CSIRO PUBLISHING

RESEARCH PAPER
https://doi.org/10.1071/SR23136

SOIL RESEARCH

Nitrogen and phosphorus leaching losses under cropping and zone-specific variable-rate irrigation

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Handling Editor:
Nick Dickinson

Received: 11 July 2023
Accepted: 20 November 2023
Published: 19 December 2023

Cite this:
Drewry JJ *et al.* (2024)
Soil Research **62**, SR23136.
doi:10.1071/SR23136

ABSTRACT

Context. Agricultural land use is intensifying globally. Irrigation and other farm practices associated with intensification, such as cultivation, grazing, and fertiliser application, can increase nutrient losses. Variable rate irrigation (VRI) systems manage irrigation to spatially variable soils and different crops (zones). We lack knowledge on nutrient losses under zone-specific irrigation for mixed-cropping systems (combined crop and livestock grazing). **Aims.** This study evaluated drainage, nitrogen, and phosphorus leaching losses under zone-specific irrigation for a temperate mixed-cropping system. **Methods.** The study site had sheep grazing and crops including peas, beans, wheat, turnips, plantain, and ryegrass-white clover pasture. It had a variable-rate centre-pivot irrigator for two soil zones (free draining Zone 1; poorly drained Zone 2). Drainage flux meters (DFMs) collected drainage leachate, and samples for measurement of nitrogen (N) and phosphorus (P) concentrations. Soil water balance data and statistical modelling evaluated nutrient leaching losses over 5 years. **Key results.** The mean leaching load of NO_x-N (nitrate + nitrite) across 5 years was 133 (s.d. 77) and 121 (s.d. 97) kg N/ha/year for Zone 1 and Zone 2, respectively. Similarly, the mean leaching load of reactive P across all years was 0.17 (s.d. 0.30) and 0.14 (s.d. 0.14) kg P/ha/year for Zone 1 and Zone 2, respectively. The nitrogen concentrations and loads generally had greater uncertainty in Zone 2. **Conclusions.** The DFMs worked well for the free draining sandy soil. However, fewer samples were collected in the silt soil, requiring the statistical modelling developed in this study. This study gave a reasonable estimate of annual leaching load means, but the indicators of their within-year variation were not reliable, partly due to differences in sampling frequency. With some exceptions, there was generally more NO_x-N leaching from the free draining Zone 1. VRI provided a system to control irrigation-related drainage and leaching in these soil zones. **Implications.** Drainage flux meters are more reliable in well-drained than in poorly drained soil. Given the lack of published studies, this study has improved knowledge of nutrient losses under zone-specific irrigated mixed-cropping systems in a temperate climate.

Keywords: cropping, drainage, irrigation, nitrate, nitrate leaching, phosphorus, soil water balance, variable rate irrigation, water quality.

Introduction

Agricultural land use intensification is occurring in many areas globally to support the demand for food production from population growth (Viglizzo *et al.* 2011; Cherubin *et al.* 2016; Camporese *et al.* 2021). Intensification of agricultural land includes the irrigation of previously non-irrigated areas. Irrigation is used to increase pasture and crop yields, but this is often associated with an increase in nutrient inputs through fertiliser, increased stock numbers, changing cropping patterns, and crop and pasture management practices (Barros *et al.* 2012; Cherubin *et al.* 2016; Drewry *et al.* 2021*a*; Koppe *et al.* 2021).

However, irrigation and other practices associated with intensification, such as cultivation, grazing, and nutrient inputs, can increase nutrient losses, and affect soil carbon, nutrient cycling, and soil health indicators (Drewry *et al.* 2021*b*, 2022*a*; Lambie *et al.* 2021;

Mayel et al. 2021; Monaghan et al. 2021; Eger et al. 2023). Efforts to reduce diffuse nutrient losses from agriculture through improved farm practices, regulation, or catchment management is challenging and ongoing (Lynam et al. 2010; Snelder et al. 2020; Srinivasan et al. 2020; Grizzetti et al. 2021; Macintosh et al. 2021; McDowell et al. 2021). Cropping patterns and crop types, fertilisation rates, and irrigation efficiency contribute to a range of nitrate losses under irrigation (Barros et al. 2012). As an example, nitrogen (N) leaching losses from centre-pivot irrigated lucerne were higher when compared with non-irrigated lucerne, with the largest losses occurring during summer irrigation (Graham et al. 2022).

Water and nutrient losses from farms can be reduced through precision agriculture practices, such as the use of management zones for improved management of irrigation and fertiliser to spatially variable soils or to different crops in mixed-cropping systems (Drewry et al. 2022b). These practices, coupled with good farm management practices, can help reduce farm inputs and nutrient losses, increase water use efficiency, and improve crop and pasture yields (Hedley et al. 2009; González Perea et al. 2018; O'Shaughnessy et al. 2019; Vogeler et al. 2019; El-Naggar et al. 2020).

Variable rate irrigation (VRI) systems have been developed for managing spatially variable soils, or for managing several crops in different areas (zones) under the irrigator. VRI has been shown to reduce drainage and nutrient losses compared with uniformly applied irrigation water (Hedley 2015; McDowell 2017; González Perea et al. 2018; Drewry et al. 2019). Although some studies have investigated the effect of different grazed crops, such as plantain, on N leaching under dairying (Rodriguez et al. 2023), losses under such crops also need evaluation under irrigated mixed-cropping systems. Mixed-cropping systems involve repeated disturbances during crop transitions, fallow periods, legacy effects of legume crops, and animal inputs, all or which may increase nutrient losses. These systems may challenge VRI systems due to changing crop water demand. There appear to be few published studies evaluating nutrient leaching losses in New Zealand cropping systems over multiple years and crop sequences (Norris et al. 2023).

A range of methods have been used to evaluate drainage and nutrient losses under irrigation, including lysimeters (Gray et al. 2021; Graham et al. 2022), modelling (Vogeler et al. 2019), and drainage flux meters (DFMs) (Loo et al. 2019; Norris et al. 2023). DFMs have a buried, cylindrical collector outfitted with a wick to provide tension for draining the column of soil above. Drainage from the soil is measured and sampled from a reservoir. These meters are simple to operate and are a useful tool for measuring drainage and solutes (Gee et al. 2009; Norris et al. 2023). Meissner et al. (2010) evaluated drainage differences between DFMs and lysimeters, and identified that further research was required to evaluate the role of DFMs in measurements of water quality and drainage in less free draining soils. Very few published studies have evaluated nutrient losses using DFMs (Norris et al. 2023). Although some studies have evaluated nutrient losses under VRI systems (e.g. McDowell 2017), there is a paucity of data for N and phosphorus (P) concentrations and leaching losses under zone-specific irrigation VRI systems for mixed-cropping systems (combined crops and livestock grazing).

This study measured drainage and N and P concentrations in leachate under two contrasting management zones of a variable rate centre-pivot irrigator for a mixed-cropping system using DFMs. The objectives were to estimate leaching losses from mixed-cropping system zones, and evaluate the potential of DFMs as a tool for estimating nutrient losses.

Materials and methods

Overview of site and soils

The study was conducted at Massey University's No. 1 Farm, near Palmerston North, New Zealand. The farm is located at 40.22°S and 175.36°E. The climate of the region is temperate. Median annual rainfall at Palmerston North (1981–2010) was 900 mm; mean annual temperature range was 9.1°C (Chappell 2015).

The study area (1.2 ha) is on a mixed-cropping site, typically cropped with peas, beans, and spring wheat, with sheep grazing between cropping events. The site has a centre-pivot irrigator with variable rate control that irrigates two management zones. The two management zones are based on soil type. These two zones were delineated using information from a soil survey (Pollok et al. 2003), an electromagnetic survey (El-Naggar et al. 2021), and measurements of a range of soil physical properties. Zone 1 soil is a Manawatū fine sandy loam, a deep, free-draining soil classified as a Fluvial Recent Soil (Hewitt 2010). Zone 2 is a Manawatū silt loam classified as a Fluvial Recent Soil and is poorly drained. Both soils are classified as a Fluvisol in the FAO Reference Soil Group (IUSS Working Group WRB 2015).

Soil analyses were undertaken to characterise the soils. Soil available water capacity (AWC) was determined in 0.1-m increments to 1 m depth (El-Naggar et al. 2020). Soil samples for physical analysis were collected in August 2016 using undisturbed cores sampled at 20-cm intervals to 1 m depth. Sampling details for the site are described in El-Naggar et al. (2021), with general physical methods in Drewry et al. (2021c). Analyses undertaken at the Manaaki Whenua – Landcare Research Soil Physics Laboratory were: particle size distribution, bulk density, porosity, and air permeability (Gradwell and Birrell 1979). Soil samples for chemical analysis were collected in August 2016. Analyses were: Olsen P, total carbon (C) and N, pH, cation exchange capacity, and exchangeable K, Mg, and Ca, with analyses undertaken at the Massey University School of Agriculture and Environment laboratory.

Crop and irrigation management

The site was cropped with a series of monoculture crops for harvest, including peas (*Pisum sativum*), beans (*Phaseolus vulgaris*), spring wheat (*Triticum aestivum*), and oats (*Avena sativa*), followed by Barkant turnips (*Brassica rapa*), plantain (*Plantago lanceolata*), chicory (*Cichorium intybus*), ryegrass (*Lolium perenne*), red clover (*Trifolium pratense*), and white clover (*Trifolium repens*) in pasture mixes grazed by animals, over the period 2016–2021 (Table 1). The cropped site is typically grazed with sheep when not in crop or is fallow, termed 'mixed cropping'.

The 86-m irrigator had one span containing 31 sprinklers, each with a spray radius of 5 m and a flow rate of 26.3 m^3/h. The pivot provided a mechanism to apply known and fixed amounts of irrigation. Soil water balance (SWB) scheduling used the FAO56-ET method to calculate daily soil water deficits to determine crop water requirements (El-Naggar *et al.* 2020).

Experimental design and drainage flux meters

An electromagnetic (EM) survey of the site was conducted to identify the two management zones. Zone maps were derived using geostatistical methods, as reported by El-Naggar *et al.* (2021). Briefly, electromagnetic and gamma radiometric data were interpolated into regular 5-m resolution grids using ordinary kriging. These were then used to derive zone maps using unsupervised clustering; further details are described elsewhere (Hedley *et al.* 2016; El-Naggar *et al.* 2021). The VRI pattern was developed for this site based on this information.

Twelve DFMs were constructed for each of two management zones using an existing design (Gee *et al.* 2002, 2009; Norris *et al.* 2023). The wick length was 0.06 m and the control tube (convergence ring) was approximately 0.015 m in height. Each DFM was installed 3–4 m apart with its top at least 0.65 m below the soil surface. The trial site was designed with three plots applied to each of the two soil

Table 1. Summary of the study site's crop management practices.

Date	Field management Zone 1	Field management Zone 2
May 2016	Bare ground	Same as Zone 1
October 2016	Chisel ploughed and cultivated. 37.75 kg N/ha and 25 kg P/ha applied. Peas (Ashton) sown 260 kg/ha	Same as Zone 1
January 2017	Peas harvested. Chisel plough and cultivation. 37.75 kg N/ha and 25 kg P/ha applied. Beans (Contender) sown 75 kg/ha.	Same as Zone 1
March–April 2017	Beans harvested. Plough and full cultivation. 37.75 kg N/ha and 25 kg P/ha applied. Oats (Milton) sown 120 kg/ha. Barkant turnips sown 3 kg/ha.	Same as Zone 1
Remaining 2017	The forage crops are grazed by approx. 75 ewes, especially in August. November 2017 plough and full cultivation. 37.75 kg N/ha and 25 kg P/ha applied. Peas (Ashton) sown 260 kg/ha.	Same as Zone 1
2018	January 2018 harvest peas. February 2018 Chisel plough and cultivation. 37.75 kg N/ha and 25 kg P/ha applied. Beans (Contender) sown 75 kg/ha, part area. Oats (Milton) sown 110 kg/ha. April harvest beans.	Same, with some mix across zones. March 2018 plough and full cultivation. 37.75 kg N/ha and 25 kg P/ha applied. Barkant turnips sown 3 kg/ha. Brassica (Pallaton Raphno) sown 8 kg/ha.
November 2018	37.75 kg N/ha and 25 kg P/ha applied. Wheat (Sensas) sown 150 kg/ha.	Same
2019	February harvest wheat. April full cultivation. 37.75 kg N/ha and 25 kg P/ha applied. Oats (Milton) sown, direct drilled 110 kg/ha.	Same, plus oats (Milton) sown 110 kg/ha, Barkant turnips sown 3 kg/ha, with full cultivation.
October 2019–2020	Ploughing and full cultivation. 37.75 kg N/ha and 25 kg P/ha applied. Plantain (7 kg/ha), perennial ryegrass (12 kg) and white clover mix (3 kg) sown, rest bare ground. Plantain mix (mown): 23 December 2019, 11 February 2020, 8 March 2020, 1 May 2020, 2 June 2020, 2 July 2020. Plantain grazed (ewes and lambs) from 1 October 2020 on approx. monthly basis until 16 June 2021.	Same as Zone 1
2020	February 36.8 kg N/ha applied. April plough and full cultivation. Oats (Milton 110 kg/ha) and peas (150 kg/ha) sown.	April 2020 direct drilled annual ryegrass.
2020	Oct 2020 plough and full cultivation. November 37.75 kg N/ha and 25 kg P/ha applied. Mix sown (Puna II chicory 5 kg/ha, Legacy white clover 2 kg/ha, Bounty white clover 2 kg/ha, Sensation red clover 4 kg/ha).	Same as Zone 1
2021	Chicory mix grazed from 6 January 2021 to 16 June 2021. Un-grazed rest of winter. Grazing recommenced 20 September 2021. Grazed by approx. 80 lambs on a 3–4 week rotation. 37.75 kg N/ha and 25 kg P/ha applied.	Same as Zone 1

N and P applications were from Cropmaster 15 fertiliser (content: N 15.1%, P 10%, K 10%, S 7.7%). February 2020 N applied as urea.

zones, with four replicate DFMs grouped in each plot (Fig. 1). The DFMs were located on the 76 m arc from the centre of the irrigator.

The 24 DFMs were installed (28 April to 26 May 2016) to collect drainage water below 0.65 m soil depth. For installation, a hole was prepared 0.20 m in diameter, and 1.8 m deep, with a hand auger. Stones were encountered at approximately 1.2–1.5 m depth in Zone 2. At installation, the 0.20-m section of pipe above the wick was repacked with soil taken from the same depths. The wick in the funnel section was wet up and then diatomaceous earth added and packed tightly. Finally, 99% pure silica sand was added, and water carefully poured over this until it measured approximately 0.01 m in depth above the sand, removing air bubbles. Pipes with collection tubes were installed beneath approximately 0.65 m to facilitate drainage water collection, as the DFMs remain in the soil. Further information is available in Karakkattu *et al.* (2020).

Drainage sampling measurements and water nutrient concentrations

Drainage volumes were measured and collected regularly using a customised pumping system. Drainage was measured on 74 occasions between 26 May 2016 and 23 June 2021. Water quality samples were collected from drainage on 40 sampling dates. Water quality samples were collected every 1–3 weeks during the first year, then approximately 2-monthly or every 80–100 mm of rainfall until approximately late 2019. From then, water quality samples were collected seasonally, due to resourcing constraints. Water samples were analysed for ammonia-N, NO_x-N (nitrate-N + nitrite-N) and reactive phosphorus by the Manaaki Whenua – Landcare Research Environmental Chemistry Laboratory, with methods described in Manaaki Whenua – Landcare Research (2021). All samples were refrigerated at 4°C during storage, and filtered at the laboratory with Whatman No. 42 filter papers prior to analysis. The ammonia-N (NH_4-N) was determined colorimetrically using the indophenol reaction with sodium salicylate and hypochlorite; NO_3-N by Cd reduction and NEDD colorimetry; and NO_x-N is reported (nitrate-N + nitrite-N). For reactive P (i.e. filterable reactive P), the orthophosphate reacted with ammonium molybdate and antimony potassium tartrate under acidic conditions, then a molybdenum blue complex was formed after ascorbic acid reduction. All analyses were performed with a QuikChem 8500 flow injection analyser (Lachat Instruments, Milwaukee, WI, USA).

Soil water balance modelling

For the SWB, a daily time-step model was developed. This model used the FAO56-ET Penman-Monteith method (Allen *et al.* 1998) and weather data derived from the Palmerston North CliFlo climate station (http://cliflo-niwa.niwa.co.nz/) (NIWA and AgResearch climate station 21963), which was

Fig. 1. Experimental layout of the site with soil types and management zones.

located only 50 m from the site, to calculate the daily ETo (reference evapotranspiration), ETc (crop evapotranspiration) and soil water deficit (SWD) values. The daily SWDs were used to determine crop water requirements for irrigation scheduling and crop management (El-Naggar *et al.* 2020, 2021). Separate SWBs were constructed per zone using farm and nutrient management (Table 1, Supplementary Fig. S1 in Supplementary material), crop, irrigation, and the AWC data collected per zone.

Statistical analysis

The measured drainage from Zone 1 was found to be much greater than the SWB-modelled drainage. There were fewer drainage and nutrient samples from Zone 2 after 2017, than for Zone 1, so zone-specific scaling was required. The approach was to estimate the parameters of a linear, quadratic, or cubic zone-specific model to estimate the SWB estimates from the DFM measurements. Overall, the cubic model was best and was adopted. The models are zone-specific and the cubic version of the correction is:

$$y_{\text{corr}} = \beta_0 + \beta_{1,i} \cdot y_{\text{dfm}} + \beta_{2,i} \cdot (y_{\text{dfm}})^2 + \beta_{3,i} \cdot (y_{\text{dfm}})^3 + \varepsilon$$

where y_{corr} is the corrected DFM cumulative drainage to match the SWB estimate, for zone i. The uncertainty is ε, assumed to be a Gaussian with a zero mean. Using the zone-specific cubic model to correct the field-measured DFM cumulative flow, the cumulative drainage for all the sample dates was evaluated.

Concentration values below the limit of detection were replaced by half the detection limit. Evaluation indicated the temporal variation is likely to be non-linear over time. A generalised additive mixed model (GAM) with a random effect for the replicate, and smoothing for the date to account for between- and within-year trends, was used. The GAM model was fitted with each nutrient treated as a Gamma with log-link. The long-term temporal trend was accounted for using a (tensor spline) smooth function of the number of years since the start of 2016, and the intra-annual temporal trend accounted for using a (tensor spline) smooth function of the day of the year. Both splines are zone-specific. A random effect was included for the group within each zone, to account for possible random variation at a site. The model used for estimation of the load during each hydrological year included terms for cumulative rainfall and irrigation. The general GAM model form was:

$$\begin{aligned} g(\mu_{i,j}) = \text{Zone}_i &+ f_{1,i}\,(\text{years since 2016}) + f_{2,i}\,(\text{day of year}) \\ &+ f_3\,(\text{years since 2016.Cumulative Rainfall}) \\ &+ f_4\,(\text{Years since 2016.Cumulative Irrigation}) \end{aligned}$$

where $\mu_{i,j} = E(Y_{i,j})$ and $Y_{i,j} = EF(\mu_{i,j}, \phi)$. $Y_{i,j}$ is a response variable (one of NO_x-N, ammonia-N, or P), $EF(\mu_{i,j}, \phi)$ is a Gamma distribution with mean $\mu_{i,j}$ and scale parameter ϕ, for zone i. The f_j(Years since 2016) and f_k(Day of year) are zone-specific smooth functions of the number of years since 1 January 2016 and the day or the year, respectively (Wood 2017), which is cyclic.

The terms for cumulative rainfall and irrigation include an interaction with the date. This form is required since rainfall and irrigation have a large proportion of zeros (i.e. no rainfall and/or no irrigation). It is not clear whether adding these terms would improve the model for load, since omitting the terms would be partially offset by the smooth terms $f_{1,1}$ and $f_{2,1}$.

The fitted GAM used the *mgcv::gam*() procedure (Wood 2017) using maximum likelihood, so models could be compared. Models using an additive random effect (group, zone, or DFM) were evaluated using the R-squared, the proportion of deviance explained, and the Akaike Information Criterion (AIC) (Table 2). The model with the random effect associated with DFMs was improved over zone and group (also repeated for the other response variables), so was chosen as the final model, explaining 53.5%, 73%, and 69.7% of the total deviance for NO_x-N, ammonia-N, and reactive P, respectively.

The nutrient loads were calculated from cumulative drainage and the nutrient concentrations from the models developed. For annual statistics of drainage and load, the period 1 July to 30 June was used, as it is common practice in the Southern Hemisphere to use this hydrological year. All statistical analyses were carried out using the statistical package 'R' ver. 4.2.0 (R Core Team 2022).

Results

Site soil characteristics

The median sand content of Zone 1 ranged from 55 to 95% and increased with depth, while the median sand content of Zone 2 was 38–60% and increased with depth (Table 3).

Table 2. Summary table for GAMs applied to all responses, using the R-squared, the proportion of deviance explained, and the Akaike Information Criterion (AIC).

Nutrient	Random effect	R-squared	Deviance explained	AIC
NO_x-N mg/L	Zone	0.431	0.436	6097
	Group	0.473	0.473	6045
	DFM	0.503	0.535	5989
Ammonia-N mg/L	Zone	0.252	0.64	84
	Group	0.346	0.66	2.3
	DFM	0.155	0.73	−144
Reactive P mg/L	Zone	0.014	0.056	−3440
	Group	0.239	0.478	−3942
	DFM	0.596	0.697	−4316

Note: The best model has the highest R-squared (0–1), highest proportion of deviance explained (0–1), or the lowest AIC. In each case, the comparison is specific to the nutrient.

Table 3. Median values of soil bulk density, Olsen P, total C and N, cation exchange capacity (CEC), sand, silt, and clay for the zones by depth.

Zone	Depth (cm)	Bulk density (Mg/m^3)	C (%)	N (%)	Olsen P (µg P/g)	CEC (meq/100 g)	Sand (%)	Silt (%)	Clay (%)
Zone 1 sandy	0–20	1.27	2.11	0.229	56.5	11.4	55	31	14
	20–40	1.45	0.51	0.059	15.7	5.6	80	13	7
	40–60	1.43	0.20	0.027	8.1	3.9	92	5	3
	60–80	1.42	0.16	0.023	3.9	2.9	91	5	4
	80–100	1.42	0.13	0.022	2.5	2.6	95	3	2
Zone 2 silt	0–20	1.32	1.98	0.218	45.9	14.0	38	43	19
	20–40	1.41	1.22	0.138	13.2	13.0	42	44	14
	40–60	1.35	0.45	0.054	4.9	7.4	39	46	15
	60–80	1.34	0.30	0.038	3.1	5.7	60	29	11
	80–100	1.40	0.29	0.038	3.4	6.1	49	38	12

Median silt (Zone 1: 3–31%; zone 2: 29–46%) and clay contents in both zones decreased with depth (Table 3). Zone 1 median cation exchange capacity values were less than in Zone 2 (Table 3). Zone 1 Olsen P values were greater than in Zone 2; bulk density, and total C and N varied between the zones and depths (Table 3). The air permeability, porosity, pH, exchangeable K, Mg, Ca, and sulfate values per zone and depth are presented in the supplementary material (Table S2). Air permeability was greater in Zone 1.

Drainage

The relationship between SWB modelled and field-measured cumulative drainage over time for the zones using the matching procedure in the methods is shown in Fig. 2. For the modelled drainage on an annual basis, the drainage in Zone 1 was less variable between years than in Zone 2. The cumulative rainfall and irrigation are presented in Fig. 3.

Nutrient concentrations and loads

There is some evidence in Zone 1 drainage concentrations of an intra-annual trend, and this trend is consistent between the DFMs (Figs 4 and S2). In Zone 2, the DFMs had fewer samples beyond 2019, so given the shorter time (2016–2019), the intra-annual trend is not clear for Zone 2 (Fig. S2 in Supplementary material).

The nutrient concentrations over time using the GAM model are presented in Fig. 4. Ammonia-N data indicate an annual effect within Zone 1, but this is not clear for Zone 2. The difference in the predictions between DFMs in Zone 1 are quite small, but likely to be greater in Zone 2. The data for NO_x-N suggests an annual effect within Zone 1, but not for Zone 2. For reactive P, the results suggest an annual effect within Zone 1, with large differences between DFMs (Fig. 4). For Zone 2, the reactive P differences between DFMs is not as large and the annual effect is less pronounced, in part likely due to sparse sampling from 2019. Overall, the adopted model gives a reasonable account of nutrient concentrations over time and between DFMs.

The timing of fertiliser application is shown by arrows shown in Fig. 4. Although variations in nutrient can be observed in Fig. 4, the relationship between the dates of fertiliser application and nutrient concentration variation is not clear. This is due, at least in part, to the seasonality in rainfall, irrigation, and the fertiliser application. A formal analysis of the relationship between these quantities would require considerably more time series data than are available.

The nutrient loads are presented in Fig. 5, showing the variability of individual points for each DFM, while the box plot corresponds to the value pooled over all DFMs (in each year and zone). Although variable, Zone 1 had mostly greater NO_x-N loads than Zone 2 (Table 4). The dominant form was nitrate rather than ammonia-N (Table 4). The load of NO_x-N during 2016 for both zones was greater than subsequent years (Fig. 5, Table 4). Zone 2 had greater variability in ammonia-N and NO_x-N loads per DFM than Zone 1. Zone 1 had much greater variability in reactive P loads per DFM than Zone 2. There were no obvious patterns in annual nutrient loads with annual rainfall and irrigation. However, the ammonia-N annual loads in Zone 2 showed a general decreasing pattern with the decreasing annual rainfall during the period.

As described in the methods, the model used for estimation of loads during each hydrological year included terms for cumulative rainfall and irrigation. A likelihood ratio test of models, with and without these terms, shows that both have a highly significant beneficial effect for reactive P ($P < 0.01$), but the benefits for NO_x-N and ammonia-N are less convincing ($P = 0.14$ and $P = 0.017$, respectively). The benefit of including these terms is adding high temporal-frequency information, but when the load was estimated over a full hydrological year, that high-frequency information was largely lost. Thus, estimates of load over a full year differ by little, if the effects of rainfall and irrigation were included or excluded. Table S1 in the Supplementary material shows the absolute difference in the estimated median load for each hydrological year for all responses. There is no obvious pattern, except that perhaps differences are larger in the sandy soil.

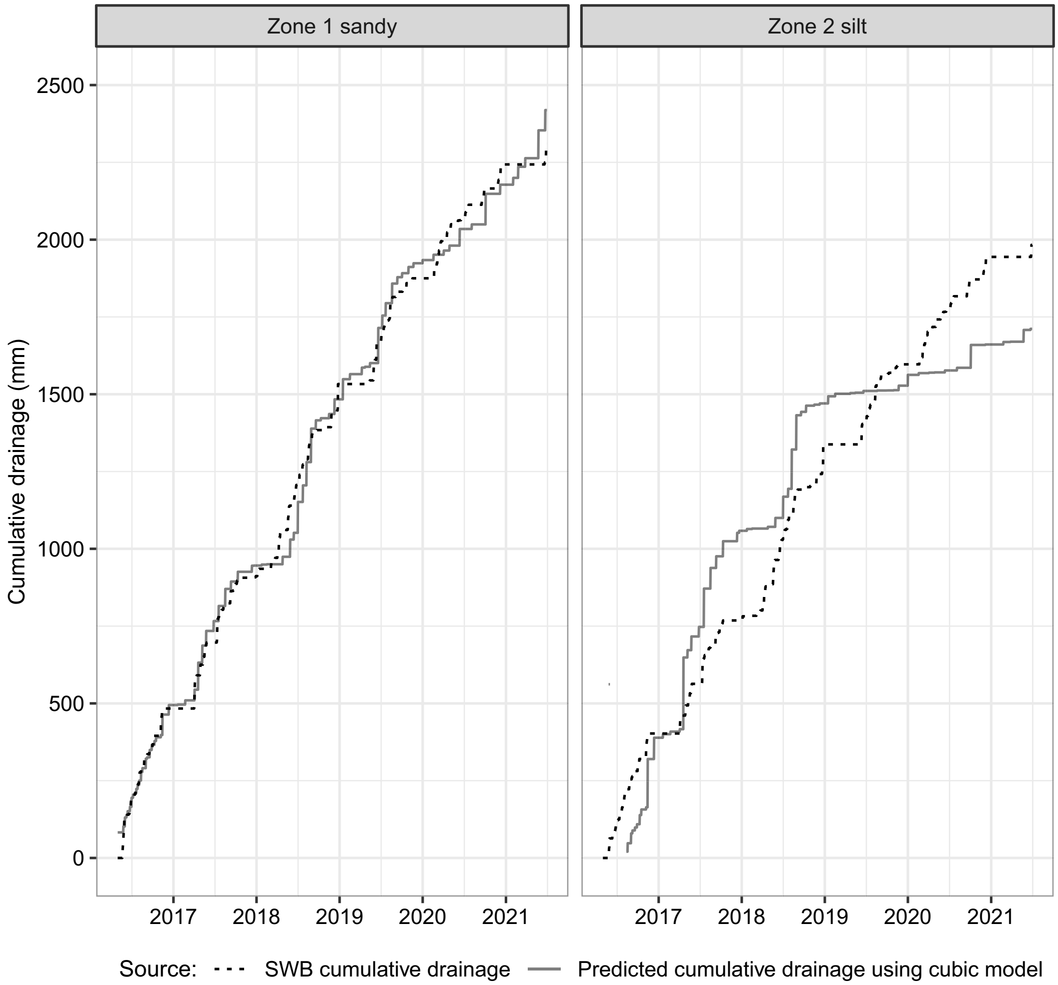

Fig. 2. Relationship between SWB cumulative drainage and predicted cumulative drainage using the cubic matching procedure, over time, for the management zones.

In summary, the median load of NO_x-N across all 5 years was 119 and 120 kg N/ha/year for Zones 1 and 2, respectively (Table 5). The mean load of NO_x-N across all years was 133 and 121 kg N/ha/year for Zones 1 and 2, respectively. The mean load of reactive P across all 5 years was 0.17 and 0.14 kg P/ha/year for Zone 1 and Zone 2, respectively (Table 5). Table 5 presents the coefficient of variation (COV; ratio of the standard deviation to the mean). Since the mean was greater than the median, the results in Table 5 show that the distributions of each nutrient are right-skewed. The high COV values for ammonia-N and reactive P in zone 2 (i.e. high standard deviation relative to the mean) in Table 5 reflect the high variation in the nutrient load between hydrological years.

Discussion

In Zone 1 (the deep free draining soil), regular collection of drainage samples occurred. However, from 2018, approximately a year and half after installation, there were fewer samples collected from DFMs from Zone 2 (the poorly drained soil). It is possible that preferential cracks caused by installation slowly reduced while the soil settled, or the DFM wick performance was not as effective later (but difficult to resolve once DFMs are installed), reducing drainage collected in Zone 2. Some DFMs were reported by Norris *et al.* (2023) to have large variations in drainage, so modelled drainage was needed for several sites. They reported it was more challenging to repack soil to replicate natural flow conditions in the heavy-textured soils, concluding the use of DFMs on clay loams is less appropriate than on freer draining soils. Similarly, Meissner *et al.* (2010) reported that DFMs work well in sandy soils, while other studies also reported high variability in drainage with DFMs and wick-based samplers (Zhu *et al.* 2002; Gee *et al.* 2009; Herath *et al.* 2014), requiring sufficient samplers to account for variability.

A key lesson from this study is that the later quarterly sampling was not frequent enough in either zone, versus the more frequent much earlier sampling. Regularity of sampling

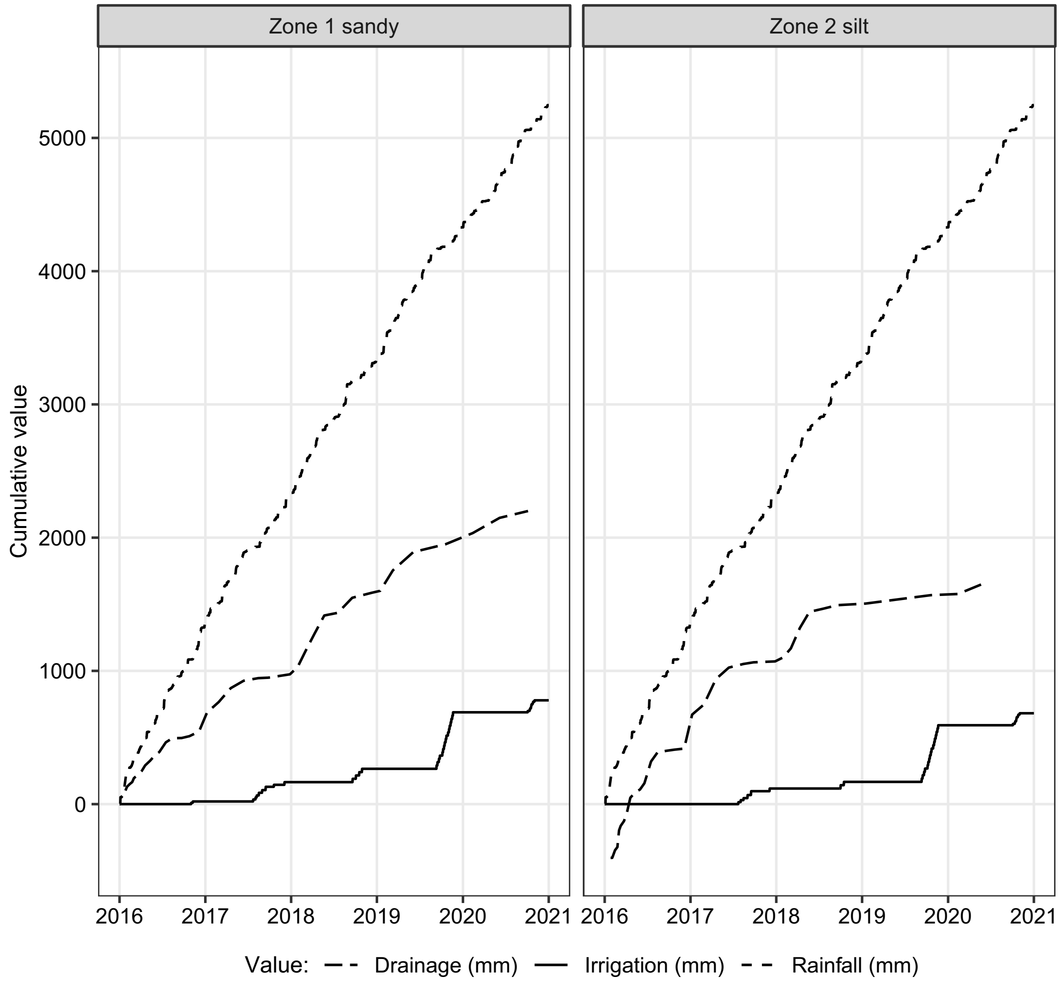

Fig. 3. Cumulative rainfall, irrigation, measured and modelled drainage using the matching procedure (mm) for the two management zones. The drainage values are calibrated using the cubic polynomial model described in the methods, so values can be negative.

is beneficial for time series and regression analysis to provide adequate samples to determine the within-year, seasonal variation, and systematic trends in the long term. For example, sampling once a month for several years (but in conjunction with drainage events) is more valuable than much more frequent sampling for one early year, particularly if budget resourcing is limited, since the long-term trend in nutrient concentration changes in the first year or so after installation before settling into a regular pattern of response to rainfall and irrigation. Our statistical modelling approach gives a reasonable estimate of annual means, but the within-year variation is not reliable, so we have not reported seasonal differences. Moreover, the long-term trend in the rainfall-plus-irrigation response differs between zones, which necessitates regular sampling. In our case, it is likely that there was inadequate frequency of sampling after 2019, which limits the accuracy of estimated nutrient load in later years for each zone. The combined DFM and statistical modelling approach used in this study worked well for Zone 1 where regular collection of drainage samples occurred. However, as there were fewer samples collected from the Zone 2 DFMs, the statistical modelling approach was particularly important in Zone 2.

In this study, a wide range of crops were grown. The site is small and is a research site, hence some management practices may differ to commercial farms, so some nutrient concentrations in both soil and water may differ. Some practices at this site, for example, the incorporation of green legume stubble into soil rather than removal, is likely to generate more N. In contrast, mowing the plantain mixed pasture would be likely to generate less N leaching, compared with leaching under grazing by sheep. This study was not designed to evaluate specific practices, but rather to get a general sense of leaching losses under an irrigated mixed-cropping system, to identify the ability of DFMs to measure leaching losses and develop a procedure for processing data from DFMs.

A challenge in measuring nutrient leaching losses in cropping systems, is that they are typically measured over a

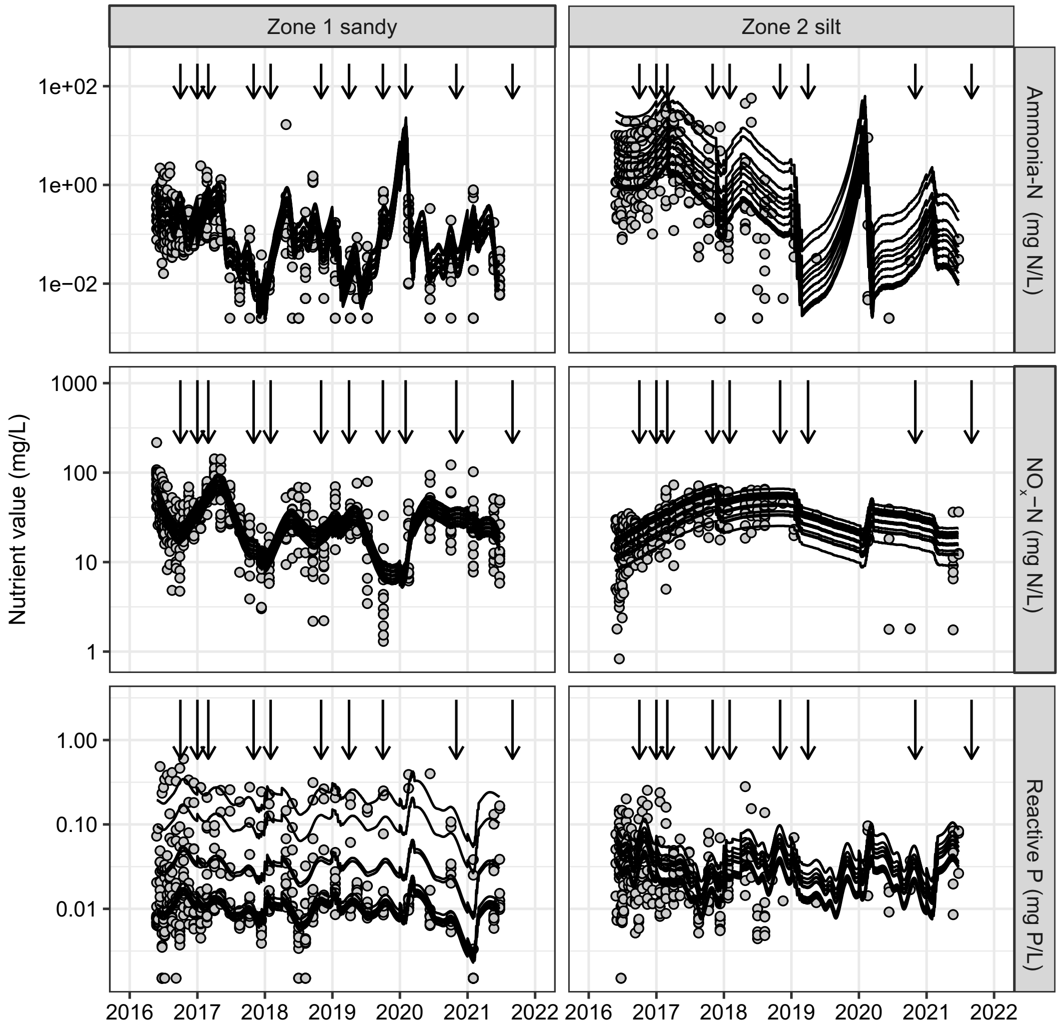

Fig. 4. Drainage nutrient concentrations over time (points), with each curve corresponding to the GAM model estimate for a specific DFM, using a random effect for each DFM. The shaded region around each line indicates plus-or-minus one standard error for each prediction. Arrows correspond to dates when fertiliser were added in each zone. Note the vertical scale is logarithmic.

single season or single crop, due to short crop rotations and practices such as cultivation (Norris *et al.* 2023). Annual NO_x-N load in our study was broadly comparable given our long measurement period and methods. However, several studies (Francis 1995; Khaembah and Horrocks 2018) were conducted in drier regions, with less drainage occurring than in our study. A wide range of nutrient loads for mixed-cropping systems in New Zealand was reported as 1–113 kg N/ha/year (median 13.5) (Srinivasan *et al.* 2020), with details available elsewhere (Drewry 2018). Most of those mixed-cropping studies have focused on nitrate-N leaching from measurements (median 52 kg N/ha/year) or modelling (median 13 kg N/ha/year). Annual losses of nitrate-N (expressed as kg N/ha/year) from cropping studies include: 25–110 (Francis 1995), 12–20 (Khaembah and Horrocks 2018), 5–119 (Tsimba *et al.* 2021), 13–151 (average 57) (Norris *et al.* 2023), and c. 10–32 (Lisson and Cotching 2011), depending on climate, soil, crop, and management. For sheep- and beef-grazed pasture under uniformly applied irrigation, nutrient loads were 17–23 kg N/ha/year (Srinivasan *et al.* 2020). In contrast, simulated winter cattle grazing of fodder beet can have >200 kg N/ha leached, depending on soil and practices (Malcolm *et al.* 2022). Comparisons of nutrient losses between studies should be used as a broad guide, but with caution, due to different soils, crops, climates, and practices. Phosphorus loads for arable and mixed-cropping systems were 0.1–2.9 kg P/ha/year (median 0.1) (Srinivasan *et al.* 2020), but leaching contributed to c. 0.2 kg P/ha/year or less, in contrast to runoff (c. 2.6 kg P/ha/year) (Drewry 2018). However, this is based on very few P loss studies under cropping systems (Drewry 2018), so values should be used with caution. For comparison, DRP loss in runoff for sheep pasture systems were up to 0.15 kg P/ha/year in hill country (Lambert *et al.* 1985), while drainage leaching losses of FRP

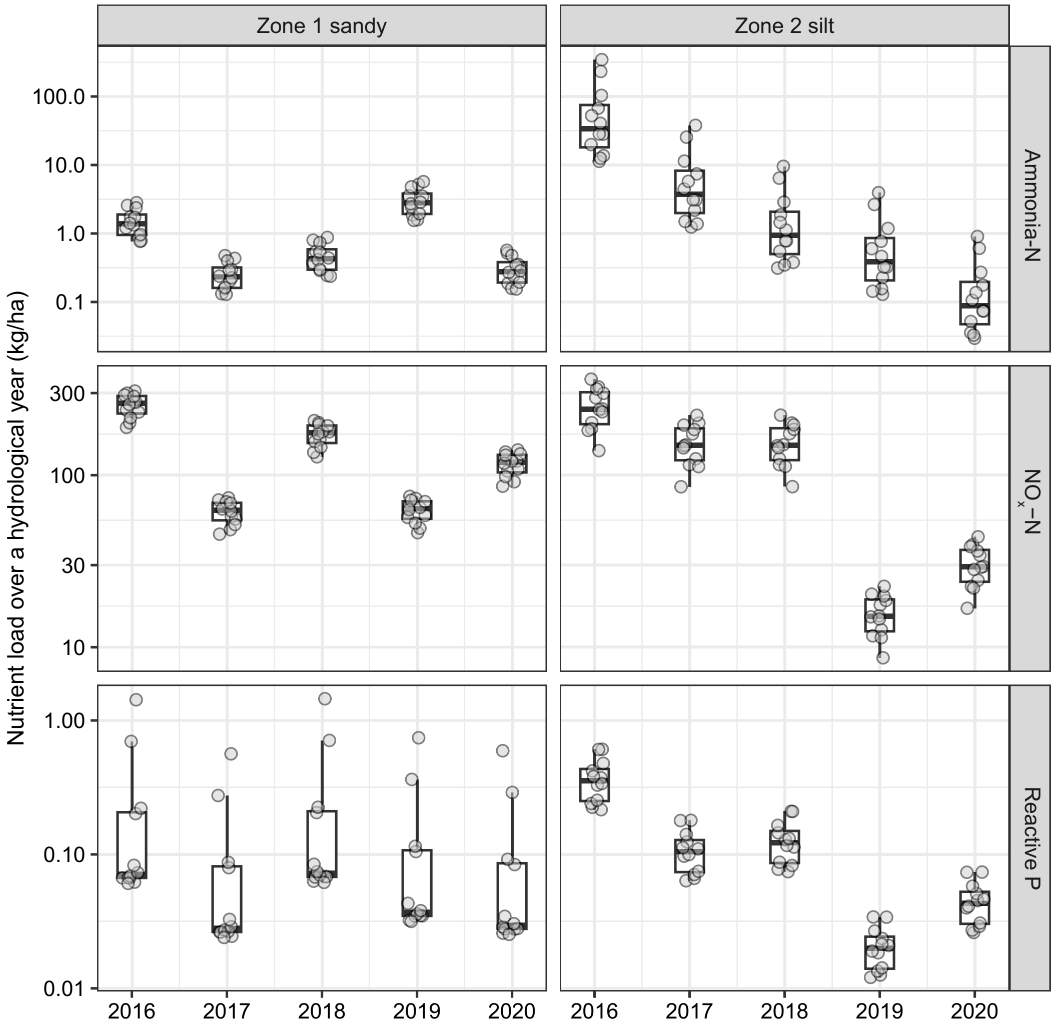

Fig. 5. Nutrient loads (kg N/ha/year or kg P/ha/year) of ammonia-N, NO_x-N and reactive phosphorus (P) for the two management zones, per year (1 July to 30 June). The points are for each DFM. The box plot is generated for the pooled value over all DFMs. For boxplots, the median is shown, and the boxes represent the inter-quartile range, (25th and 75th percentile), and whiskers represent 1.5 times the inter-quartile range. Note the scale is logarithmic.

Table 4. Median nutrient leaching loads (kg N/ha/year and kg P/ha/year) of ammonia-N, NO_x-N and reactive P for the two management zones, per year (1 July to 30 June).

Median nutrient leaching load	Zone	2016	2017	2018	2019	2020
Ammonia-N	Zone 1 sandy	1.38	0.23	0.43	2.79	0.28
	Zone 2 silt	34.4	3.78	0.95	0.39	0.09
NO_x-N	Zone 1 sandy	261	62.6	176	63.9	119
	Zone 2 silt	242	149	149	15.1	29.3
Reactive P	Zone 1 sandy	0.071	0.028	0.072	0.037	0.03
	Zone 2 silt	0.356	0.105	0.123	0.02	0.043

were up to 0.03 kg P/ha over 1.5 years in sheep-grazed winter forage crops (McDowell and Houlbrooke 2009). In our study, reactive P losses are broadly comparable to other studies, but there are few similar studies for comparison.

Overall, in our study, there was generally greater NO_x-N leaching from the free draining zone 1. Zone 1 drainage was also temporally more responsive to irrigation and rain events than the poorly draining zone 2. The VRI system provided a system to control irrigation-related drainage and leaching in these two soil zones. The practical and broader significance of our results is that, where spatially variable soils (or crops) exist under irrigators, irrigation can be managed in specific zones to reduce irrigation-induced drainage and nutrient leaching. However, there were some significant rain events during the trial, which can override the impact of VRI.

Factors important in P loss include soil P concentration and the ability of soil to retain P: high soil P concentrations can

Table 5. Summary of the median, mean, standard deviation, and coefficient of variation of the nutrient leaching load (kg N/ha/year, or kg P/ha/year) over all hydrological years (1 July to 30 June) for all nutrients and zones.

Zone	Nutrient	Median load (kg/ha/year)	Mean load (kg/ha/year)	Standard deviation load (kg/ha/year)	Coefficient of variation
Zone 1 sandy	Ammonia-N	0.527	1.15	1.31	1.14
	NO_x-N	119	133	77.1	0.58
	Reactive P	0.067	0.17	0.30	1.72
Zone 2 silt	Ammonia-N	1.31	18.3	54.9	2.99
	NO_x-N	120	121	96.6	0.80
	Reactive P	0.08	0.14	0.14	1.05

pose a risk to water quality, while P leaching is typically greater in sandy soils (McDowell 2017; Macintosh *et al.* 2019; Drewry *et al.* 2021*b*). Soil Olsen P agronomic targets in New Zealand for sheep-grazed pastures are 20–30 mg/L (Morton and Roberts 2009). Targets for crops include: high yielding oats (20 mg/L, 0–15 cm), peas (10 mg/L) (Nicholls *et al.* 2009), and for cropping soil quality (20–40 mg/kg) (Drewry *et al.* 2021*b*). In New Zealand, industry-derived Olsen P target values are reported volumetrically, whereas regional authority soil quality values are reported gravimetrically, with further details elsewhere (Drewry *et al.* 2022*c*). Median Olsen P concentrations were 57 and 46 mg/kg (0–20 cm) for Zone 1 and 2 respectively. This suggests concentrations are higher than required, and associated risk of P leaching is also higher, so mitigation measures (such as reducing the rates of P fertiliser) could be adopted. Soil P can take many years to decline depending on practices and mitigation strategies (Dodd *et al.* 2014; McDowell and Smith 2023).

Drainage fluxmeters have several advantages such as ease of management, cost effectiveness, and their ability to capture drainage events. However, there are disadvantages, including the small spatial representation due to their small cross-sectional size, so sufficient replication is required. After installation, there is a period while the soil settles which may affect drainage and concentrations. Considerable effort was made to model the SWB, drainage, and losses in our approach. We agree with Norris *et al.* (2023) that if DFMs become more widely available, that technical skill is needed to interpret the data. Several suggested improvements to DFMs have been reported, including the use of a one-way valve system to prevent backflow from temporary high water tables and reducing the constructed depth of the DFM (Meissner *et al.* 2010). From our experience, several potential improvements could be made to the DFMs including automating some components with digital recording and interfaces, providing compartments for multiple samples, and use of emerging sensor technology for water quality. Further refinement of wick lengths would be useful to ensure DFMs can be used more efficiently in soils that are not free draining. The wick length could be scaled to approximate the tension exerted by the different matrix of the silt loam versus the sandy soil.

Conclusions

The DFMs in this study worked well for the free draining soil, but fewer drainage samples were collected in the Zone 2 poorly drained soil. The combined soil water balance and statistical modelling data were needed to determine nutrient losses. The nutrient concentrations in Zone 1 had some evidence of an intra-annual trend, but this was not clear for Zone 2. The nutrient concentrations and loads generally had greater uncertainty in Zone 2. Some management practices may differ compared with commercial farms, so caution should be applied in extrapolating these results. Our approach gave a reasonable estimate of annual leaching load means, but the within-year variation was not reliable, so we have not reported seasonal differences. This was partly as the sampling in the later period was less frequent. An implication for future research is ensuring regularity of sampling in the long term, with careful interpretation of the data. With some exceptions, there was generally more NO_x-N leaching from the free draining Zone 1. Zone 1 drainage was temporally more responsive to irrigation and rain events than Zone 2. However, the estimates of nutrient loads over a full year differed by little, if the effects of rainfall and irrigation model terms were included or excluded. The VRI system provided a system to control irrigation-related drainage and leaching in these two soil zones. Where spatially variable soils (or crops) exist under irrigators, irrigation can be managed in specific zones to reduce irrigation-induced drainage and nutrient leaching. Given the lack of published data, this study has improved knowledge of nutrient leaching losses under zone-specific irrigated mixed-cropping systems in a temperate climate.

Supplementary material

Supplementary material is available online.

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Data availability. The data that support this study cannot be publicly shared due to ethical or privacy reasons and may be shared upon reasonable request to the corresponding author if appropriate.

Conflicts of interest. No potential conflicts of interest was reported by the authors.

Declaration of funding. Funding was provided by the New Zealand Ministry of Business, Innovation and Employment (MBIE) Strategic Science Investment Funded (SSIF). Funding was also provided in part by the Manaaki Whenua – Landcare Research and Plant and Food Research led Endeavour programme, Maximising the Value of Irrigation, (contract CO9X1309).

Acknowledgements. The project research was a collaboration between Manaaki Whenua – Landcare Research and Massey University. From Plant and Food Research we thank Steve Green for initial advice, provision of the DFMs and help with their installation, and providing the customised pumping system; Carlo van den Dijssel for assistance with DFM installation; and Brent Clothier for initial advice. We thank Massey University for use of the site and Mark Osborne for managing the farm operations and providing farm management information. From Manaaki Whenua – Landcare Research, we thank Pierre Roudier and John Dando for assistance with DFM installation, Jagath Ekanayake for providing telemetry, installation assistance, and discussions about potential DFM improvements, Paul Peterson for field assistance, Sujatha Senanayake and the Environmental Chemistry laboratory team for water quality analyses, and colleagues for reviewing the manuscript and editing.

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