firm and harder to penetrate between 40–60 cm depth. Further details of the properties of these soils can be found in Palmer and Wilde (2007).

Management practices and crop rotations for both sites for the study period are summarised in Table 1. Tillage, seed density, depth of sowing and other management practices on the plots followed the growers' typical practices. Herbicide and insecticide were applied as needed.

Treatments and experimental design in the Potatoes site

The fertiliser treatments for the first (sowing date: 24 December 2019, harvest date: 09 September 2020) and second potato season (sowing date: 05 November 2020, harvest date: 20 August 2021) are indicated in Table 2. The experimental design in the first and second season consisted of four replicates of three fertiliser treatments and the control in four blocks which were arranged in a randomised complete block design. There were 16 plots, each was 3.5 m wide x 16 m long. All treatments had sufficient P and K for optimum crop growth.

The fertiliser treatments for the first year aimed at studying the effects of fertiliser type, and the way they deliver N, on potato production and nitrate-N leaching. For the second year, the aim was to compare the effect of increasing N fertiliser amounts on potato production and N leaching. Since part of the treatments are different between seasons, treatments of different seasons were compared only when the treatments were consistent (i.e. 'standard practice' (STD) and 'control' (C)).

In the first crop season, soil samples were collected weekly for the first two months and monthly for the remaining period. A sample of soil from 0–30 cm depth and another sample from 30–60 cm depth were collected in the centre of the potato ridge from each plot. In the second crop season, samples for both depths were collected and bulked from three locations in the bed (top, middle and bottom of the bed) to better

Table 2. Fertiliser treatments at the Potatoes site.

FIRST SEASON			
Treatment	Total N applied (kg ha^{-1})	Type of fertiliser	Timing
Control (C)	0	n.d.	Sowing
Standard practice (STD)	180	Yara Mila Complex®[1]	Sowing
Split application of liquid fertiliser (LF)	180	Urea	33% applied 4 weeks after sowing and 67% applied 6 weeks after sowing
Controlled release fertiliser (CR)	180	SmartFert®[2]	Sowing
SECOND SEASON			
Treatment	**Total N applied** (kg ha^{-1})	**Type of fertiliser**	**Timing**
Control (C)	0	n.d.	Sowing
Standard practice (STD)	180	Yara Mila Complex®	Sowing
Good practice (GP)	240	Yara Mila Complex®; urea	75% applied at sowing and 25% applied 6 weeks after sowing
Excess (EXC)	300	Yara Mila Complex®; urea	60% applied at sowing and 40% applied 6 weeks after sowing

[1] Yara Mila Complex nutrient composition: 12-5-15.
[2] SmartFert nutrient composition: 44-0-0.

represent conditions in the bed and furrow soil. The topsoil and subsoil samples were sent to a laboratory for analysis of nitrate-N concentrations.

In the second potato growing season, suction cups were installed at 60 cm depth in the mid-point between ridge and furrow to help quantify nitrate-N leaching. Three suction cups were installed in each plot resulting in 48 suction cups, and soil solution samples were collected the day after larger rainfall events (approximately >15 mm rain). Nitrate-N concentrations from suction cups samples were analysed using a QuikChem 8500 flow injection analyser.

Cumulative nitrate-N leaching rates were calculated by using a drainage depth estimated by a soil water balance (Avendaño 2023) and the measured nitrate-N concentrations of the drainage water in the suction cups. Leaching rates per event were calculated by multiplying nitrate-N concentration by the drainage accumulated between rainfall events.

Fresh crop yields were measured from 2 × 1 m sections from the two central rows of each treatment plot. Note that potatoes were ground stored by the farmer until later in the year. Therefore, the yield estimations were done when the potato tubers were deemed ready for harvest (maturity date). For the first season, the potato yield estimation was done on 18 May 2020, while for the second season it was done on 14 May 2021.

Treatments and experimental design in the Green vegetables site

A bank of 20 lysimeters (5 lysimeters per treatment) were placed in a trench (10 m long and 2 m wide) in the grower's field in December 2019 (Figure 2). A crop of beetroot was grown in the lysimeters in the first season (sowing date: 16 January 2020, harvest date: 27 April 2020), and this was followed by Pak choi in the second season (sowing date: 11 February 2021, harvest date: 06 April 2021).

Figure 2. Lysimeters at the Green vegetables site.

The treatments in the Green vegetables site aimed at studying the effect of N fertiliser rate on intensive vegetable production and nitrate-N leaching (Table 3). Similar to the Potatoes site, the effect of a slow-release fertiliser, in this case chicken manure (CM), on crop production and N leaching was also evaluated. All treatments had sufficient P and K for optimum crop growth.

During excavation, the subsoil and topsoil were carefully separated to refill lysimeters. The lysimeters were 75 L in volume, with a radius of 0.2 m and height of 0.6 m. A piece of wicking fabric was set at the bottom of each lysimeter to maintain a fixed water tension at the bottom of the lysimeters.

A soil sample (0–20 cm soil depth) was collected from each lysimeter before sowing and after harvesting. Nitrate-N was analysed from each soil sample.

Table 3. Fertiliser treatments at the Green vegetables site.

FIRST SEASON			
Treatment	Total N applied (kg ha^{-1})	Type of fertiliser	Timing
Control (C)	0	n.d.	Sowing
Standard practice (STD)	117	Nitrophoska®; Calcium ammonium nitrate	31% applied at sowing and 69% applied 4 weeks after sowing
Chicken manure (CM)	117	Manure[1]	Sowing
Reduced fertiliser programme (RF)	72	Nitrophoska®	Sowing
SECOND SEASON			
Treatment	**Total N applied** (kg ha^{-1})	**Type of fertiliser**	**Timing**
Control (C)	0	n.d.	Sowing
Standard practice (STD)	50	Calcium ammonium nitrate	Sowing
Chicken manure (CM)	100	Manure	Sowing
Excess (EXC)	100	Calcium ammonium nitrate	Sowing

[1] Manure nutrient composition: 1-0-0.

All the plant biomass was harvested from lysimeters, and fresh weight was measured. The beetroot leaves and stems biomass were measured separately from the beetroot tubers. After biomass estimation, the beetroot tubers were incorporated into the soil on 16 June 2021.

Drainage water from the lysimeters was collected in 5 L containers at the outlet pipe. After larger rainfall events (approximately >15 mm rain), accumulated drainage water was weighed to estimate drainage volume using the standard density of water (1 g m^{-3}). Samples were collected in 10 mL container for nitrate-N analysis. Nitrate-N concentration was analysed from each sample using a QuikChem 8500 flow injection analyser. In each year of measurement, the flow-weighted mean nitrate-N concentration of each treatment was estimated by dividing the cumulative nitrate-N leaching rates by the cumulative drainage water.

Four piezometers were installed in the field surrounding the lysimeters to monitor the level and quality of shallow groundwater: two piezometers to a depth of 1 m ('BH1' and 'BH3'), and the others at 3 m ('BH4') and 5 m ('BH2') from ground level. The 5 m depth piezometer was screened (had perforations) at the bottom 2 m, the 3 m depth piezometer was screened for the bottom 1 m, and the remaining two piezometers were screened for the entire 1 m length.

Once installed and operating, groundwater from piezometers was purged at least 3 times its volume with a peristaltic pump before sampling (U.S. Environmental Protection Agency 2013; National Environmental Monitoring Standards 2019). Water was then collected in 100 mL containers and nitrate-N was analysed with a TriOS OPUS spectral sensor.

Data analysis

Normality of the residual errors and homoscedasticity of variance assumptions were checked on every dataset in order to fit a linear mixed model in R statistical software. If the normality assumption was not met, results were fitted to a Generalised Additive Model for Location, Scale and Shape (GAMLSS) to identify whether there were any statistical differences between two or more treatments (Stasinopoulos and Rigby 2007). Data distribution fitted into the different GAMLSS models was selected depending on the dataset. The different replicates were deemed to be a random effect variable in the model, and time and treatment were deemed to be fixed effects. A comparison between estimated marginal means from the model identified any statistical differences between treatments, following the Tukey method for adjusting the p-value.

Results

Soil nitrate-nitrogen and crop yields in the Potatoes site

In general terms, the soil at the Potatoes site had a mean nitrate-N content of 26 kg N ha^{-1} in the 0–30 cm soil depth and 24 kg N ha^{-1} in the 30–60 cm soil depth at the start of the trial.

The control treatment (C) had the lowest nitrate-N concentrations, both in the topsoil and subsoil, and the variations were also small in both seasons ($p < 0.05$) (Figure 2, Table 4).

When comparing the nitrate concentration of topsoil among the fertilised treatments, the control release fertiliser treatment (CR) had the smallest mean soil nitrate-N concentration (10.1 mg nitrate-N kg^{-1}) in the first potato growing season ($p < 0.05$) (Figure 2,

Table 4. Mean and estimated marginal mean (EMM) nitrate-N concentrations of topsoil (0–30 cm) and subsoil (30–60) for the first and second seasons of the Potatoes site (C for control; CR for controlled release fertiliser; LF for split liquid fertiliser; GP for good practice; EXC for excess and STD for standard practice).

FIRST SEASON					
Depth 0–30 cm			Depth 30–60 cm		
Treatment	Observed mean (mg nitrate-N kg^{-1})	EMM (log-scale)^	Treatment	Observed mean (mg nitrate-N kg^{-1})	EMM (log-scale)^
C	5.0 (2.2)	1.5 Aa	C	4.0 (2.2)	1.2 Aa
CR	10.1 (9.0)	2.1 Bb	CR	6.0 (3.4)	1.6 Bb
LF	16.6 (14.2)	2.5 Cc	LF	9.6 (8.0)	1.9 Bb
STD	18.3 (11.6)	2.7 Cc	STD	7.3 (3.2)	1.9 Bb
SECOND SEASON					
Depth 0–30 cm			**Depth 30–60 cm**		
Treatment	**Observed mean (mg nitrate-N kg^{-1})**	**EMM (log-scale)^**	**Treatment**	**Observed mean (mg nitrate-N kg^{-1})**	**EMM (log-scale)^**
C	7.4 (2.5)	2.0 Aa	C	5.5 (1.7)	1.7 Aa
STD	9.3 (2.4)	2.2 ABa	STD	9.6 (4.6)	2.2 Bb
GP	12.4 (4.2)	2.5 Bb	GP	10.3 (3.7)	2.3 Bb
EXC	21.3 (8.4)	3.0 Cc	EXC	14.7 (5.9)	2.6 Bc

^Different letters indicate significant differences between means of treatments (upper-case $p < 0.01$ and lower-case $p < 0.05$, Tukey method for p-value adjustment).

Table 4). In contrast, the standard practice (STD) and liquid fertiliser treatments had the largest mean soil nitrate-N concentration (18.3 and 16.6 mg nitrate-N kg^{-1}, respectively) ($p < 0.05$). The mean soil nitrate-N concentration was 45% greater in the STD treatment than in the CR treatment. However, for the subsoil, there were no significant differences measured in the mean soil nitrate-N content between the fertilised treatments (Table 4).

There were significant differences in potato yields between all treatments ($p < 0.05$). The smallest mean crop yield was measured in the C treatment (28 t ha^{-1}), followed by the liquid fertiliser (LF) treatment with 36 t ha^{-1}, the CR treatment with 42 t ha^{-1}, and the STD treatment with 52 t ha^{-1} (Figure 2). Interestingly, while CR was the treatment with fertiliser applied that had the lowest surface soil nitrate-N content, it had the second highest potato yield (Figure 2).

In the second potato growing season, the excess treatment (EXC) showed the largest soil nitrate-N concentrations, with concentrations 129% and 53% greater than the STD treatment in the topsoil and subsoil, respectively. In the 0–30 cm soil depth, the good practice (GP) treatment was significantly larger than the standard practice (STD) treatment by 33% ($p < 0.05$), but no significant differences were found in the 30–60 cm soil depth between these two treatments. The STD treatment had a 3% difference between the topsoil and subsoil mean nitrate-N concentrations, while the GP and EXC treatments had 20 and 45% greater mean nitrate-N concentrations in the topsoil than in the subsoil.

Mean nitrate-N concentrations measured in the topsoil and subsoil of the C treatment in the second growing season were 48% and 38% greater compared to the first season, respectively (Table 4). The STD treatment had considerably smaller mean topsoil nitrate-N concentration (decrease in 49%) and greater mean subsoil nitrate-N concentration (increase in 32%) in the second season than in the first season (Table 4).

All fertilised treatments showed significantly greater potato yields than the C treatment ($p < 0.05$), but there were no significant differences between the yield of the

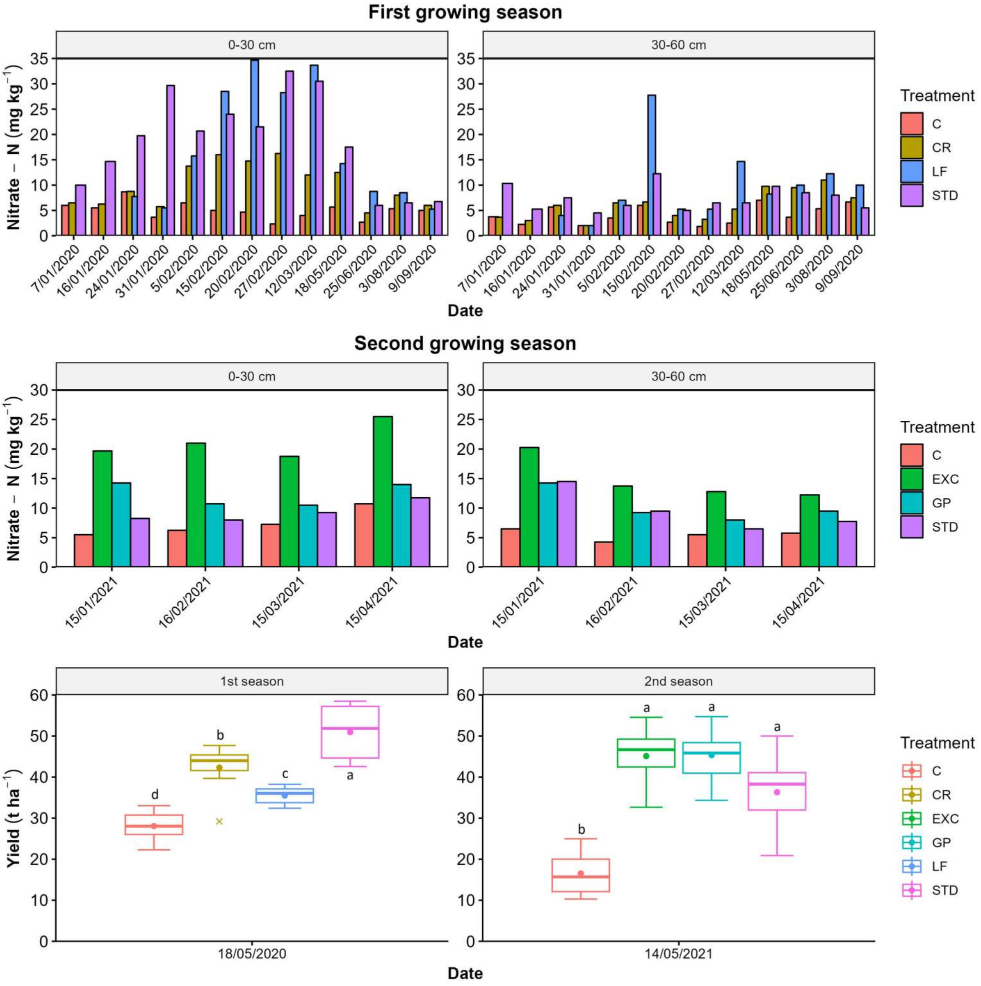

Figure 3. Mean soil nitrate-N concentrations in the 0–30 cm and 30–60 cm of soil and crop yields for each treatment between Jan-2020 and May-2021. Bars indicate standard deviations for each treatment (C for control; STD for standard practice; CR for controlled release fertiliser; LF for split liquid fertiliser; GP for good practice and EXC for excess). Different letters indicate significant differences between means of treatments (upper-case $p < 0.01$ and lower-case $p < 0.05$, Tukey method for p-value adjustment).

fertilised treatments (Figure 3). The yield of the STD treatment was 16 t ha^{-1} less for the second season than for the first season.

Nitrate-N in drainage water in the Potatoes site

Simulated cumulative drainage volumes from the water balance were estimated as 190 mm for the period of measurement. Since the potato plants grow and mature before the drainage period starts, all treatments had approximately the same drainage volume. Nitrate-N leaching rates between May to August 2021 were calculated as 43, 65, 76 and 109 kg N ha^{-1} for treatments C, STD, GP and EXC, respectively.

Table 5. Mean concentrations of nitrate-N in the suction cups (60 cm depth) for the period of sampling in the Potatoes site (C for control; STD for standard practice; GP for good practice and EXC for excess). Standard deviation given in brackets.

Treatment	n	Observed mean (mg nitrate-N L^{-1})	Estimated mean (mg nitrate-N L^{-1})^
C	72	22.6 (9.5)	22.5 Aa
STD	72	34.2 (10.0)	33.8 Bb
GP	72	40.0 (12.6)	39.6 Bc
EXC	71	57.4 (17.9)	55.6 Cd

^Different letters indicate significant differences between means of treatments (upper-case $p < 0.01$ and lower-case $p < 0.05$, Tukey method for p-value adjustment).

The mean soil water nitrate-N concentration in suction cups in the C treatment fluctuated between 20 and 32 mg L^{-1} and were the smallest values among the treatments. In contrast, the EXC treatment had the largest concentrations, which fluctuated between 40 and 75 mg L^{-1} (Table 5). The mean nitrate-N concentration in the soil water was significantly different between all treatments ($p < 0.05$). At 1% significance, there were still statistically significant differences between mean soil water nitrate-N concentrations of all treatments, except between treatments STD and GP (Table 5).

The soil water collected under the STD and GP treatments had mean soil water nitrate-N concentrations which were 51% and 77% greater than the C treatment, respectively. The soil water in suction cups under the EXC treatment had the highest mean nitrate-N concentration, which was 153% and 67% greater than the C and STD treatments, respectively.

Soil nitrogen and crop yields in the Green vegetable site

Initial soil N concentrations of samples taken before the establishment of the lysimeters were approximately 32 mg N kg^{-1} (112 kg N ha^{-1}) in the 0–30 cm soil depth and 18 mg nitrate-N kg^{-1} (79 kg N ha^{-1}) in the 30–60 cm soil depth.

Measurements done during the trial showed that the treatments had similar values for mean topsoil nitrate-N concentration over time (Figure 4). The last two measurements (09 April 2021 and 19 November 2021) were the lowest for the sampling period, as they were done after the last N fertiliser application for the season. As a reminder, note that nitrate-N concentrations samples taken in April and May each year reflect concentrations after crop harvest, while samples taken in November reflect concentrations before sowing of the next crop. The STD treatment had significantly larger nitrate-N concentrations than the rest of the treatments in the first sampling event, with concentrations 93% more than the reduced fertiliser (RF) treatment (Figure 3, Table 6).

The beetroot fresh tuber yield in the lysimeters were 63 t ha^{-1} in the C treatment, 65 t ha^{-1} in the STD treatment, 70 t ha^{-1} in the RF treatment and 73 t ha^{-1} in the CM treatment. There were no significant differences between the treatments.

For the Pak choi, there were significant differences in fresh yield between the C and EXC treatment ($p = 0.032$). The lowest yield was measured on the C treatment with a mean of 96 t ha^{-1}, while the largest yield was measured on the EXC treatment with a mean of 130 t ha^{-1} (Figure 5).

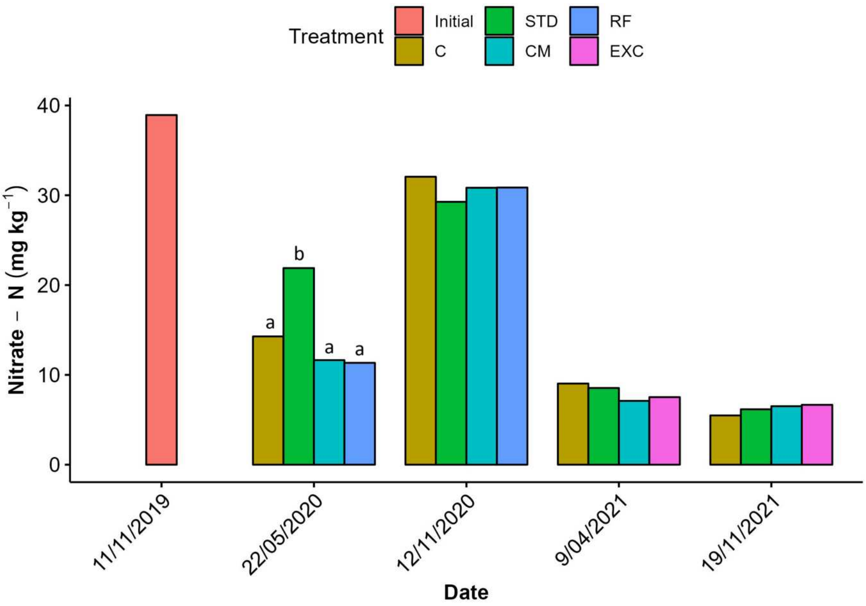

Figure 4. Mean nitrate-N concentrations in the 0–20 cm of soil from each treatment in the lysimeters. Bars indicate standard deviations for each treatment (C for control; STD for standard practice; CM for chicken manure, RF for reduced fertiliser programme and EXC for excess).

Drainage, nitrate-N concentration and leaching losses in the Green vegetables site

Most drainage events occurred during the winter and spring seasons, however, some heavy rainfalls in early summer also resulted in appreciable drainage volumes from the lysimeters. There were no significant differences in mean drainage volumes, mean nitrate-N concentrations, or mean nitrate-N leaching rates between treatments in either year. Only mean nitrate-N concentration of leachate from treatment STD in the first year was significantly different, with approximately 18–35% greater than the others (Table 7).

Piezometers in the Green vegetables site field

The shallow groundwater in the piezometers was closest to the surface during the summer season following large rainfall events. The depths of groundwater level observed

Table 6. Overall mean nitrate-N concentration of topsoil for the sampling period in the Green Vegetables site (C for control; STD for standard practice; CM for chicken manure; RF for reduced fertiliser programme and EXC for excess). Standard deviation given in brackets.

Treatment	Observed mean in the first year (mg nitrate-N kg^{-1})^	Observed mean in the second year (mg nitrate-N kg^{-1})
C	23.2 (10.8) ab	7.7 (2.4)
STD	25.6 (9.22) b	7.6 (2.6)
CM	21.2 (11.0) a	6.9 (2.5)
RF	21.1 (11.7) a	–
EXC	–	7.2 (2.1)

^Different letters indicate significant differences between means of treatments ($p < 0.05$, Tukey method for p-value adjustment).

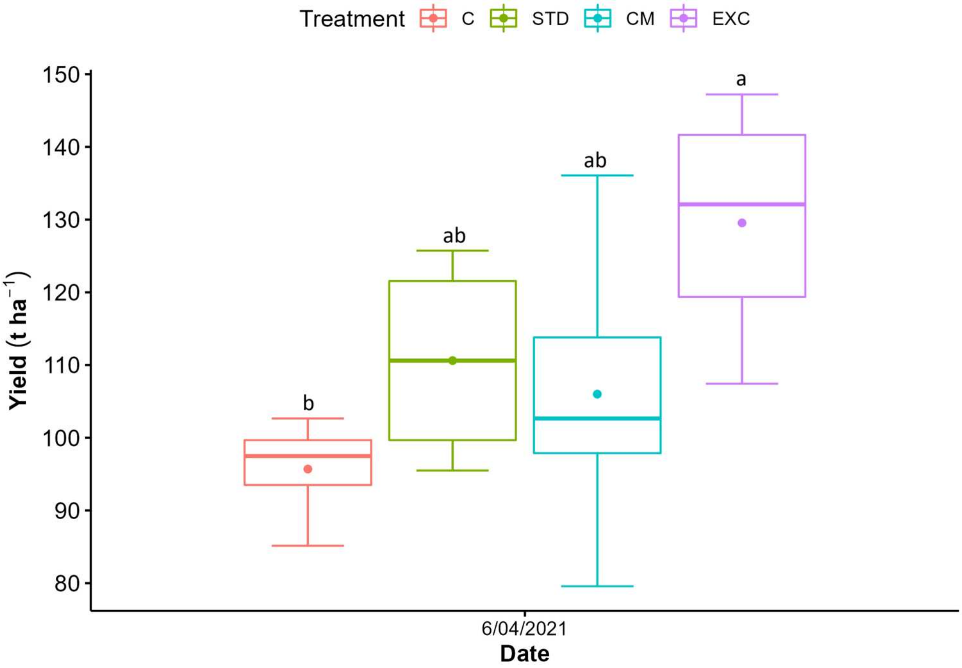

Figure 5. Pak choi yield means, medians, quartiles, maximums, and minimums (t ha^{-1}) for each treatment in the lysimeters (C for control; STD for standard practice; CM for chicken manure and EXC for excess). Different letters indicate significant differences between means of treatments ($p < 0.05$, Tukey method for *p*-value adjustment). The dot indicates mean, the horizontal bold line indicates median, the box indicates lower and upper quartiles (Q1 and Q3), and the whisker indicates minimum and maximum values.

Table 7. Cumulative drainage, flow weighted mean concentrations of nitrate-N in drainage and cumulative nitrate-N leaching rates from the lysimeters in the Green Vegetables site (C for control; STD for standard practice; CM for chicken manure, RF for reduced fertiliser programme and EXC for excess). Standard deviation given in brackets.

	First year		
Treatment	Cumulative drainage (mm)	Nitrate-N concentration in drainage^ (mg L^{-1})	Cumulative nitrate-N leaching (kg ha^{-1})
C	358 (198)	48.6 (8.9) a	186 (111)
STD	309 (133)	65.6 (8.7) b	212 (111)
CM	426 (68)	52.5 (7.0) a	222 (37)
RF	368 (102)	55.5 (4.1) a	207 (66)
Second year			
Treatment	**Cumulative drainage (mm)**	**Nitrate-N concentration in drainage (mg L^{-1})**	**Cumulative nitrate-N leaching (kg ha^{-1})**
C	501 (325)	33.8 (7.3)	154 (93)
STD	570 (319)	34.4 (11.4)	176 (101)
CM	535 (226)	36.8 (4.2)	188 (66)
EXC	517 (188)	32.9 (4.9)	166 (52)

^ Different letters indicate significant differences between means of treatments ($p < 0.01$, Tukey method for *p*-value adjustment).

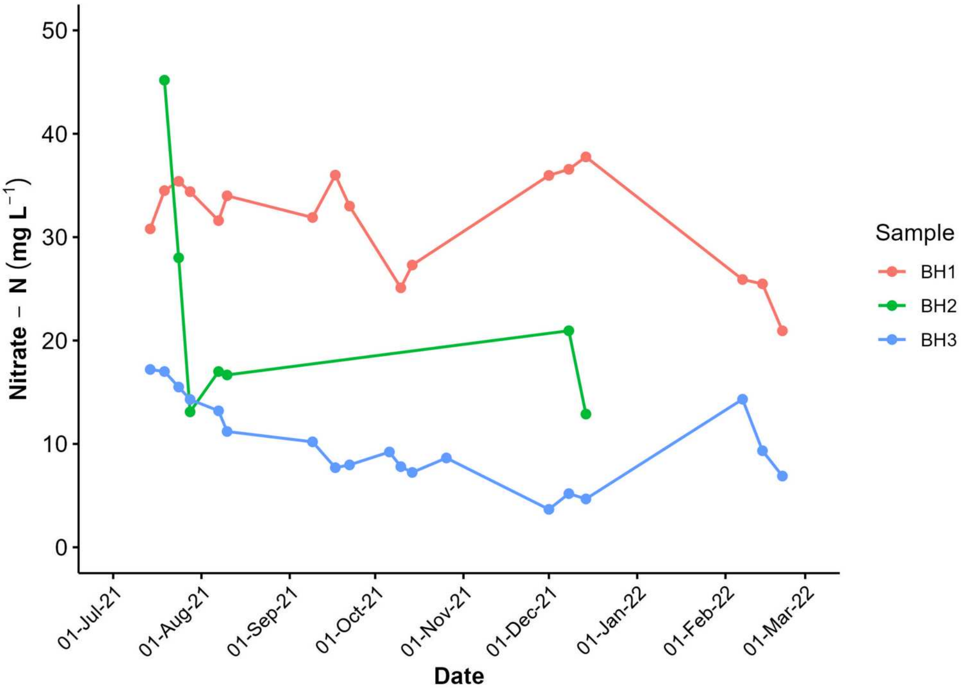

Figure 6. Nitrate-N concentrations in the piezometers (BH1 for piezometer at 1 m depth, BH2 for piezometer at 5 m depth and BH3 for piezometer at 1 m depth).

in the two shallow piezometers (1 m depth) (BH1 and BH3) were similar during the sampling period, with variations between 0 and 1 m below ground level. In contrast, the deeper piezometer (5 m depth) (BH2) had water levels between 3.6 and 4.6 m below ground level. No water was observed in the piezometer BH4 (3 m depth).

Groundwater in the piezometer BH1 had larger nitrate-N concentrations than the other piezometers (Figure 6), with a mean nitrate-N concentration 1.44 and 3.14 times greater than mean concentrations found in piezometers BH2 and BH3.

Overall, nitrate-N concentrations of piezometers tended to be higher in July 2021, although nitrate-N concentrations in BH1 were greatest in December 2021. Shallow piezometers (1 m depth) had an overall mean nitrate-N concentration of 20.8 mg L^{-1} between July 2021 and March 2022.

Between July and October 2021, the mean nitrate-N concentration in both shallow piezometers (1 m depth) was 21.4 mg L^{-1}, which was similar to the mean nitrate-N concentration of drainage water in the STD treatment in the lysimeters (19.6 mg L^{-1}) for the same period.

Discussion

Soil nitrate-N and crop yields

The type of crop rotation clearly influenced the residual N (kg ha) in this catchment, with shallow market gardens having substantially larger pre-planting soil nitrate-N concentrations. The greater pre-planting soil nitrate-N concentrations found under green vegetables (Figures 2 and 3, Tables 4 and 6) can be largely explained by the mineralisation of N from residues of the previous fennel crop. Although these pre-planting soil nitrate-N concentrations are seemingly large, N fertiliser rates applied by the growers in this study are considered common practice, and fall within the recommended range for beetroot crop (40–150 kg N/ha for a soil available N of 120 kg/ha in the first 15 cm) (Reid and Morton 2019).

As a result of the COVID-19 pandemic and low customer demand, the beetroot crop in the Green vegetables field was not harvested as scheduled but left to grow, leading to greater-than-usual crop biomass. This crop was then incorporated into the soil, which possibly resulted in large soil nitrate-N concentrations later in the season due to mineralisation (November 2020). This may have contributed to higher nitrate-N concentrations observed in both soil and soil water in the first year compared to the second year at the Green vegetables site (Figure 4 and Table 6). Though this may seem circumstantial, it indicates that incorporating unharvested crops back to the soil may lead to increased soil N and leaching rates. Depending on the market demand and quality issues, crops in the area may be left unharvested, and when they do, often large vegetable crop biomass is left in the field and reincorporated.

Rainfall was found to greatly influence soil nitrate-N concentrations, soil water nitrate-N concentration and crop yields. For instance, the smaller potato yields observed in the second growing season was most likely affected by the large rainfall event that occurred shortly after planting in November 2020 (approximately 100 mm over seven days, including one day with 33 mm). This could also explain why subsoil nitrate-N concentrations were larger in the second growing season than in the first season (Figure 3, Table 4), as greater rainfall amounts could transport nitrate-N to deeper soil horizons.

Similarly, the large rainfall events that occurred on days five and seven after applying N fertiliser in the Green vegetables site possibly transported nitrate-N to lower layers in the soil, therefore increasing the risk of nitrate-N leaching in the winter months. This suggests that, although split applications of N fertiliser are generally considered ‘good practice’, they are at higher risk and may cause the undesired effect of more nutrient losses if the applications happen just before intense rainfall events.

The effects of heavy rainfall on vegetable crops are not yet well understood, but studies indicate that waterlogging is likely to have negative impacts on root function, growth, and development, shoot growth and development, and crop yields (Evans and Fausey 1999; Satchithanantham 2013). This could impact the ability of plants to absorb nutrients.

This variability notwithstanding, the soil nitrate-N values from the current study, with its smaller fertiliser rates, agree reasonably well with the values recorded in other studies (Martin et al. 2001; Francis et al. 2003)

Soil nitrate-N content was variable at both sites and years; other researchers have also reported large variability in their measurements (Cambouris et al. 2008). Fraser et al. (2013), in their study of arable crops (wheat, barley and peas) under intensive tillage in the Canterbury region, reported an overall mean of 125 kg N ha^{-1} soil nitrate-N with a standard deviation of 103 kg N ha^{-1} in the 0–60 cm soil depth (back-calculated from confidence intervals and assuming t distribution). These values are comparable to the variability found in the present study (Tables 4 and 6).

Since the release of N of controlled released fertilisers is constant over time, which was confirmed by our results (Figure 3), this could be both, beneficial for the reduction of nitrate-N loss risk (Figure 3, Table 4), and detrimental to the expected yield of farmers (Figure 3). Given that the N demand for potatoes peaks at 40 days after planting, the CR practice might not have supplied sufficient N at this time to meet this sharp increase in demand. A complementary application of soluble N fertiliser could address this shortfall in N supply at this critical time and reduce N losses without compromising crop yields (Wilson et al. 2010; Reid and Morton 2019), but more studies of any such practice are needed in New Zealand. In general, other studies suggest that vegetable crops receiving CR fertilisers have similar yields to those with conventional fertilisers, but results for soil nitrate-N are less consistent (Martin et al. 2001; Wilson et al. 2010; Xing et al. 2016), indicating that soil nitrate-N can even increase when using controlled release fertiliser (Zebarth et al. 2012; Clément et al. 2021).

Similar to the CR treatment, the lower yields of potatoes found in the treatment with split liquid fertiliser (LF) can be explained by the late application of N fertiliser. Studies of Rens et al. (2018), Sparrow and Chapman (2003) and Zotarelli et al. (2021) highlighted the importance of fertilising potatoes in the initial stages (before and at emergence) to maximise tuber yields. In addition, the larger nitrate-N concentrations found in deeper layers under this practice might suggest that more N is prone to leaching and less available to plants.

In the Potatoes site, soil nitrate-N concentrations from the various treatments were as expected, both in the surface and subsurface soil, during the second growing season. Overall, treatments with more N fertiliser applied (GP and EXC) had greater soil nitrate-N concentrations than the typical N fertiliser amount.

The effect of increased N fertiliser rate on soil nitrate-N concentration was variable depending on the site. While at the Potatoes site, soil nitrate-N concentrations increased with increasing N fertiliser rate, this was not the case at the Green vegetables site. This could be explained by the differences in the N application rate at the sites. At the Green vegetable site, the increase in N fertiliser compared to the typical rates was relatively small (50 kg N ha^{-1}), therefore, much of this extra N could have been removed by greater crop N uptake. In comparison, the difference between the STD and EXC at the potato site was large (180 kg N ha^{-1}). This difference in application rate was reflected in the soil nitrate-N concentrations, and explains why soil nitrate-N concentrations increased significantly in the Potatoes site (9 mg kg^{-1}) compared to the Green vegetables site (decrease of 0.4 mg kg^{-1}) under typical practice.

Generally, excess N application did not produce significantly larger yields than those associated with the regular N rates used by growers (Figures 2 and 4). Similar results were obtained by Craighead and Martin (2003) for process potatoes in Canterbury. They suggested that there is some increase in process potato yields with increasing N fertiliser above 150 kg N ha^{-1}, but this increase is marginal, with an extra 2 t ha^{-1} yield for every 30–50 kg N ha^{-1} applied, and in some process varieties like Kennebec, there is no such increase in yield (Craighead and Martin 2003). Furthermore, these authors found that N fertiliser applications increased potato yields to an optimum but also reduced tuber dry matter (Craighead and Martin 2003). Similarly, Reid et al. (2020) observed almost no yield improvement for beetroot receiving between 320 and 480 kg N ha^{-1} of applied N. Other authors agree with the marginal yield response to larger N applications

(Martin et al. 2001; Sparrow and Chapman 2003; McPharlin and Lancaster 2010). However, they also highlight that this response changes with soil texture (i.e. potato yields decrease if grown in loamy soils and/or reach a plateau in sandy soils when applying large amounts of N fertiliser) (McPharlin and Lancaster 2010) and that yields can often depend more on the field history rather than the fertiliser programme (Sparrow and Chapman 2003). Therefore, there is no generic recommended optimum N fertiliser rate.

Drainage volumes

The variability in cumulative drainage from lysimeters is remarkably large (Table 7). The small surface area of the lysimeters may increase the variability within treatments, making it more difficult to find statistical differences. Other studies in New Zealand have reported similar variability (Giltrap et al. 2014; Herath et al. 2014; Duncan et al. 2016; Rodríguez Gelós 2020; Gunaratnam 2021).

There are a number of factors that could have influenced within-treatment drainage variability in this study, but most likely, the small differences in soil properties, including structure, and vegetation cover led to variations in drainage that became larger as they accumulated over time. Furthermore, some of the variability in drainage could be associated with the repacking of the lysimeters (Corwin 2000; Saporito et al. 2016). Cameron et al. (1996) and Cassel et al. (1974) also explain that the repacking of soil in lysimeters can affect pore size distribution and hydraulic properties. Finally, there is also some intrinsic variability associated with the lysimeter method. For instance, studies have suggested that edge flow effect can considerably influence measurements in lysimeters, and this could occur either with or without the use of a petroleum seal (Williams et al. 2020).

Nitrate-N concentrations and fluxes in drainage water

Similar to nitrate-N concentrations in the soil, increasing N fertiliser rates generally produced larger nitrate-N concentrations in drainage water (Figure 3 and Table 4), but exceptions to this rule were found in the Green vegetables site where increases in nitrate-N concentrations in drainage with increasing N fertiliser rates were small, possibly due to the removal of N by crop uptake (Figure 5). Soil nitrate-N concentrations after harvest and before the drainage season were smaller in the EXC treatment (Figure 4).

As noticed in previous studies (Di and Cameron 2002; Fraser et al. 2013), large nitrate-N concentrations and N leaching losses occurred under green vegetable crop cultivation, particularly during the fallow period and drainage season, and so care should be taken to minimise the potential leaching associated with these periods.

The large nitrate-N concentrations found in piezometers installed at the Green Vegetable site (at 1 and 5 m depth) support the large nitrate-N concentrations found in the drainage water in lysimeters, as mean nitrate-N concentrations in both areas were similar (mean difference of 1.76 mg L^{-1} between July and October 2021). The difference in nitrate-N concentrations between the two piezometers installed at 1 m depth could have been associated with a dilution effect, as runoff and ponding tended to occur near piezometer BH3. This runoff, ponding and dilution occurred because the paddock slopes towards BH3, and runoff water normally has low nitrate-N concentrations (Burkitt 2014). In addition, constant saturation conditions could have promoted denitrification process in this piezometer.

N leaching losses from the control treatments (no N fertiliser programme) were, relative to corresponding treatments, large. This is likely due to an accumulation of N in the soil profile and the historic rotations and fertiliser applications, as vegetable systems tend to have shallow roots and absorb N only in the surface horizons of soil. Martin et al. (2001) and Francis et al. (2003), who also used ceramic cups at 60 cm under potatoes, obtained similar mean nitrate-N concentrations in drainage to those reported here for their control treatment.

The use of chicken manure produced similar nitrate-N leaching rates to the current practice under green vegetable crops (Table 7). Therefore, organic amendments may not be effective in reducing N leaching rates from vegetable systems. Given the large variability obtained in this study, further research with a more detailed monitoring of drainage volumes should be conducted.

This study confirms that large nitrate-N concentrations in drainage can be expected under current management of vegetable crop systems in New Zealand (Clothier et al. 2007; Horizons Regional Council 2012; Norris et al. 2017), with a mean concentration of 33.8 mg nitrate-N L^{-1} under the potato crop and an overall mean concentration of 51 mg nitrate-N L^{-1} under vegetable crops (resulting in an overall mean loss of 201 kg nitrate-N ha^{-1} yr^{-1}). By using a water balance model to estimate drainage and the nitrate-N concentrations in drainage water from suction cups, nitrate-N leaching losses under the potato crop were calculated as 65 kg ha^{-1} for the monitoring period (May to August 2021). Nitrate-N concentrations and nitrate-N leaching losses in drainage water were generally much larger in soils cultivated with green vegetables, where residual nitrate-N concentrations in the soil profile were also larger than those cultivated with a potato-onion rotation (Figure 3). This suggests that residual nitrate-N contents should be used to inform fertiliser and crop management programmes if large nitrate-N leaching losses in vegetable systems are to be avoided. Since 2019, growers of the area started to adopt new fertiliser recommendations (Reid and Morton 2019) and have begun using Nitrate Quick Test sampling before the application of fertiliser (Bloomer et al. 2020).

Calculated nitrate-N leaching losses for the potato crop of this study were smaller than those obtained by Martin et al. (2001) and Francis et al. (2003) in the Pukekohe area, possibly due to the large difference in N fertiliser applications (242–472 kg N ha^{-1} in Martin et al. (2001) and 481 kg N ha^{-1} in Francis et al. (2003) cf 180 kg N ha^{-1} used in this study), but similar to those reported by Williams and Tregurtha (2003) for an Oamaru site, and to those reported by Herath et al. (2014) for the Manawatu area. Generally, nitrate-N concentrations and N leaching amounts for vegetable crops reported here were similar to those reported by Norris et al. (2017) for similar crops at a nearby location, but considerably larger than those reported by Francis et al. (2003). Variability in nitrate-N leaching rates, though seemingly high, was also within the normal range, with similar values for the standard error to those reported by Fraser et al. (1994), Cameron et al. (2002) and Di and Cameron (2002).

The results of this study, their variability and the challenges notwithstanding, will be used for the calibration and use of field-scale models like APSIM Next Generation.

Outside of New Zealand, studies have often measured leaching losses over a range of depths. In Canada and the US, studies have measured nitrate-N concentrations under potatoes using suction cups at 90 cm (Clément et al. 2020) and 120 cm (Wilson et al. 2010), reporting lower concentrations (18.7–24.8 g nitrate-N m-3, and 1.7–14.1, respectively) than the values measured in the present study. Clément et al. (2020) explained that variability in nitrate-N concentrations in drainage over years is highly associated with the distribution of seasonal rainfall and irrigation timing.

Conclusions

Large nitrate-N concentrations in soil (7.6–25.6 mg kg^{-1}) and leaching losses (65–212 kg ha^{-1}) under vegetable crops were found in representative crops and soils of New Zealand with typical management. Variability in these results was also large, although within the expected range. Green vegetable crop rotations had larger nitrate-N concentrations in drainage water than potato-onion crop rotations due to larger amounts of residual N and N mineralisation. Nonetheless, constrains on crop management imposed by the COVID-19 pandemic led to greater nutrient losses from the green vegetable rotation in part of the study period.

Of the range of in-field mitigation practices investigated here, controlled release fertiliser application produced lower levels of nitrate-N in the soil. However, the use of controlled release fertiliser (treatments C and CM) or liquid fertiliser (LF) did not maintain or increase crop yields compared to regular practices (STD), probably because of a deficit in N at crop planting and emergence.

Furthermore, for potato crops, N fertiliser applications larger than the current practice of the growers (treatments GP and EXC) did not improve crop yields considerably, but produced significantly larger nitrate-N concentrations in drainage water. Therefore, to reduce the risk of N leaching, optimum N fertiliser programmes that aim towards reaching yields before a plateau in yield are encouraged.

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