Nitrogen leaching from two high-rainfall dairy farms in the Lake Rotorua catchment: Summary 2016-2020

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Contents

1. Executive Summary

Information on nitrogen (N) leaching losses from farm systems under high rainfall (>2000 mm/year) is lacking in New Zealand and is required to increase confidence in predictions of N leaching, including those estimated using the OVERSEER® Nutrient Budgets model. The aim of this project was to obtain measurements of N leaching under grazing from two dairy farms in the Lake Rotorua catchment under high rainfall. Farms were selected to be representative of free-draining pumice soil (Paterson farm) and slower-draining podzolised pumice soil (Butterworth farm), which are the predominant soils of the catchment.

Porous ceramic cup leachate collectors (approximately 150 per farm) were installed at a soil depth of 600 mm in four (Paterson) or five (Butterworth) paddocks on each farm in April 2016. Thereafter, samples of leachate were collected following intervals of approximately 100 mm of drainage and analysed for nitrate-N and ammonium-N. At the same time, lysimeters containing intact cores of soil (500 mm diameter x 700 mm depth) were established to directly measure drainage at each site. After observing possible issues due to surface run-off after rain on both farms, collectors for capturing surface run-off water were established. Due to the possible effects on measured N concentrations from a rising water-table on parts of the Butterworth farm, several dipwells were set up to measure changes in the water-table level over time.

Nitrate-N concentrations in leachate followed the pattern found in other research studies with concentrations highest in winter and lowest in summer. Maximum average nitrate-N concentrations for both farms occurred in July 2016 at approximately 4 and 8 ppm (Butterworth and Paterson farms, respectively). Peak nitrate-N concentrations in leachate were higher on Paterson farm than Butterworth farm in each year of the trial and this was reflected in the total amounts of nitrate-N leached. Based on integration of the N concentrations in the leachate and the lysimeter drainage measurements, 42, 30, 26 and 16 kg nitrate-N/ha were leached from Butterworth farm and 80, 43, 39 and 20 kg nitrate-N/ha from Paterson farm annually from 2016/17 to 2019/20. The 2016/17 year combined the highest recorded nitrate-N concentrations with higher than normal rainfall. Concentrations were lowest in 2017/18, but lower than average rainfall in 2018/19 and 2019/20 meant these years had the lowest annual nitrate leaching losses. In 2019/20, the low N leaching losses were associated with little N leaching over the last 6-months, whereas when leaching measurements continued in June/July 2020 the extra N leaching was near that for the annual total, illustrating the large seasonal variability in N leaching. Over all years, the leaching of ammonium-N contributed only an additional 1-3 kg N/ha/year on both farms.

The lysimeter drainage measurements did not account for surface run-off, which was observed at both farms. Based on data from a concurrent Phosphorus Mitigation Project, it was possible to estimate the volume of run-off and the nitrate and ammonium lost in run-off from Paterson farm from 2017/18 to 2019/20. The estimated volume of run-off was equivalent to 136, 38 and 68 mm in 2017/18, 2018/19 and 2019/20, respectively. Ammonium-N and nitrate-N losses in run-off ranged from 0.5 to 1.8 kg N/ha/year. However, by reducing the volume of drainage used to calculate the amount of N leached by the volume of the run-off, the nitrate-N leaching figures at Paterson farm were reduced from 43 to 38 kg N/ha in 2017/18, from 39 to 38 kg N/ha in 2018/19 and from 20 to 19 kg N/ha in 2019/20. When the ammonium and nitrate lost in the run-off was added to the

leached-N, the annual total inorganic N losses to water from 2017/18 to 2019/20 were 42, 40 and 21 kg N/ha (i.e. very similar to estimated N leaching using lysimeter drainage and ignoring run-off).

In all four years of the trial, less N was leached from Butterworth farm than from Paterson farm (by 15 – 48%). The most likely cause of this is slower drainage and greater gaseous N loss by denitrification in the podzol soil found on Butterworth farm. A hard ignimbrite layer at about 1-2.5 m depth with an associated perched water table and wetter soil conditions would have contributed to increased N loss risk from denitrification, as shown in published research on similar soils near Reporoa.

The use of the OVERSEER® Nutrient Budgets model to calculate N leaching generally showed higher estimates than the measured losses. However, when the use of the model was adjusted to account for the specific grazing times in the measurement paddocks and modified for lower rainfall/drainage in the last two years, there was much less difference between measured and modelled data, particularly for the pumice soil. The use of the podzolized pumice soil for the Butterworth farm (using S-map) in the model was found to result in a higher estimate (by approximately 25%) of N leaching compared to if the non-podzolized pumice soil had been selected. This suggests that the factors driving N leaching for this soil type in the model may need reviewing. Information from this study will be provided to Overseer Limited so that it can be used as part of their model review and validation process.

2. Background

The Bay of Plenty Regional Council has defined a sustainable nitrogen (N) load for Lake Rotorua in their Regional Policy Statement. To meet this target there will be a requirement for a significant decrease in N inputs to the lake, including those from dairy farms in the Lake Rotorua catchment. There have been few actual measurements of N leaching from farms in the catchment to inform farmers, policy makers and the public of the magnitude of N loss from farms, and moreover, no studies from the high-rainfall areas that constitute a significant proportion of farms in the catchment. Currently, N leaching from farms is estimated using the OVERSEER® Nutrient Budgets model (hereafter called OVERSEER). OVERSEER has been well validated across New Zealand for rainfall of about 1000-1300 mm/year. In addition, a trial was recently conducted on the Parekarangi farm in the Rotorua catchment with rainfall of approximately 1500 mm/year. However, there have been no measurements of N leaching from farms in high-rainfall areas (e.g. 2000+ mm/year) in New Zealand and therefore no data to validate N leaching estimates from OVERSEER under high rainfall. Thus, there is a need for measurements of N leaching from dairy farms with high rainfall to validate OVERSEER and to demonstrate to farmers and sector groups the magnitude and significance of N leaching in the lake Rotorua catchment.

Previous research has shown that soil properties can influence N leaching risk. For example, Scholefield *et al.* (1993) measured three-fold higher N leaching from grazed pastures in England under free-draining soils (that had been mole/tile drained) compared to poorly-drained soils with no artificial drainage system. Thus, it is worthwhile examining

N leaching under soils of contrasting drainage to understand possible effects related to soil properties and drainage characteristics.

The objective of this study was to measure N leaching from two case-study dairy farms in the high rainfall area around Lake Rotorua, covering contrasting free-draining and podzolized pumice soils, for use in validation of OVERSEER.

3. Methods

In April 2016, trials were set up on two well-established dairy farms in high-rainfall areas in the Lake Rotorua catchment; J and S Butterworth's farm on a Mamaku Sandy Loam (Humose Orthic Podzol) near Mamaku and C and J Paterson's farm on an Oropi Sand (Allophanic Orthic Pumice) off the Rotorua-Tauranga Road (38.0905S, 176.0835E and 38.0080S, 176.1962E, respectively). Long-term average rainfall was 2099 mm at Butterworth farm and 2323 mm at Paterson farm. Daily rainfall was measured at both sites from the start of May 2016.

Porous ceramic cup leachate collectors were installed at a depth of 600 mm in five adjacent 1.3 ha paddocks at Butterworth farm (30 collectors per paddock) and in four 2.8 ha paddocks at Paterson farm (36 collectors per paddock). The number of collectors was based on a previous leaching trial in the Rotorua catchment (Sprosen and Ledgard, 2016) and earlier work in the Lake Taupo catchment (Betteridge *et al*., 2005; Hoogendoorn *et al*., 2011). The aim was to collect leachate samples after approximately 100 mm of drainage but in practice the unpredictability of high rainfall events meant sample collection intervals varied. Samples were analysed for nitrate (plus nitrite, which is usually negligible) and ammonium N using a segmented flow analyser.

At each farm, drainage was measured using five lysimeters (500 mm diameter x 700 mm depth) that contained 650 mm long intact soil cores (leaving a 50 mm lip to prevent overflow) (Figure 1). The lysimeters were sealed with petroleum jelly to prevent edge flow (Cameron *et al*., 1992) before being placed in trenches and the space around them backfilled with soil, level with the surrounding paddock. Drainage from the lysimeters was collected and the volume and nitrate and ammonium concentrations of the drainage were measured at each leachate sampling.

In the first year of the trial, high water table levels were noticed in some paddock areas on the Butterworth farm which could have resulted in leachate samplers collecting samples of ground water rather than leachate. Two dipwells were installed to monitor groundwater levels. Consequently, the lysimeter site was moved and some leachate collectors were relocated in the trial paddocks to ensure they were only collecting leachate (drainage water) and not groundwater. Lysimeter location and leachate collector layout were consistent for the rest of the trial. At Paterson farm, the water table was very deep and not an issue, and no dipwells were installed.

Figure 1. Lysimeter cores (intact soil) being collected at Paterson farm.

It was noted that there appeared to be significant surface flow of water at the sites after heavy rainfall and, therefore some risk that the lysimeter estimates of drainage might be overestimated. Therefore, in September 2016, three run-off collectors were installed at each site to collect samples of rainwater flowing across the surface of the paddocks and directly into drains or ponds (Figure 2). These collectors were checked at each sampling and if run-off had occurred a sample was taken for nitrate and ammonium analysis.

From winter 2017, pasture samples were collected on a seasonal basis (grazing timing and pasture management, such as weed spraying, permitting). Pasture clippings were taken at approximately 5 cm height from a transect across each of the trial paddocks. The samples were taken prior to the paddock being grazed. All the Butterworth paddocks were grazed as one block and hence all the Butterworth paddocks were sampled on the same date. The Paterson paddocks were grazed at differing times and therefore the sampling sometimes had to be spread over several weeks.

Soil samples were collected from three depths at two sites within the trial area of each farm in 2017 to get representative estimates of soil physical characteristics. The soils were analysed for bulk density and porosity and the averages for each farm are presented in Appendix 1.

Farm data was obtained for all measurement years, including use of N fertiliser on the paddocks in which leaching was measured. This data was used in the OVERSEER model (Science version 6.3.4) to predict N leaching from the trial paddocks. Since OVERSEER is a long-term average model, the long-term average rainfall information was used for the assessment (i.e. 2099 and 2323 mm/year for Butterworth and Paterson farms, respectively).

Figure 2. Run-off collector at Butterworth farm

4. Results and Discussion

4.1 Farm management practices

Both farms are managed as year-round grazing systems with low-medium inputs of brought-in feeds (representing systems 2 or 3 in the DairyNZ farm system categorisation, where system 1 has little-no inputs of brought-in feeds while system 5 has high brought-in feed inputs). For both farms, some cows are grazed off-farm over winter and replacements are grazed off-farm. Farm dairy effluent is applied onto the land on both farms, but not on the paddocks with leachate samplers.

The trial paddocks on the Paterson farm had annual fertiliser-N inputs (split over 4 applications during the year) of 118, 104 and 82 kg/ha in 2016/17, 2017/18 and 2018/19, respectively. In 2019/20, 64 kg N/ha was applied, spread over six applications (Appendix 2). The corresponding annual input of fertiliser-N to trial paddocks on the Butterworth farm was 200 kg/ha in each of the first three years of the trial, dropping to 130 kg/ha in the final year.

At Butterworth farm, the five trial paddocks were immediately adjacent and were grazed consecutively as a single 6.5 ha block. The four trial paddocks at Paterson farm (totalling 10.5 ha) were spread over a wider area of the farm and were grazed independently. Grazing details are presented in Appendix 3. The trial paddocks on Butterworth farm were used for grazing only. However, at Paterson farm typically two of the trial paddocks were closed-up for hay or silage in late-spring/summer each year.

Pasture samples were analysed for total-N concentration on seven occasions (Table 1). With the exception of spring 2019, Paterson farm pasture had higher average N concentrations than the Butterworth farm pasture (average 3.8 and 3.2%, respectively) and is more similar to the average value of 3.7%N considered as typical of NZ dairy pasture (MfE, 2020). The reason for this is not clear, although at most of the samplings, the Paterson pasture had visibly more clover (which typically has a higher N concentration than ryegrass) than the Butterworth pasture. It is not possible to test the statistical significance of this difference but assuming it was a real difference, cows on the Paterson farm would have a higher N intake for a similar pasture intake and hence greater N excretion than on the Butterworth farm. This is not accounted for in the OVERSEER modelling, which has an internal estimate of N concentration based on pasture type and N fertiliser inputs. The relatively low N concentrations in pasture on the Butterworth farm may reflect some factor affecting lower N availability from soil, including via lower clover content, but was likely influenced by greater denitrification associated with soil moisture levels and reducing conditions as noted later in the report.

Table 1. Seasonal total-N concentrations in pasture (%) in 2017-2020. Samples were taken prior to grazing from paddocks J2-J6 of Butterworth farm and P27-P33 of Paterson farm.

Paddock	2017 Winter	2017 Spring	2018 Autumn	2018 Spring	2019 Autumn	2019 Spring	2019/20 Summer
J2	3.32	2.77	3.64	2.66	3.5	3.0	2.8
J3	3.48	2.45	3.88	3.32	3.5	2.9	3.2
J4	3.20	2.59	3.62	2.77	3.7	2.8	3.1
J5	3.36	2.48	3.65	2.96	3.9	3.1	3.1
J6	3.96	2.94	3.61	3.02	3.5	2.9	3.2
P27	3.75	3.55	4.39	3.78	4.8	2.9	4.2
P31	3.81	3.79	4.85	3.43	4.5	3.4	3.3*
P32	4.51	3.61	3.57	3.55	4.6	2.9	3.4*
P33	4.14	2.66	4.48	3.71	3.4*	2.9	3.8
Average							
Butterworth	3.46	2.65	3.68	2.95	3.62	2.94	3.08
Paterson	4.05	3.40	4.32	3.62	4.33	3.03	3.68

*Paddock not sampled on the same date as rest of farm

4.2 Rainfall, drainage and groundwater

During the trial, periods of high rainfall were not restricted to the winter months with Butterworth farm recording its highest monthly rainfall in December 2018 and Paterson farm in March 2016 (Figure 3). Cumulative rainfall on the farms for the four years of the trial (based on a June 1st to May 31st year) is presented in Figure 4. Cumulative rainfall in the first year of the trial was well above the long-term average on both farms (2680 vs. 2099 mm at Butterworth farm and 2873 vs. 2323 mm at Paterson farm). The difference was mostly due to unusually high autumn rainfall. Rainfall in the second year of the trial was similar to the long-term average but the final two years of the trial were drier than average with the difference being due to less rain than usual falling in late-summer and autumn. Over the duration of the trial, annual rainfall on both farms varied by over 1000 mm.

The effect of the drier than usual conditions in the summer and autumn of 2019 and 2020 was that there was no drainage on the farms from the end of December through to May in the final two years. The highest total drainage through the lysimeters was in the 2016/17 year with 1830 and 2000 mm recorded on the Butterworth and Paterson farms, respectively (Figure 5). Drainage was much lower in the final two years of the trial with averages of 1210 and 1065 mm on Butterworth and Paterson farms, respectively. Note, lysimeters do not account for any surface run-off that may occur during periods of heavy rain. As a result, they may overestimate drainage (see section 4.4).

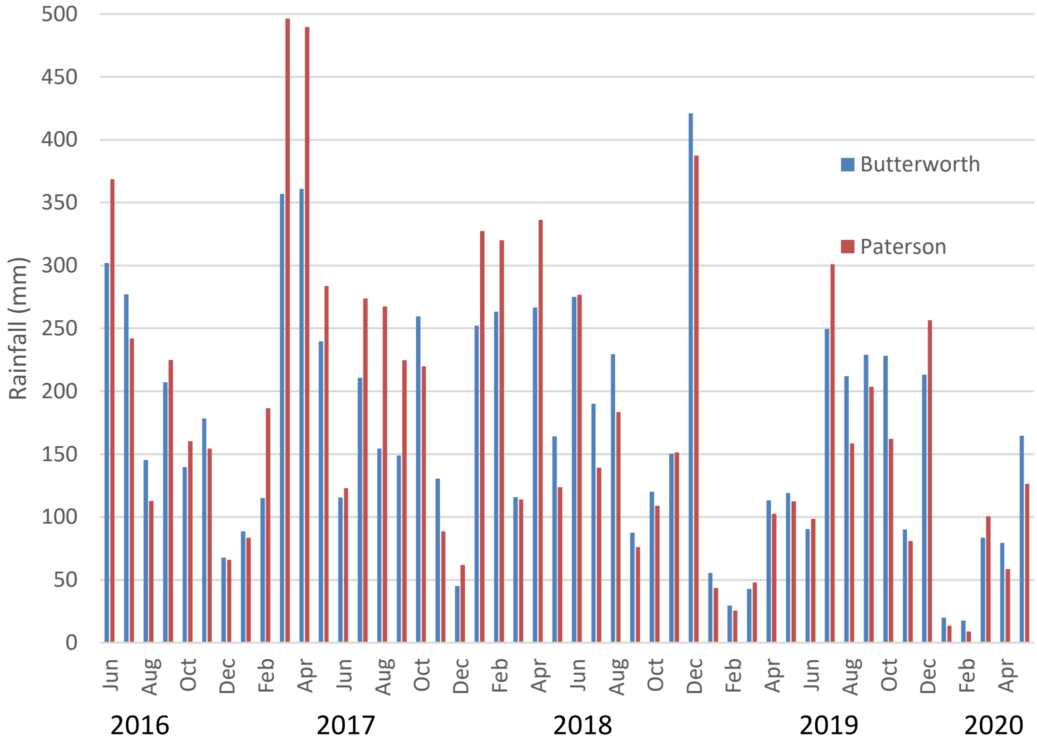
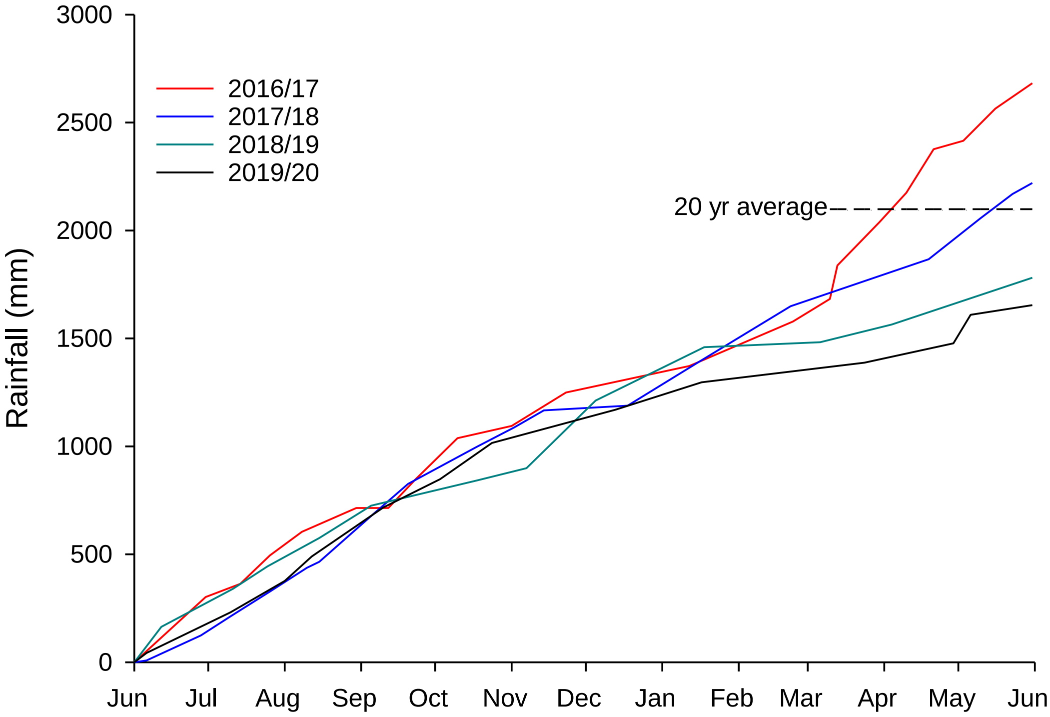


Figure 3. Monthly rainfall at Butterworth and Paterson farms: June 2016-May 2020.



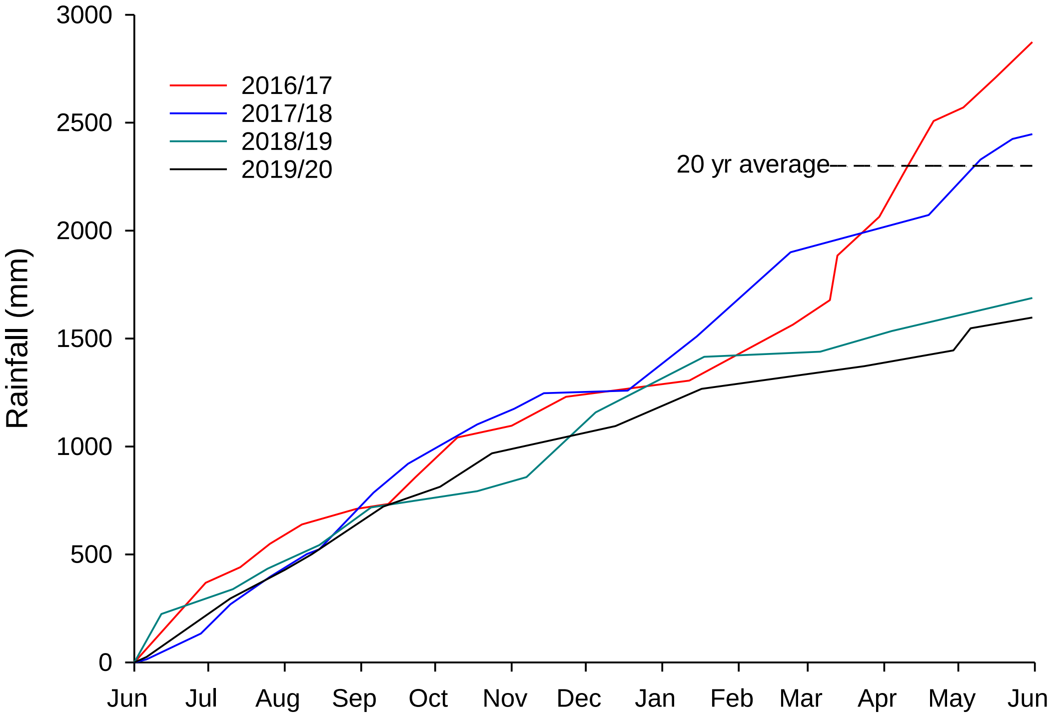
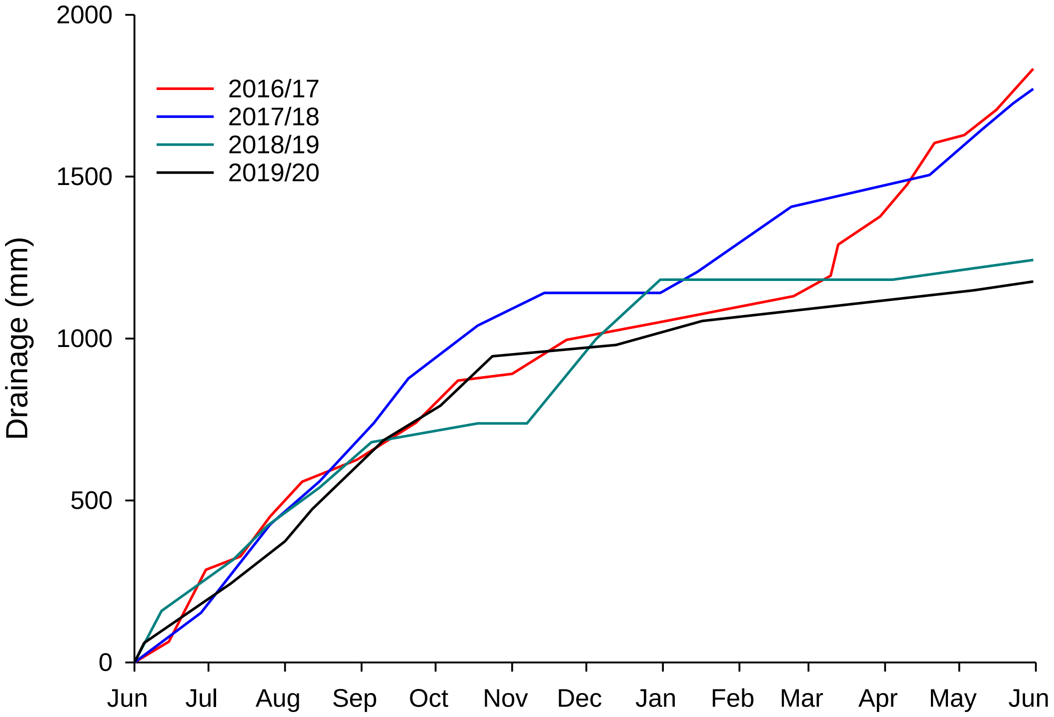


Figure 4. Cumulative rainfall for June-May during the four years of the trial. Top graph: Butterworth farm, bottom graph: Paterson farm.



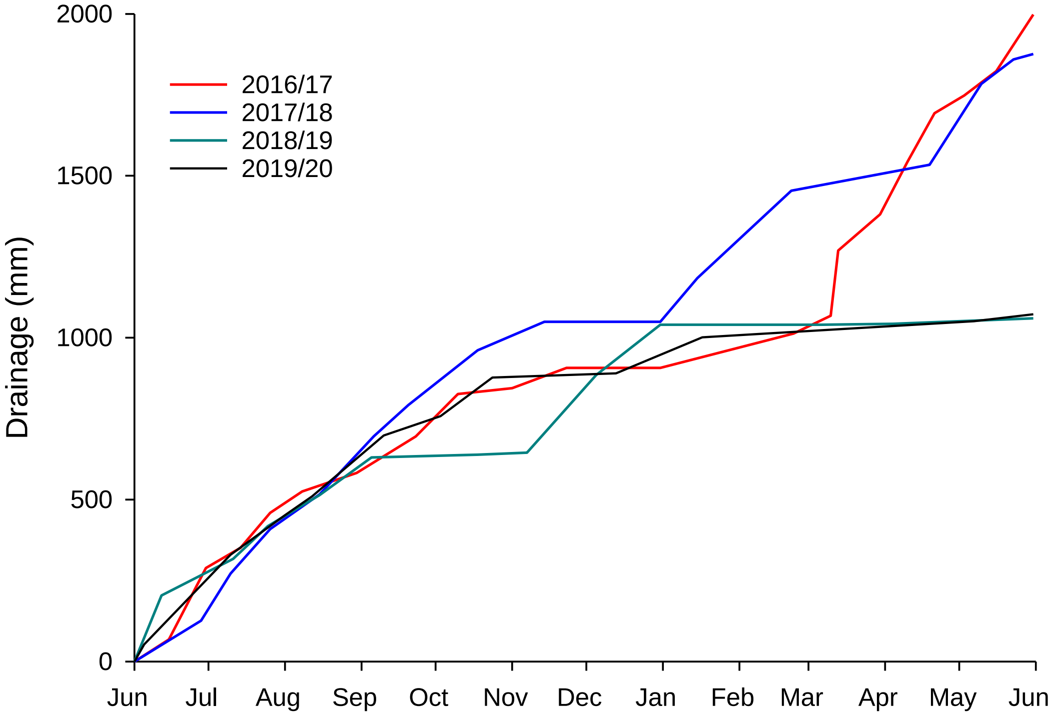


Figure 5. Cumulative drainage (measured using lysimeters) 1st June – 31st May, for the four years of the trial. Top graph: Butterworth farm, bottom graph: Paterson farm.

Groundwater levels at Butterworth farm rose rapidly following rainfall (Figure 6). Levels were high throughout the winters but also rose noticeably following high rainfall events in early 2017 and 2018. Low rainfall in the first halves of 2019 and 2020 resulted in the water table remaining below measurement level for the first five months of both years. Water samples from the dipwells had average ammonium-N and nitrate-N concentrations of 0.1 and 0.3 ppm, respectively. These N concentrations reflect base levels in groundwater as well as additions from leached N via mixing of the two sources.

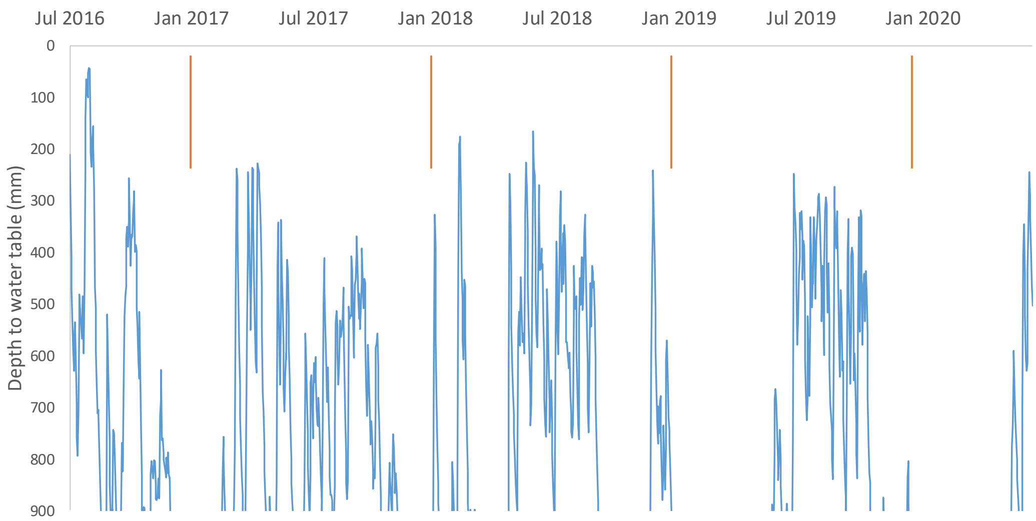


Figure 6. Average depth to groundwater in two dipwells at Butterworth farm. July 2016 to July 2020. No measurements below 900 mm.

4.3 N leaching

During the trial the highest average nitrate-N concentrations in the leachate samplings have consistently occurred in winter, when the soil nitrate built up in spring has leached down to the collectors and the lowest have occurred in spring/summer when plant uptake is at its maximum (Figure 7). The highest leachate nitrate concentration was recorded at Paterson farm in July 2016. On both farms, the 2017 winter peaks were the lowest of the annual peaks. These values represent the average from all leachate collectors for each sampling date and in practice there was wide variation across individual samplers depending on whether they intercepted leaching of N from a urine patch.

Average nitrate-N concentrations in leachate often peak in winter following a build-up of inorganic-N (nitrate, nitrite and ammonium) in the soil over late summer and autumn due to relatively low rainfall and slowing plant growth (e.g. Shepherd *et al*., 2011). In 2017, heavy rainfall in autumn (Figure 3) may have prevented any such inorganic N build-up leading to lower nitrate-N concentrations in the winter drainage. In each year, Paterson farm had the highest winter nitrate concentrations, dropping back to the same or lower concentrations as Butterworth farm in spring and summer.

Ammonium-N concentrations in the leachate averaged less than 0.5 ppm at each sampling. Thus, the concentrations of ammonium were much lower than those for nitrate across all seasons and particularly in winter.

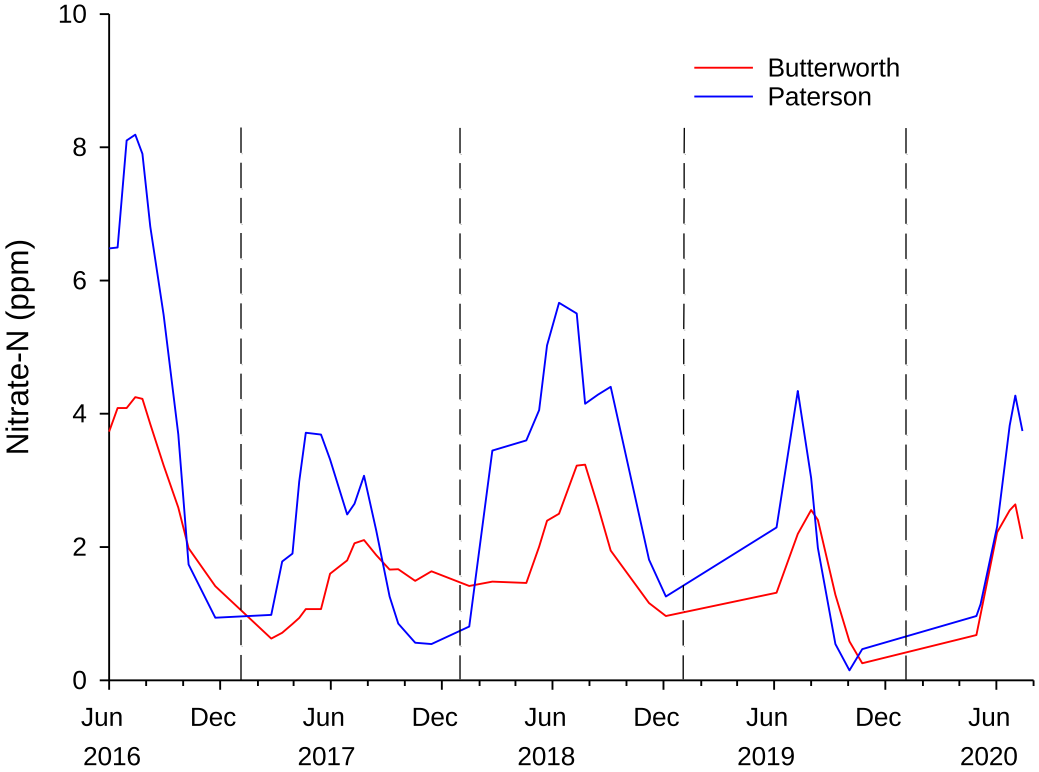


Figure 7. Nitrate-N concentrations (arithmetic means) in leachate samples (data are average values from up to 150 samplers) for June 2016 to June 2020.

The highest nitrate-N leaching losses were recorded in the first year of the trial. This was due to that year having a combination of the highest nitrate concentrations in leachate and the most drainage. Despite the higher nitrate-N concentrations in the winter/spring of 2018 (Figure 7), the amount of nitrate-N leaching in 2018/19 was slightly lower than in 2017/18 (26 and 39 kg N/ha in 2018/19 versus 30 and 43 kg N/ha in 2017/18 at Butterworth and Paterson farms, respectively; Figure 8). This was due to there being less drainage in 2018/19. Both farms recorded the least annual nitrate leaching in the final year of the trial. This was in part due to another relatively dry late-summer/autumn but may also have been influenced by the reduced N fertiliser applications on both farms, which may have resulted in less pasture growth and animal intake, hence less urine N deposition that year.

There was some variation between paddocks in the amounts of nitrate-N leached. For example, paddock J5 in Butterworth farm had higher N leaching than other paddocks in the last three years, while paddock 27 at Paterson farm consistently had the lowest N leaching. This reflects inherent variability between paddocks rather than management practices, since the soils, topography, pasture and amounts of fertiliser-N added were the same within each farm and differences in the timing of grazing were small.

Ammonium-N leaching losses ranged from 1-3 kg N/ha/year at both farms, giving average total annual inorganic-N leaching losses over the four trial years of 30 and 48 kg N/ha on Butterworth and Paterson farms, respectively. This finding is similar to that from other N leaching studies on grazed pasture (e.g. Ledgard *et al*., 1999; Welten *et al*., 2014).

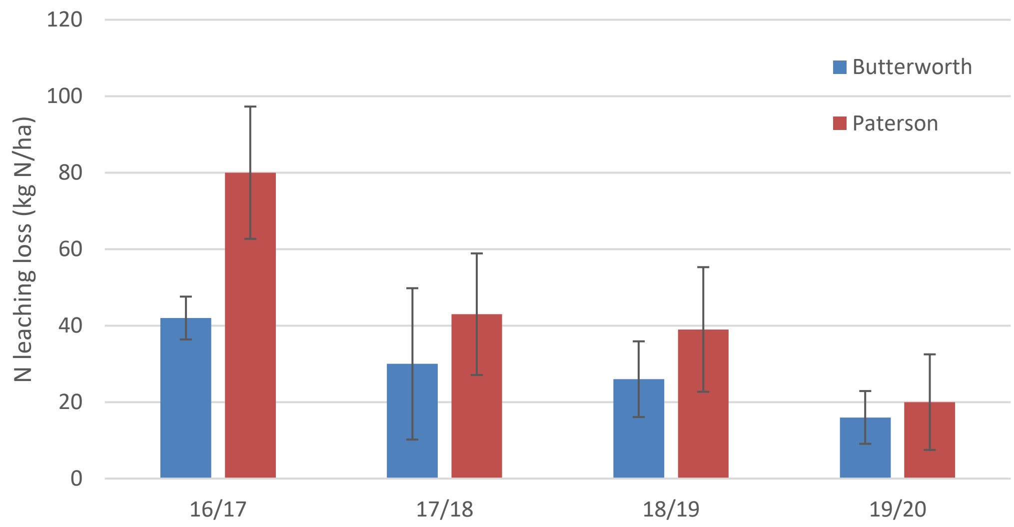


Figure 8. Nitrate N leaching losses (kg N/ha/year): 2016/17 to 2019/20. Bars represent ±1 standard deviation.

4.4 Surface run-off from paddocks

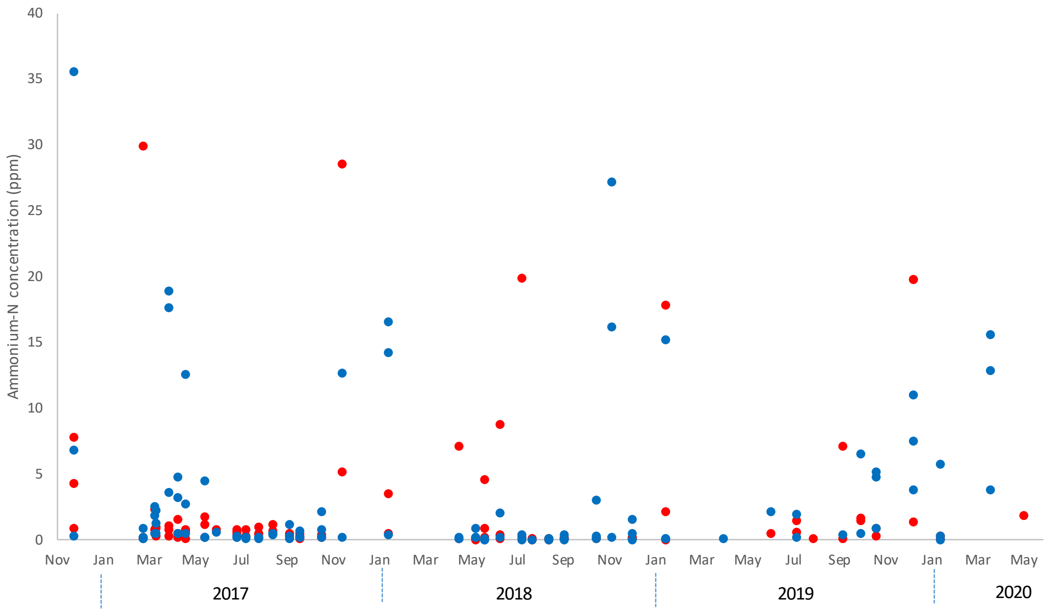
Surface run-off was observed on both farms immediately after periods of heavy rain. In estimating drainage using lysimeters it is assumed that all surplus water leaves as drainage (recognising that the edge of the lysimeters extended about 25mm above the soil surface). Consequently, drainage from the lysimeters will have overestimated the drainage from paddocks when run-off has occurred. If the run-off water contained less N than the leachate, then N losses will also have been overestimated. Since the installation of the run-off collectors in September 2016, over 200 samples have been analysed for nitrate and ammonium concentrations. These concentrations are highly dependent on the timing and location of urine patches. Approximately 70% of samples had ammonium-N concentrations of less than 1 ppm and 60% of samples had nitrate-N concentrations of less than 1 ppm. However, concentrations as high as 35 ppm ammonium-N and 19 ppm nitrate-N were recorded (Figure 9).

Average ammonium-N concentrations in run-off over all samplings were 2.3 and 2.8 ppm at Butterworth and Paterson farms, respectively. Corresponding nitrate-N concentrations were 1.4 and 2.2 ppm. However, the collectors used do not measure the amount of run-off and once the container was filled it was unable to collect any further sample so there was a bias towards sampling the initial run-off which may not be representative of the total run-off event. Another trial being run concurrently at Paterson farm was able to provide additional run-off data. The phosphorus mitigation project (PMP, Levine *et al.*, 2017) measured and sampled all the run-off from several hectares of the farm between December 2017 and November 2018. The depth of run-off over the period was 163 mm with nitrate-N and ammonium-N concentrations of 0.32 and 1.00 ppm respectively (data provided by Brian Levine). The lower N concentration figures in the bulk run-off samples compared to the collectors in the present study appear to confirm the overestimation of run-off N by the individual collectors.

A simple rainfall-based model was used to estimate the amount of run-off at Paterson farm. When hourly rainfall exceeded a certain figure, the excess rainfall was assigned to run-off. Using the run-off volume measured by the PMP trial for calibration, 11 mm of rain per hour was used as the threshold. This model predicted 136 mm of run-off in the 2017/18 year, 38 mm in 2018/19 year and 68 mm in 2019/20 (Figure 10). In 2017/18, most of the run-off was associated with intense rainstorms in the summer/autumn period and rainfall was much lower than normal during this period in 2018/19 and 2019/20, resulting in less run-off. Although there was more run-off in 2019/20 than in 2018/19, it had less effect on N leaching as most of it occurred in December, when nitrate-N concentrations in leachate were low (Figure 7).

Lack of paddock scale run-off collection on the Butterworth farm (such as for the PMP trial at Paterson farm) meant there was no way to validate the run-off model for use at Butterworth farm.

Using the model to estimate drainage and run-off, nitrate-N losses for Paterson farm in 2017/18, 2018/19 and 2019/20 were re-calculated (Table 2). In the 2017/18 year, accounting for run-off reduced calculated nitrate and ammonium N leaching by 11%. However, an additional 0.5 kg N/ha of nitrate-N and 1.5 kg ammonium-N were lost in run-off (based on the average concentrations in run-off from the PMP trial). Thus, the total amounts of N lost in leaching & run-off in 2017/18 were slightly lower (8%) when both flow processes were recognised. Much lower run-off in 2018/19 and 2019/20 meant the reduction in N loss due to run-off was negligible. The run-off process and its implication for different soils warrants further research, including on the podzolized pumice soil which is potentially more prone to run-off. In practice, the potential to mitigate N loss in run-off and the strategies used will be different to those for mitigating N leaching.



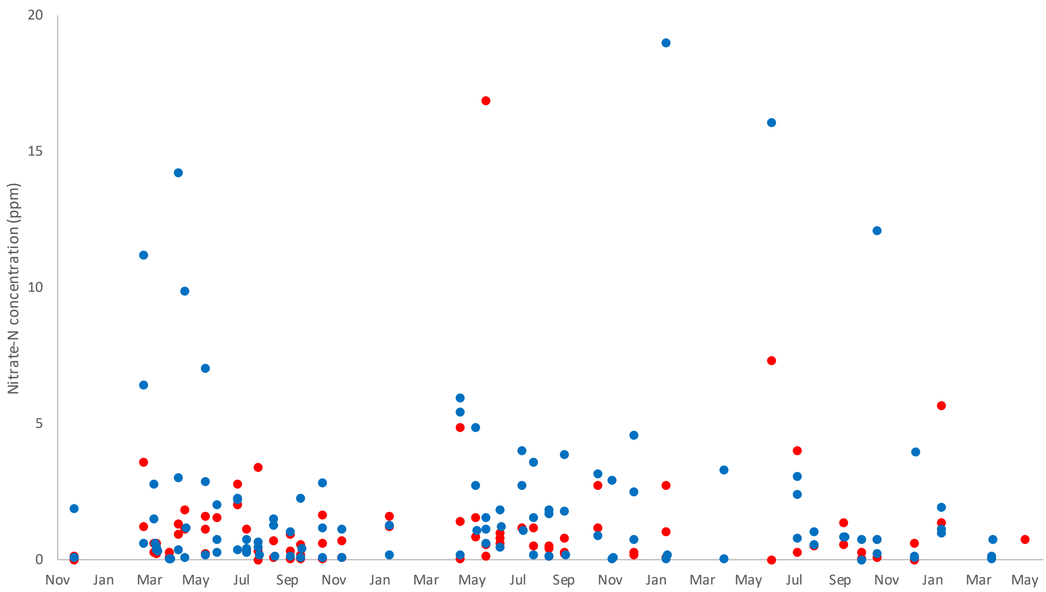


Figure 9. Ammonium-N (A) and nitrate-N (B) concentrations in run-off samples measured from individual run-off collectors between November 2016 and January 2019. Red denotes Butterworth farm, while blue denotes Paterson farm.

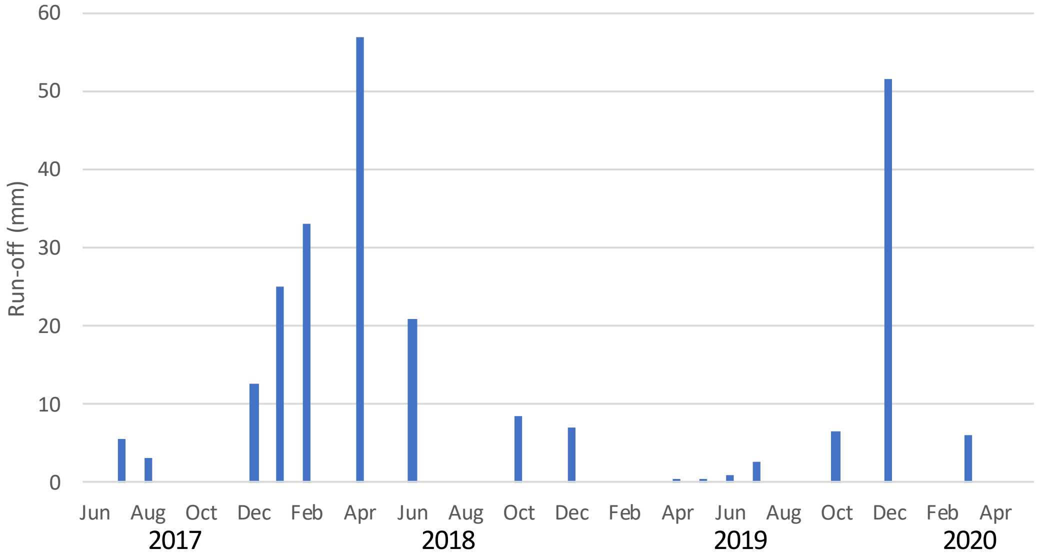


Figure 10. Calculated monthly run-off of rainfall at Paterson farm: June 2017-May 2020.

Table 2. Paterson farm nitrate and ammonium N losses to water. The first data-set assumes no run-off, while the second data-set was recalculated based on modelled run-off volumes in 2017/18, 2018/19 and 2019/20 years and the average nitrate-N concentration in run-off measured from December 2017 to November 2018 (Brian Levine, PMP). All figures are in kg N/ha/year.

	2017/18	2018/19	2019/20
No run-off adjustment:			
Drainage (mm)	1876	1060	1072
Nitrate-N leached	43	39	20
Ammonium-N leached	3	2	1
Total inorganic-N leached	46	41	21
Adjusted for run-off:			
Drainage (mm)	1740	1022	1004
Nitrate-N leached	38	38	19
Ammonium-N leached	3	2	1
Nitrate-N run-off	0.5	<0.5	<0.5
Ammonium-N run-off	1.5	0.5	0.5
Total inorganic-N leached + run-off	42	41	21

4.5 OVERSEER analyses

A summary of estimates of N leaching using the OVERSEER model for the paddock areas that contained leachate samplers for the Paterson and Butterworth farms is given in Tables 3 and 4. Analyses were based on a modification of files used for their resource consents, using OVERSEER Science version 6.3.4. This set the farm structure, blocks and general practices. The files were then updated with relevant farm animal, productivity and input information for the years of study. The file was restructured to include an additional block, which represented the paddocks in which the leachate collectors were located. The main farm block that previously included these paddocks was reduced in size accordingly. Long-term average rainfall data was used, and this resulted in estimates of the amount of drainage of 1388 and 1596 mm/year for Butterworth and Paterson farms, respectively. These drainage values were slightly lower than those measured in 2016/17 and 2017/18 but higher than those measured in 2018/19 and 2019/20 (section 4.2).

Note that the OVERSEER results in Table 3 refer to results for the specific block which had the leachate collectors. They recognised N cycling driven by the general farm system relating to whole farm production including use of brought-in feeds, but were based on the relevant soil type (according to S-map) and actual N fertiliser rates for the leaching-measurement block in the base system. The soils selected in OVERSEER for the leachate block were identified as S-Map sibling Mku_1a.1 for the Butterworth farm and S-Map sibling Oropi_2a.1 for the Paterson farm. For each soil, the corresponding profile available water (PAW) to 60 cm soil depth was defined as 102 and 120 mm, respectively. The pasture growth rate estimated for these blocks (in 2019/20) was 14.1 and 14.5 t dry matter/ha/year for Butterworth and Paterson farms, respectively. Additionally, an assessment was done using OVERSEER adjusted for the actual timing of grazings for the relevant paddocks (accounting for monthly differences; see adjusted[1] data outlined in Table 3). When the latter was used, it resulted in lower calculated values for N leaching that were closer to the measured values. It should also be noted that OVERSEER is intended for use for longer term estimates using average climate data, whereas the last two years had low rainfall and drainage relative to the longer-term average and there were very large monthly differences (e.g. about 1 kg N/ha leached throughout all of January-May 2020, whereas there was 18 kg N/ha leached in the following two months). Thus, a further adjustment using OVERSEER was applied by adjusting for the actual monthly drainage data as best possible (see adjusted[2] data in Table 3) and this resulted in calculated annual N leaching values that were closer to the measured values for those two years. Bearing in mind these factors and the annual variation in N leaching, the final adjusted calculated values were of a similar magnitude to those for the measured values. While it is not recommended that OVERSEER files are adjusted each year for differences in climate, it was relevant in this case to illustrate that it can show appropriate temporal trends in data. The analysis also illustrates the importance in accounting for detailed animal management practices within a farm where blocks are being examined separately for N leaching.

Table 3. Estimation of calculated N leaching (kg N/ha/year) in the leachate sampling paddocks of the Paterson farm using the OVERSEER model (Science version 6.3.4) compared to that measured (nitrate, nitrite and ammonium). Measured data has not been adjusted for run-off. The adjusted[1] modelled data was based on adjusting files to account for actual timings of grazings (see Appendix 3), while adjusted[2] modelled data attempted to account for actual monthly drainage values for the drier years of 2018/19 and 2019/20.

	Measured	Modelled	Modelled (adjusted[1])	Modelled (adjusted[2])
2016/17	83	(90)[3]		
2017/18	46	78	71	
2018/19	41	76	53	48
2019/20	21 (40)[4]	74	68	49
Average (2017-2020)	36 (42)[4]	76	64	49

[3] From general base farm file before trial start, using OVERSEER version 6.3.4

[4] Bracketed values include 18 kg N/ha leaching that occurred in June/July, because Jan-May had only 1 kg N/ha leached

A similar assessment for the Butterworth farm generally showed higher estimates of N leaching using OVERSEER than for the measured results (Table 4). Calculated values were reduced when they were adjusted to account for the actual grazing events (see adjusted[1] results) but they were still about two-fold higher. An attempt was also made to account for lower drainage in the last two years (model adjusted[2]) and this showed a correspondingly lower N leaching in 2019/20. However, it resulted in a surprisingly higher calculated N leaching for 2018/19. This was likely due to the very high December drainage. However, it cannot be ruled out that the specific adjustment for the drainage pattern (including for December) was not functioning properly in the model, but this could not be checked out in this case. An attempt was also made to adjust for the lower pasture N concentration measured on the Butterworth farm in OVERSEER, but it showed little change for 2018/19 (-2%) whereas it was 25% lower in 2019/20. Reducing pasture %N will change N eaten and therefore decrease N excreted.

Table 4. Estimation of calculated N leaching (kg N/ha/year) in the leachate sampling paddocks of the Butterworth farm using the OVERSEER model (Science version 6.3.4) compared to that measured (nitrate, nitrite and ammonium). Measured data has not been adjusted for surface run-off. The adjusted[1] modelled data was based on adjusting files to account for actual timings of grazings (see Appendix 3), while adjusted[2] modelled data also used actual monthly drainage values (from the lysimeters) for the drier years of 2018/19 and 2019/20.

	Measured	Modelled (base)	Modelled (adjusted[1])	Modelled (adjusted[2])
2016/17	44	(88)[3]		
2017/18	32	71	67	
2018/19	28	72	60	73[4]
2019/20	18 (31)[5]	60	55	48
Average (2017-2020)	26 (30)[5]	68	61	

[3] From general base farm file before trial start, using OVERSEER version 6.3.4

[4] Influenced by very high December drainage and some uncertainty about whether model modification for actual drainage pattern was functioning fully

[5] Bracketed values include 13 kg N/ha leaching that occurred in June/July, because Jan-May had only 1 kg N/ha leached

Choice of soil type is important for the analysis and it affects results from OVERSEER. When the OVERSEER file for the Butterworth leaching paddocks was changed from the specific S-map defined soil sibling to a podzol selected according to soil order, it resulted in the same estimated N leaching value (± 1 kg N/ha/yr). This sensitivity analysis based on soil also included selecting for soil order as a pumice or a gley soil for 2018/19, and the calculated N leaching changed from 55 kg N/ha/year to 44 and 26 kg N/ha/year, respectively. Thus, surprisingly the podzol soil properties in OVERSEER (based on S-map) are such that higher N leaching losses are predicted compared with that for the free-draining pumice soil. However, it should be noted that Landcare Research is carrying out soil survey field work around Mamaku in late 2020 to improve S-map polygons and related soil parameters. Thus, any implications for this trial and the OVERSEER analysis results should be reassessed when the S-map data becomes available.

As well as the specific soil properties, the presence of a perched water table can potentially lead to higher soil moisture conditions in soil layers above it and this could increase the potential for denitrification of nitrate in soil into the atmosphere as nitrous oxide and/or dinitrogen. This would decrease the surplus N in soil prone to loss by leaching, as noted in the UK research of Schofield *et al*. (1993). In a recent study by Ormiston Associated Ltd. (2019), the nearby soils around the Mamaku village were examined and they noted an impermeable ignimbrite later at depths of 0.85-2.75 m below the soil surface. This is also likely to have occurred below the paddocks on the Butterworth farm and was supported by areas with perched water table during wet winter periods (see Figure 6).

Detailed research on this topic has also clearly shown that moving from free-draining to poor-draining pumice soils under dairying in the Reporoa basin can result in an increase in redox (oxidation reduction reaction) conditions in soil above impervious or unsaturated soil conditions (Clague *et al*., 2019). This has been shown to be associated with lower nitrate concentrations in drainage water and increased N loss by denitrification (Clague *et al*., 2015). Indicators of risk of denitrification associated with redox conditions in pumice soils with hard ignimbrite can be found via increased levels of sulphate and of dissolved iron, oxygen and manganese (Clague *et al*., 2019). A limited number of bulked groundwater samples from July 2018, 2019 and 2020 from the Butterworth farm were analysed but showed no elevated levels of sulphate (5-6 ppm), dissolved iron (<0.02 ppm) or dissolved manganese (0.02-0.08 ppm). This drew on archived samples, which unfortunately had to be bulked due to the relatively large volume required for analysis. Further research on these and other indicators of redox conditions and associated variability with depth to groundwater and ignimbrite layers, as well as the temporal variation and denitrification potential, would be worthwhile to better understand this as a driver of reduced N leaching.

Information from this study will be provided to Overseer Limited so that it can be used as part of their model review and validation process.

5. Conclusions

The trial period covered a wide range in annual rainfall (over 1000 mm), with a particularly wet year initially, an ‘average’ year and two dry years. The wet year corresponded with the highest recorded nitrate concentrations in leachate and consequently the greatest leaching losses (80 and 42 kg N/ha from Paterson and Butterworth farms, respectively). The smallest losses occurred in the last year of the trial (20 and 16 kg N/ha from Paterson and Butterworth farms, respectively). That year had the lowest rainfall but the leaching losses may also have been affected by reduced N fertiliser use on farms during that year. Large annual variations in nitrate leaching are not unknown (Ledgard *et al*., 1999; Sprosen and Ledgard, 2016) and underscore the importance of obtaining results over a multi-year period to understand the typical average level of N leaching and the variation between years. Leaching of ammonium-N contributed only 1-3 kg N/ha/year on both farms.

Direct run-off of rainfall to waterways occurred on both farms and the effect of this on N leaching losses was able to be estimated at Paterson farm. There, run-off reduced the estimated nitrate-N leaching loss by 9% (4 kg N/ha) in 2017/18. However, taking into account the nitrate and ammonium lost in run-off, the overall reduction in total inorganic-N lost to water that year was 8%. In the much drier final two years of the trial the reduction in total inorganic-N loss due to run-off was less than 3%. Thus, overall, the run-off process had only a minor effect on inorganic-N losses to water.

In all four years of the study, Butterworth farm had lower nitrate-N leaching losses than Paterson farm (20 to 48% lower) with the difference being greatest in the years of highest leaching. Stocking rates and grazing practices were similar on both farms with lower annual N fertiliser use on Paterson farm. A likely factor reducing N for leaching (and plant uptake) in the podzol soil is the greater removal of N via denitrification. Scholefield *et al*. (1993) showed greater denitrification in poorer draining soils. Similarly, measurement of nitrous oxide (one product of denitrification and a greenhouse gas) emissions from urine at sites across NZ showed much larger losses from poorer-draining soils (approximately five-fold higher; de Klein *et al*., 2003). Larger N losses by denitrification may also be a factor associated with the lower N concentrations in pasture on Butterworth farm. A factor contributing to enhanced soil moisture levels on Butterworth farm was the perched water table under the area, which was observed to vary through the year and to be relatively high in winter/spring (Figure 5).

Estimation of N leaching from the farms using OVERSEER indicated higher N leaching values than those measured, particularly for the Butterworth farm. This was influenced by the relatively low measured N leaching during the last two drier years, since application of OVERSEER is based on use of long-term average climate data. Monthly rainfall and drainage patterns vary considerably between years compared with long-term average distributions used in the model (and monthly drainage is a key driver of N leaching in the model).

Using specific experimental data does create challenges when comparing with annualized estimates from OVERSEER. When the OVERSEER files were adjusted for exact timings of grazings through the year it reduced calculated N leaching, and when it was also adjusted for actual drainage it gave similar estimates to the measured values on the pumice soil on the Paterson farm. This illustrates that assumptions around specific grazing times within blocks on a whole-farm farm in OVERSEER may differ from actual practices and this flows through in timing and amount of N deposition in urine which is a driver of N leaching. Adjustment for grazing similarly gave reduced N leaching on the Butterworth farm but adjustment for drainage gave mixed results probably associated with the podzolized soil selection in OVERSEER. However, it does appear that the appropriateness of the soil properties for the Mamaku soil (classified as a podzol) in representing the Butterworth farm needs re-examination. The effect of these properties was to give higher calculated N leaching values than for the pumice soil, possibly through assumed preferential flow through a podzol soil. Effects of the hard ignimbrite layer which is often within 1-3 m of the surface of these soils on a perched water-table, and the associated increased soil moisture status and greater denitrification risk would likely reduce the risk of N leaching on this soil. This has also been shown in research on similar pumice soils in the Reporoa area (Clague *et al*., 2015, 2019). This information and research findings from this study will be provided to Overseer Limited for use as part of their model review and validation process, as well as a recommendation to review the factors driving the high N leaching loss risk on these podzolized pumice soils.

6. Acknowledgements

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8. Appendices

8.1 Appendix 1

Soil physical characteristics of the top three visible horizons (corresponding to average sampling depths of 0-10, 10-20 and 20-40 cm) collected from two sites on each of the two study farms.

Farm	Depth	pH*	Bulk density (g/ml)	Pore space (% of total volume) >300 microns	30-300 microns	<30 microns	Total porosity
Butterworth	top	5.8	0.70	10.0	6.3	57.4	73.7
	middle		0.76	19.2	10.3	41.7	71.2
	lower		0.69	14.2	15.7	44.9	74.8
Paterson	top	5.9	0.67	16.4	12.2	46.2	74.9
	middle		0.81	15.1	18.9	35.3	69.3
	lower		0.83	15.9	16.1	36.8	68.8

*0-7.5 cm sample depth

8.2 Appendix 2

Seasonal N fertiliser use (kg N applied/ha) between summer 2016 and autumn 2020. Paterson trial paddocks were not always all fertilised in the same month.

		Butterworth	Paterson
2016	Summer		26
2016	Autumn	19	36
2016	Aug	*	31
2016	Oct/Nov	*	21
2016/17	Dec/Feb	*	30
2017	Mar/Apr	*	36
2017	Aug		21
2017	Oct	45	21
2017	Nov	25	
2018	Jan	30	26
2018	Feb	35	
2018	Apr	35	36
2018	May	30	
2018	Aug	45	20
2018	Sep	35	
2018	Oct		21
2018	Nov	19	
2018	Dec	35	23
2019	Mar	40	18
2019	May	25	
2019	Jun	20	
2019	Aug		10
2019	Sep	45	4
2019	Oct		3
2019	Nov		10
2019	Dec	20	12
2020	Mar	45	25

*While detailed N fertiliser information for the 2016/17 year is unavailable, the farmer advised that rates and timing were similar to those in the 2017/18 year.

8.3 Appendix 3

Grazing history of the trial paddocks in 2017-2020*. Numbers refer to herd size (cow numbers) x hours grazed, respectively.

	Butterworth	Paterson (individual paddocks)			
	Trial Block	P27	P30	P31	P32
Sep 2017	468 x 72				
Oct	473 x 72				
Nov	555 x 48				
Dec	467 x 72				
Jan 2018	467 x 72			260 x 24	260 x 24
Feb	460 x 72	255 x 24		255 x 48	255 x 24
Mar		244 x 12	244 x 12	244 x 12	
Apr	437 x 72	234 x 24		234 x 24	234 x 12
Jun	440 x 77	166 x 144			
Aug			96 x 84		30 x 48
Sep	500 x 31	235 x 36	250 x 24	185 x 48	235 x 24
Oct	560 x 30	230 x 24	260 x 12	260 x 12	260 x 12
Nov	550 x 35	260 x 24	260 x 24	260 x 24	260 x 24
Dec	555 x 29		260 x 12	cut	
Jan 2019	560 x 29	264 x 36	260 x 12	260 x 12	cut
Feb	552 x 30	220 x 24	270 x 12	270 x 24	
Mar		220 x 24	250 x 24		
Apr	540 x 42		195 x 48		220 x 24
May		170 x 72		170 x 96	
Jun	13 x 120		173 x 49		96 x 36
Aug		138 x 35		171 x 28	
Sep	500 x 36			242 x 12	210 x 24
Oct	540 x 36	255 x 24	255 x 12	255 x 12	255 x 24
Nov	545 x 37	cut	260 x 12		260 x 12
Dec	540 x 36	265 x 24	265 x 36	265 x 48	
Jan 2020		265 x 12		256 x 24	cut
Feb	535 x 40	256 x 36		256 x 36	
Mar		256 x 12	256 x 12	256 x 12	256 x 12
Apr	490 x 48	220 x 35	220 x 24	220 x 24	

* No data for Paterson grazing prior to 2018