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MODELLING NITROGEN LOSSES DURING PASTURE RENEWAL IN EDENDALE, SOUTHLAND, NEW ZEALAND

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Abstract

The **S**imple **C**rop **R**esource **U**ptake **M**odel operating within the **A**gricultural **P**roduction **S**ystems s**IM**ulator (SCRUM-APSIM) was used to evaluate nitrogen (N) losses from two alternative pasture renewal programmes for a dairy farm located in Southland, New Zealand. The renewal programmes were compared using weather data from three locations (Edendale, Gore, and Invercargill) for two years (2-year; 2019–21) after a 6-year-old ryegrass-clover pasture was terminated. In the Pasture-Pasture programme, grazed pasture was planted in April 2019 (autumn). In the Pasture-Tulip-Pasture, tulips receiving a range of fertiliser treatments (45, 85 and 125 kg N ha^{-1} y^{-1}) were planted in May 2019 and the field returned into pasture in April 2020. Simulations of six continuous seasons (6-year) and two seasons at a time over 30 years (30-year), were run to produce long-term N loss estimates across variable weather conditions.

In the first season of the 2-year simulations, greater N leaching was predicted from the Pasture-Tulip-Pasture treatments than the Pasture-Pasture treatment. Predicted N leaching under tulips increased with the rate of applied fertiliser. Greater-than-average rainfall during the season was the main factor influencing N leaching, but the soil N available for leaching was determined by the amount of N in the soil as indicated by strong correlation of fertiliser N rate with N leaching (R^2>0.88). In the second season, we estimated greater leaching from the Pasture-Pasture treatment than the Pasture-Tulip-Pasture treatment.

The 6- and 30-year simulation results indicated similar or lower N leaching from the Pasture-Tulip-Pasture treatments relative to the Pasture-Pasture treatment, depending on the amount of N applied to the tulip crop. Nitrogen returned in urine was the main source of leached N under pasture. These results suggest potential environmental benefits from including tulips as a break crop in a pasture renewal process where potential mineralisable N is taken into account and fertiliser N is applied judiciously. This conclusion assumes that the land planted in tulips does not increase the intensification of the remaining dairy platform.

The information from the modelling will assist the tulip bulb growing sector to quantify N leaching and assist in catchment management of N leaching to meet water quality objectives.

Key words: Simulation modelling, pasture renewal, tulips, nitrogen leaching

Introduction

In New Zealand, managed pastures are periodically renewed because of sward deterioration leading to a decline in yield and feed value (e.g. Kerr *et al.*, 2015). A common practice in the renewal process is to spray out the old pasture with herbicide followed by full cultivation and establishing the field directly into new pasture (Pasture-Pasture). An alternative method is for the cultivated land to be planted in a break crop for a season or part of the season before being returned into pasture (Pasture-Crop-Pasture). Renewal of pasture following a crop rotation has been shown to be effective at reducing weed and pest burdens (Liebman and Davis, 2000; Tozer *et al.*, 2015). In Southland and Otago, tulips grown for bulb export have become an important horticultural crop included in rotation of pasture renewal programmes (Fraser *et al.*, 2020).

Farm fields coming out of tulip crops are cultivated again before reseeding pasture, hence more cultivation operations are expected under the Pasture-Crop-Pasture programme than the Pasture-Pasture programme. Soil disturbance, breaking up and burying pasture residues associated with cultivation can release mineral nitrogen (N), which can be taken up by plants, incorporated into the soil organic pool or lost through leaching (Betteridge *et al.*, 2011). Furthermore, tulip crops may require additional fertiliser inputs, which may enhance the risk of nutrient loss, depending on the soil type and fertiliser management. Under the New Zealand National Policy Statement for Fresh Water Management (NPSFM, 2020), regional councils are required to ensure land use management is consistent with the achievement of water quality objectives. Simulation modelling can be an effective way to quantify specific land use nutrient loading to catchments and therefore assist in identifying the effects of different land uses and management on water quality.

The objective of this study was to use a modelling approach to compare N losses associated with including or excluding tulips as a break crop in a pasture renewal programme for a dairy farm system in Edendale, Southland, New Zealand.

Methodology

Study site

The modelling exercise was conducted for a dairy farm located near Edendale, in the Southland region of New Zealand (46˚21’28.47”S, 168˚46”20.49”E, 27 m.a.s.l). The field had been in grazed pasture for 6 years prior to the tulip trial. This represents a typical rotation practice in the region, with tulips commonly grown in fields that have been in pasture for several years. The soil at the site is a Waikiwi silt loam, described as deep well drained with a high profile available water (PAW; 0–2 m) of 350–400 mm and moderate permeability. Soil parameters were obtained from the New Zealand National Soils Database (https://soils.landcareresearch.co.nz/tools/national-soils-database/nsd-development/), complemented with published pedo-transfer functions (Cichota *et al.*, 2013) and SMAP (converted into APSIM soil library as described by Vogeler *et al.* (2022)). Climate data were obtained from the Edendale Fire and Emergency weather station (Edendale weather), the National Institute of Water and Atmospheric Research (NIWA, 2020) Gore station (46° 6' 54''S, 168° 53' 13.2''E) and Invercargill station (46° 24' 38''S, 168° 53' 0.2''E). Radiation data were not available at Edendale and therefore the Gore radiation data were used instead.

Simulation tool

The **S**imple **C**rop **R**esource **U**ptake **M**odel operating within the **A**gricultural **P**roduction **S**ystems s**IM**ulator (SCRUM-APSIM) was used to model N leaching losses from tulips and pasture. The SCRUM uses a set of coefficients to describe different crops in a manner similar to the OVERSEER crop model (Cichota *et al.*, 2010), and so the two models have similar functionality with regard to crop processes. However, the soil processes related to water movement and N cycling include the full functionality available in APSIM. The SCRUM-APSIM has been successfully tested for several crops and used to assess the environmental impacts of other farming systems (e.g. Khaembah *et al.*, 2015; Khaembah and Horrocks, 2018). SCRUM-ryegrass was adapted to simulate the pasture phase. The model was modified to include the fixation of atmospheric N mimicking the presence of clover. An N fixation rate factor equal to 50% of that used for clover was set, enabling the sward to fix some N. Within APSIM, the models function on a daily time-scale, allowing continuous simulation of changes in the N and water status in response to weather, management and crop uptake (Holzworth *et al.*, 2018).

Simulation setup

To estimate basic initial soil conditions, a simulation of a grazed pasture was run in APSIM to mimic the 6 years prior to the renewal process. In this simulation the AgPasture model was used to simulate a mixed perennial ryegrass-white clover pasture; this model was used as it describes the dynamic changes in clover content and N fixation and was expected to provide a realistic turnover of residues and hence the status of soil organic matter. In the simulation, the pasture was assumed to be grazed by dairy cows in typical rotational grazing. APSIM does not have a cow model but grazing can be simulated as a generic defoliation with excreta return functions used to account for N returned in urine and dung. In the model, a grazing event was triggered when standing pasture biomass was 3 t dry matter (DM) ha^{-1} and grazed to a residual of approximately 1.5 t DM ha^{-1}. Urea (20 kg N ha^{-1}) was applied after each grazing event, except in winter (common farm practice), resulting in application of 120–260 kg N ha^{-1} y^{-1} over the 6-year period. Nitrogen returned in excreta was estimated based on a stocking rate of three cows per hectare. The resulting soil N conditions (inorganic and organic) from this 6-year simulation were then used as base to initialise the pasture renewal simulations. Further adjustments (i.e. increase in the amount of surface organic matter and soil fresh organic matter, assumed to represent the sprayed pasture and residues accumulated during the pasture phase) were made to allow a closer match between measured (Fraser *et al.*, 2020) and predicted soil mineral N for the measurements made on 5 August 2019.

Two pasture renewal programmes (Pasture-Pasture and Pasture-Tulip-Pasture) were evaluated for two seasons: 1 March 2019 – 29 February 2020 (Season 1) and 1 March 2020 – 28 February 2021 (Season 2) as illustrated in Figure 1. In the Pasture-Pasture programme, the field was cultivated on 23 March 2019 and re-planted into pasture on 1 April 2019. For the Pasture-Tulip-Pasture programme, the field was cultivated on 30 April 2019 prior to planting tulips and then on 30 March 2020 before establishing new pasture on 1 April 2020. Tulips were planted on 17 May 2019 and harvested 11 February 2020. Fertiliser management of the tulip crop in the model was based on the 2019–2020 experimental assessment of N use by tulips conducted on the study site (Fraser *et al.*, 2020).

Renewal programme	Season 1 (2019–20)												Season 2 (2020–21)											
	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F
Pasture → Pasture	C	Permanent pasture																						
Pasture → Tulip → Pasture		C	Tulips										C	Permanent pasture										

Figure 1. Two pasture renewal programmes evaluated for nitrogen loss using SCRUM-APSIM. **C** represents cultivation. Season 1 was 1 Mar 2019–29 Feb 2020 and Season 2 was 1 Mar 2020–28 Feb 2021.

Additional simulations were run to assess the carry-over effects of tulip cultivation on the pasture renewal programme and the response to weather and soil variability. These simulations were run as follows:

1. For 6 years continuously (1995–2001 at Gore and 2015–21 at Gore and Invercargill) to assess the effect of weather conditions and the time taken for the two renewal programmes to achieve similar soil N conditions as indicated by soil organic and mineral N contents. The same could not be done at Edendale because weather data were available for 2019–2021 only.
2. For 30 years (1990–2020), simulating two seasons at a time (1990–92, 1991–93 etc.) to determine long-term N leaching estimates across temporal variations in weather conditions. These simulations were run using Gore weather data only. Fertiliser N treatments for tulips were simplified, with N supplied as urea only. A second soil (Waikiwi-2) with PAW of 368 mm (0–2 m depth) and higher permeability than Waikiwi was included in the evaluation to test the sensitivity of outputs to variations in soil properties.

Crop management

Nitrogen inputs for tulips based on the five fertiliser N treatments evaluated in the experiment by Fraser *et al*. (2020) are presented in Table 1.

Table 1. Details of fertiliser nitrogen (N) treatments evaluated for tulips by Fraser *et al*. (2020). CAN = calcium ammonium nitrate and DAP = di-ammonium phosphate.

Treatment	Date of application, amount (kg N ha^{-1}) and fertiliser form			
	17 May 2019	5 Aug 2019	21 Aug 2019	3 Nov 2019
Tulip45N (Control)	45 (DAP)	–	–	–
Tulip85N	45 (DAP)	40 (CAN)	–	–
Tulip125N	45 (DAP)	80 (CAN)	–	–
Tulip125NSplit	45 (DAP)	30 (CAN)	30 (CAN)	20 (Nitrabor™)
Tulip125NUrea	45 (DAP)	80 (Urea)	–	–

Fertiliser application to pasture was 144 kg N ha^{-1} (Verplancke R, Pers. Comm.) and reflected a typical practice of the farm. Nitrogen was applied in five splits (August, October, November and December of 2019 and January 2020). All applications were in the form of N-protect® except for August (Ammo 36™) and November (di-ammonium phosphate, DAP).

Pasture was managed as simple defoliation rotation as described earlier. The fraction of the area affected by urine was described after Shorten and Pleasants (2007) and Pleasants *et al.* (2007). Tulips did not require irrigation during the 2019–20 season. For the long-term simulations, automatic irrigation was used in the model. Crops were irrigated between 15 October and 25 December based on soil water deficit calculated to a depth of 0.5 m. Irrigation was triggered when the moisture in the top 0.5 m of the soil profile was ≤70% of PAW. The trigger resulted in application of 25 mm of water. A minimum return period of 3 days was used in the model. Pasture was not irrigated.

Results and discussion

Measured total yield for tulips did not differ between N treatments (P = 1.0) and ranged from 17.4 to 17.5 t DM /ha (Fraser *et al.*, 2020). Therefore, 17.5 t DM /ha was used as tulip yield input in SCRUM-APSIM. As SCRUM operates within the APSIM framework, insufficient N to meet the crop's demand would result in reduced production. It was therefore important to ascertain the model's accuracy in estimating N uptake across treatments to provide confidence in N removal from the system by the tulip crop. As shown in Figure 2, N uptake was well simulated ($R^2 = 0.98$), and predicted values were within the bounds of replicated measured data.

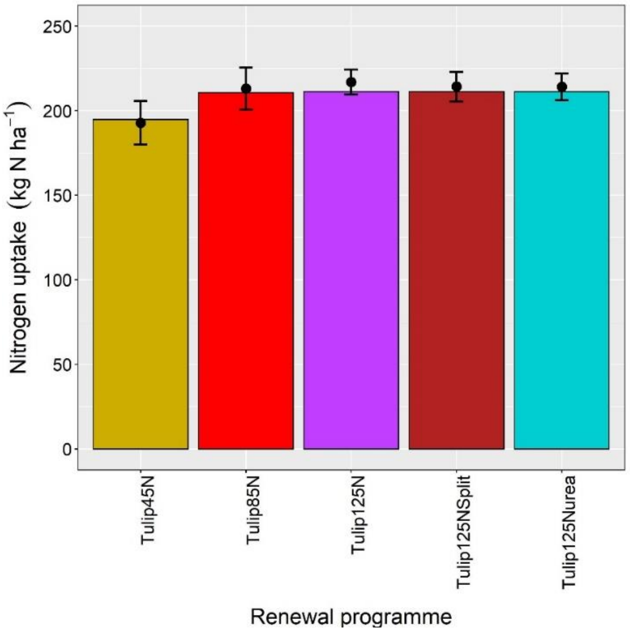

Figure 2. Measured (symbols [mean ± SD]) and SCRUM-APSIM-predicted (bars) N uptake for tulip crops evaluated across five fertiliser nitrogen (N) treatments. All tulip crops received 45 kg N ha^{-1} applied as di-ammonium phosphate (DAP) at planting in autumn. Top-dress fertiliser was applied in spring. Tulip45 represents no additional spring fertiliser, Tulip85N and Tulip125N represent 40 and 80 kg N ha^{-1} of top-dressing applied as calcium ammonium nitrate (CAN) in a single dose, Tulip125Split represents 80 kg N ha^{-1} of top-dressing applied as CAN in three splits, Tulip125Nurea represents 80 kg N ha^{-1} of top-dressing applied as urea in a single dose.

There were differences in the amount of N leaching predicted at the three evaluated locations. Overall, greater N leaching was predicted at Edendale than the other locations (Figure 3). These differences reflected rainfall differences, with greater total amounts recorded at Edendale (1266 mm) than Gore (1122 mm) and Invercargill (1134 mm) during the 2019–20 season. For the 2020–21 season, the respective total rainfall amounts were 1085, 914, 996 mm. There was consistency in response across sites with greater N leaching predicted from the Pasture-Tulip-Pasture treatments in the 2019–20 season and from the Pasture-Pasture treatment in the 2020–21 season (Figure 3). There was a correlation of N leaching with fertiliser N input ($R^2 = 0.88–0.98$) in the Pasture-Tulip-Pasture programme (Figure 3), indicating that increase in N applied to tulip crops increased N available for leaching. Results from the Fraser *et al*. (2020) study showed no difference in yield and plant N uptake when

45–125 kg N ha^{-1} was applied to tulips, indicating that reducing fertiliser N to reduce surplus N in the soil at risk of leaching is an option that can be undertaken to reduce leaching without compromising yield.

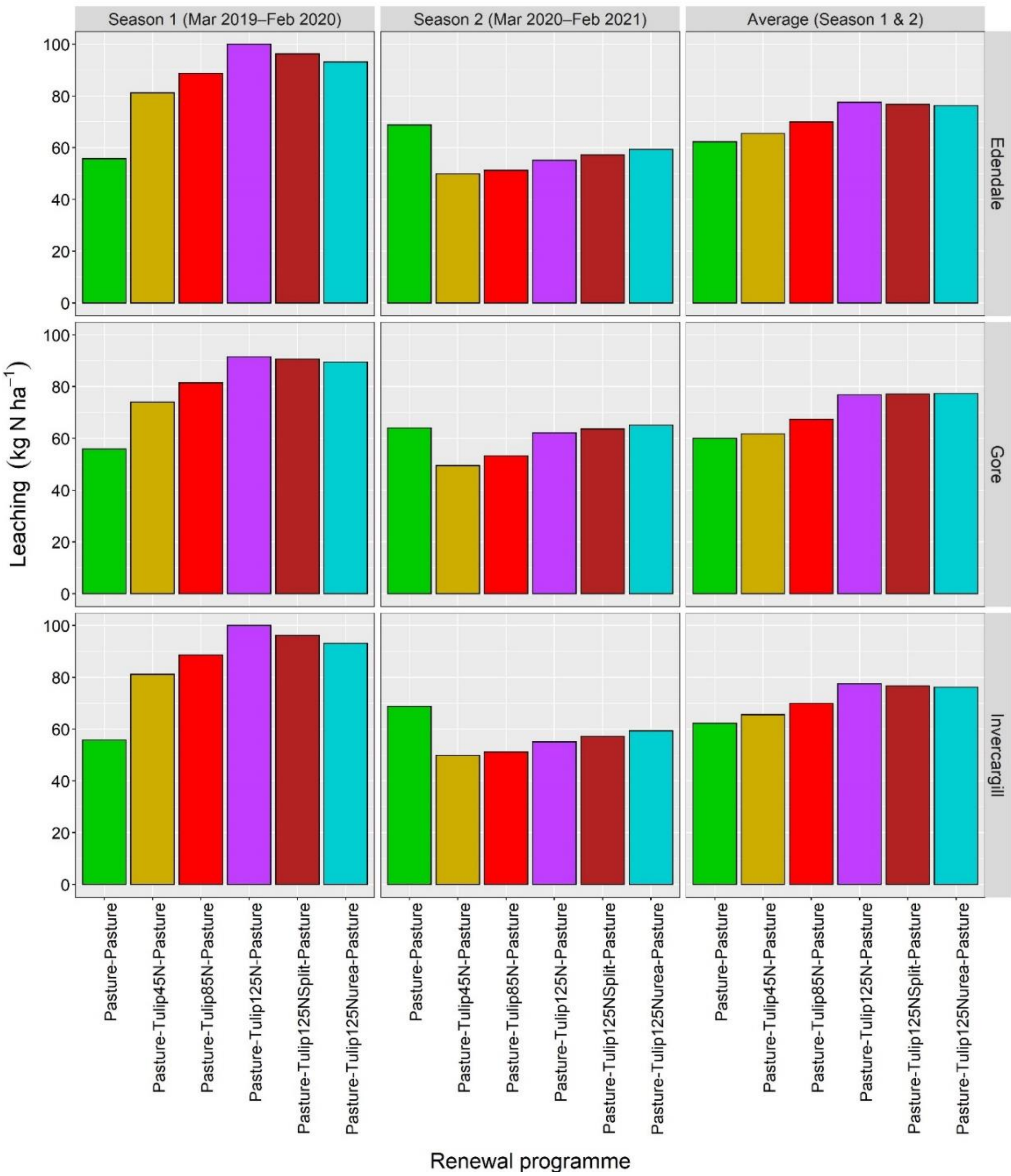

Figure 3. Annual nitrogen (N) leached at 0.6 m depth predicted by SCRUM-APSIM from Pasture-Pasture and Pasture-Tulip-Pasture programmes in Edendale, Southland, New Zealand. Tulip crops were evaluated across five fertiliser N treatments. All tulip crops received 45 kg N ha^{-1} applied as di-ammonium phosphate (DAP) at planting in autumn. Top-dress fertiliser was applied in spring. Tulip45 represents no additional spring fertiliser, Tulip85N and Tulip125N represent 40 and 80 kg N ha^{-1} of top-dressing applied as calcium ammonium nitrate (CAN) in a single dose, Tulip125Split represents 80 kg N ha^{-1} of top-dressing applied as CAN in three splits, Tulip125Nurea represents 80 kg N ha^{-1} of top-dressing applied as urea in a single dose.

On average, the model estimated greater mineralisation (289 kg N ha^{-1}) from the Pasture-Pasture treatment than the Pasture-Tulip-Pasture treatments (242 kg N ha^{-1}) during the 2019–20 season (Figure 4). Less N was mineralised during the 2020–21 season, but the response pattern was the same. The difference in mineralised N between programmes can be attributed to an earlier (March 2019) cultivation event in the Pasture-Pasture treatment which resulted in the post-cultivation accumulation of mineralised N for longer than the Pasture-Tulip-Pasture treatments where cultivation occurred in April 2019. The 242 kg N ha^{-1} of predicted mineralised N from the Pasture-Tulip-Pasture treatments for the 2019–20 season aligns well with the 252 kg N ha^{-1} of potentially mineralisable N estimated from soil tests (Fraser *et al*., 2020). This also demonstrates the importance of taking into account the rich pool of N that is commonly associated with sprayed-off old pasture when prescribing fertiliser N inputs.

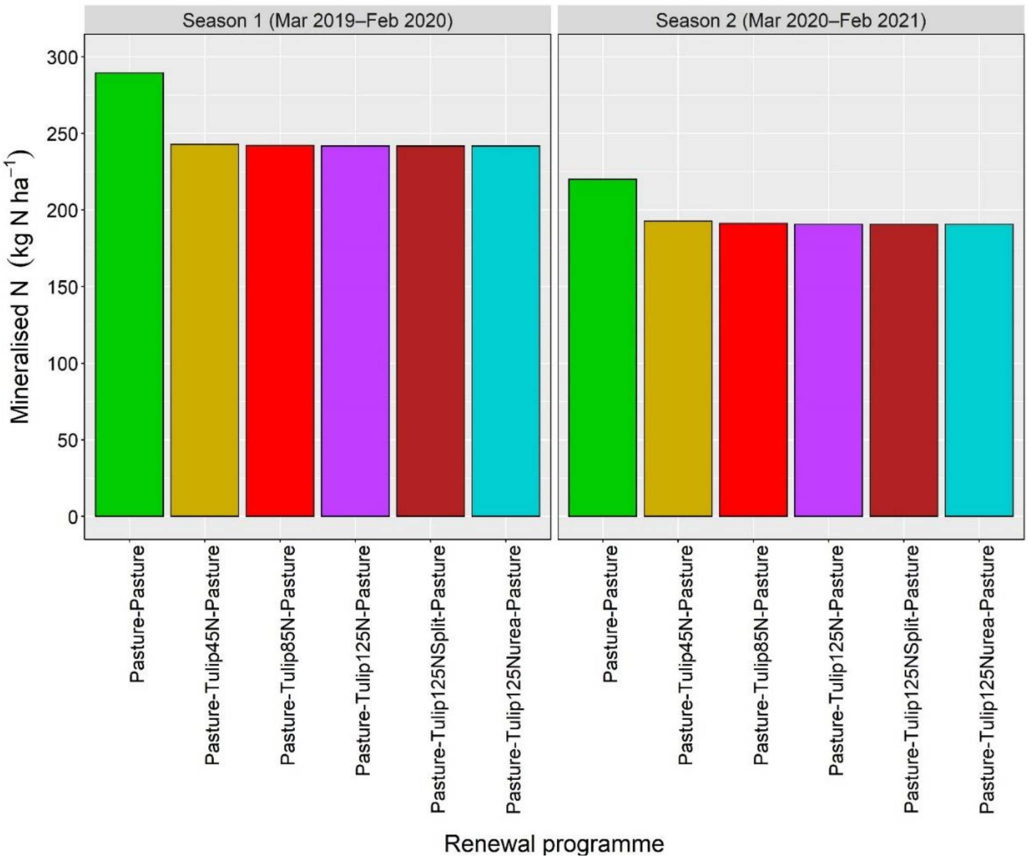

Figure 4. Annual mineralised nitrogen (N) over two seasons as predicted by SCRUM-APSIM from Pasture-Pasture and Pasture-Tulip-Pasture programmes in Edendale, Southland, New Zealand. Tulip crops were evaluated across five fertiliser N treatments. All tulip crops received 45 kg N ha^{-1} applied as di-ammonium phosphate (DAP) at planting in autumn. Top-dress fertiliser was applied in spring. Tulip45 represents no additional spring fertiliser, Tulip85N and Tulip125N represent 40 and 80 kg N ha^{-1} of top-dressing applied as calcium ammonium nitrate (CAN) in a single dose, Tulip125Split represents 80 kg N ha^{-1} of top-dressing applied as CAN in three splits, Tulip125Nurea represents 80 kg N ha^{-1} of top-dressing applied as urea in a single dose.

Nitrogen from deposited urine was estimated as the main source of leached N under the grazed pasture. Studies have shown that the N excreted in urine is readily available in the soil and can be 200–2000 kg N ha^{-1} per cow urine patch (Selbie *et al.*, 2015). Standoff facilities to capture urine and spreading it evenly on paddocks at the right time can be effectively used to mitigate N leaching. These mitigations were not considered in this study.

Predictions for six continuous seasons (2015–21) at Gore presented in Figure 5 show the response pattern of N leaching in the first two seasons was similar to that found for the 2019–21 season (Figure 3), i.e. greater for the Pasture-Tulip-Pasture treatments than the Pasture-Pasture treatment in the season of pasture/crop establishment and reversed in the following season.

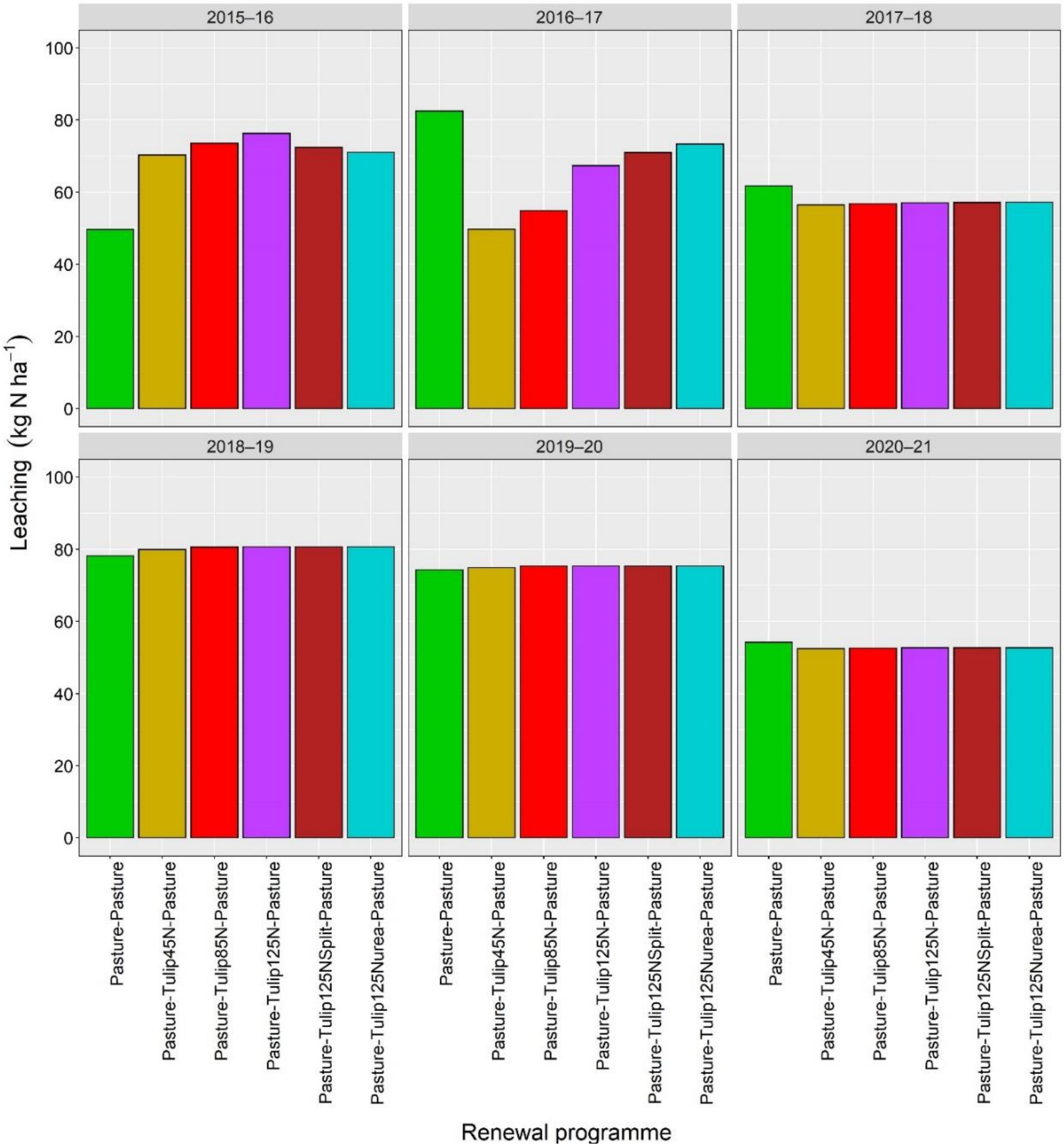

Figure 5. Annual nitrogen (N) leaching predicted over six seasons (2015–21) by SCRUM-APSIM from Pasture-Pasture and Pasture-Tulip-Pasture programmes in Edendale, Southland, New Zealand. Tulip crops were evaluated across five fertiliser N treatments. All tulip crops received 45 kg N ha^{-1} applied as di-ammonium phosphate (DAP) at planting in autumn. Top-dress fertiliser was applied in spring. Tulip45N represents no additional spring fertiliser, Tulip85N and Tulip125N represent 40 and 80 kg N ha^{-1} of top-dressing applied as calcium ammonium nitrate (CAN) in a single dose, Tulip125Split represents 80 kg N ha^{-1} of top-

dressing applied as CAN in three splits, Tulip125Nurea represents 80 kg N ha^{-1} of top-dressing applied as urea in a single dose. Tulips in the Pasture-Tulip-Pasture treatments were established on 17 May 2016 and fields returned to pasture on 1 April 2016. The weather data from the Gore weather station were used in the simulations.

The difference in leaching between renewal programmes treatments quickly diminished from the third season onwards (Figure 5), indicating that differences between the two systems is mainly associated with the first two years. Applying ≤85 kg N ha^{-1} to tulip crops resulted in 2–4% less leaching from the Pasture-Tulip-Pasture treatments than the Pasture-Pasture treatment over the 6-year period. Leaching from the Pasture-Tulip-Pasture treatments was 2.5% greater than the Pasture-Pasture treatment where 125 kg N ha^{-1} was applied to tulip crops. The same response pattern was predicted for leaching for a different season series (1995–2001) at Gore and the 2015–21 series at Invercargill (results not shown). However, as expected, leaching estimates reflected the overall effect of weather conditions.

The temporal pattern of predicted soil mineral N (0–0.6 m depth, Figure 6) from the renewal programmes over 2015–21 was consistent with leaching predictions (Figures 3 & 5). Clear differences in soil mineral N between renewal programmes were evident only in the first two seasons. Thereafter, the two programmes converged with little differences in soil mineral N predicted after March 2017 as pasture growth and grazing events evened out. The convergence of the programmes after two seasons indicate short-term carry-over effects of including tulips in a pasture renewal process, with the first two seasons from crop establishment accounting for the majority of the variation in soil mineral N. The same pattern of soil mineral N was predicted for 1995–2001 at Gore and 2015–21 at Invercargill (results not shown).

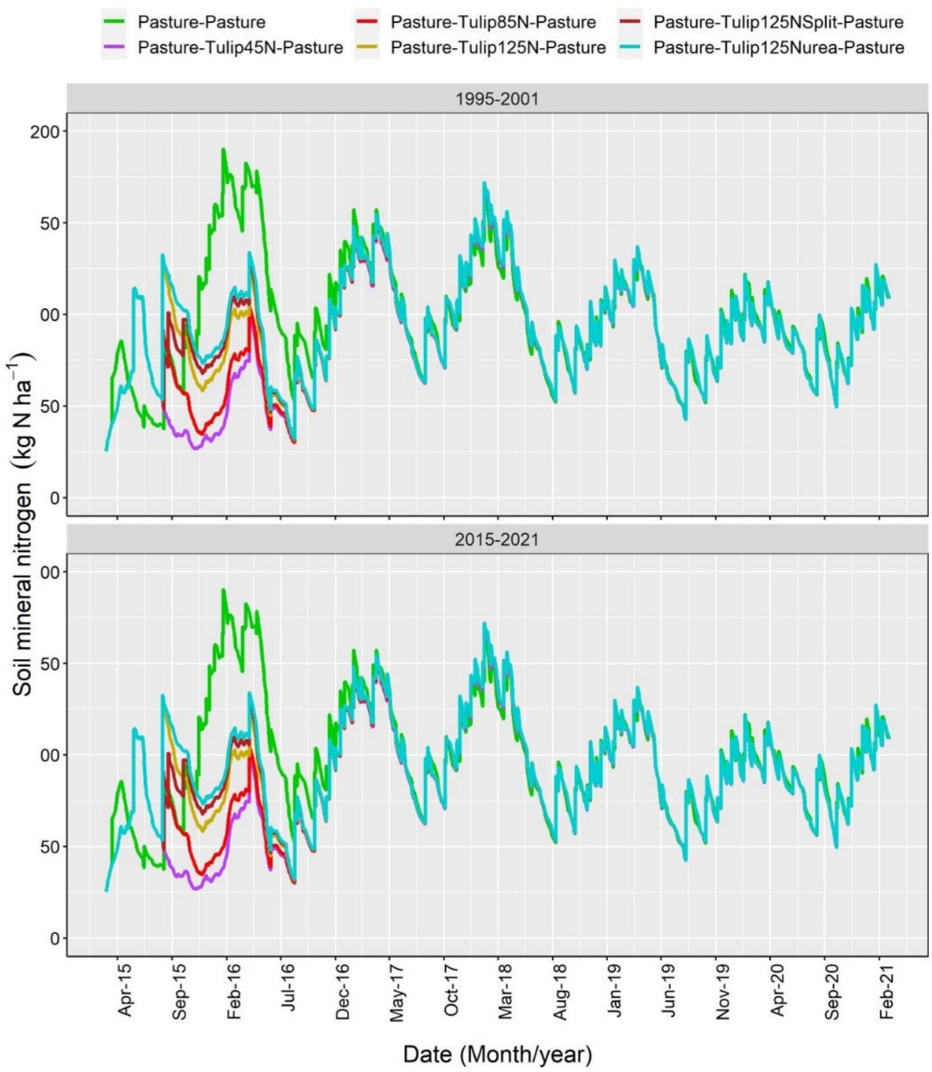

Figure 6. Soil mineral nitrogen (N; 0–0.6 m depth) over six seasons (1995–2001 and 2015–21) predicted by SCRUM-APSIM from Pasture-Pasture and Pasture-Tulip-Pasture programmes in Edendale, Southland, New Zealand. Tulip crops were evaluated across five fertiliser N treatments (Fraser et al, 2020). All tulip crops received 45 kg N ha^{-1} applied as di-ammonium phosphate (DAP) at planting in autumn. Top-dress fertiliser was applied in spring. Tulip45N represents no additional spring fertiliser, Tulip85N and Tulip125N represent 40 and 80 kg N ha^{-1} of top-dressing applied as calcium ammonium nitrate (CAN) in a single dose, Tulip125Split represents 80 kg N ha^{-1} of top-dressing applied as CAN in three splits, Tulip125Nurea represents 80 kg N ha^{-1} of top-dressing applied as urea in a single dose. Tulips in the Pasture-Tulip-Pasture treatments were established on 17 May 2016 and fields returned to pasture on 1 April 2016. The weather data from the Gore weather station were used in the simulations.

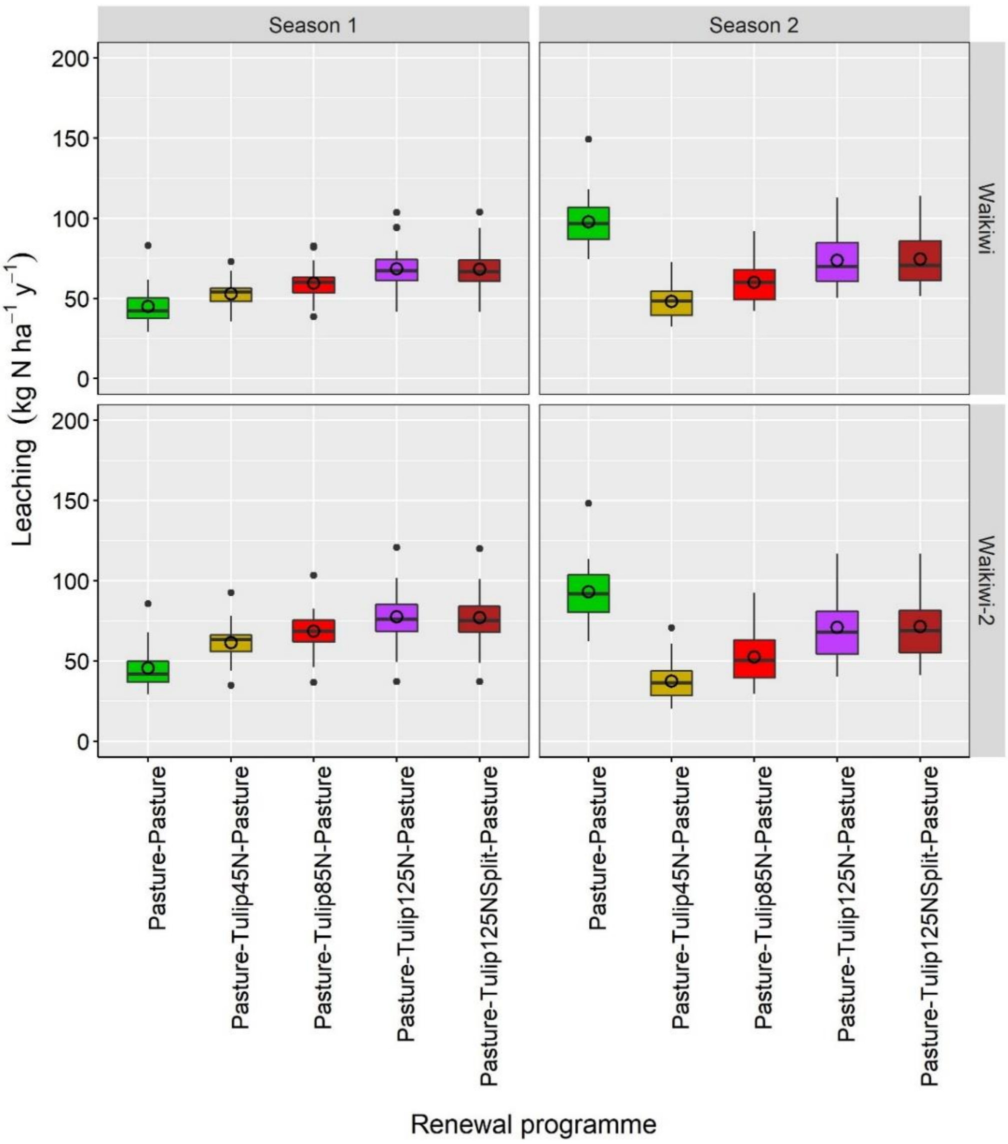

Figure 7. Boxplots showing nitrogen (N) leaching predicted by SCRUM-APSIM (at 60 cm depth) for Pasture-Pasture and Pasture-Tulip-Pasture renewal programmes and two soil types in Edendale, Southland, New Zealand. The renewal programmes were simulated over 30 years (1990–2020). There were four fertiliser N treatments for tulip crops. All tulips crops received 45 kg N ha^{-1} applied as di-ammonium phosphate (DAP) at planting in autumn. Top-dress fertiliser as urea was applied in spring. Tulip45N treatment represents no additional top-dress fertiliser. Tulip85N and Tulip125N represent 40 and 80 kg N ha^{-1} of top-dressing applied as urea in single dose, Tulip125Split represents 80 kg N ha^{-1} top-dress N applied in three splits. The mean is represented by the circle. The Gore weather data were used in simulations.

A two-season series of simulations using weather data for 30 years was conducted on the premise that differences between renewal programmes was mainly associated with the first two seasons as discussed above. The summary of the results from these simulations enabled comparison of the two systems and their variability across two soil types and temporal range of weather conditions in Southland. Model estimates indicated greater N leaching losses from the Pasture-Tulip-Pasture treatments in the first season and from the Pasture-Pasture programme in the second season (Figure 7), consistent with the results from the experimental period and 6-year simulations (Figures 3 & 5). The same pattern was observed for the two soils, with higher values, as expected, in the more permeable Waikiwi-2 soil (Figure 7).

The two-season average N leaching predicted over 30 years showed soil-type differences depending on fertiliser inputs to tulip crops. For both soils, application of ≤85 kg N ha^{-1} to tulips resulted in a 16–29% reduction in leaching from the Pasture-Tulip-Pasture relative to the Pasture-Pasture treatment. When N applied to tulips increased to 125 kg N ha^{-1}, there was no difference in leaching between renewal programmes on the Waikiwi soil (71 kg N ha^{-1} across treatments). However, on the Waikiwi-2 soil, with greater permeability, predicted leaching was 6–8% greater in the Pasture-Tulip-Pasture treatment than the Pasture-Pasture treatment. These results largely indicate that the environmental outcomes of using tulips as a break crop prior to establishing pasture will depend on N management, environmental conditions and soil type. Strategic fertiliser N management to reduce the risk of N leaching has been demonstrated in a recent study involving a range of soil types and crops (Khaembah *et al.*, 2021).

Conclusions

This modelling compared N leaching from pasture renewal programmes in Southland based on the inclusion or exclusion of tulips as a break crop. Results indicate that N leaching from including tulips in a pasture renewal programme depends on rainfall, soil type and N management. With appropriate management, the inclusion of tulips in a pasture renewal programme can reduce N leaching to waterways compared with the conventional renewal system.

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