release of N from the organic soils. The C:N ratio was slightly higher in LD, and the low base growth and high response to N fertiliser is evidence of N limitation. However, it does not appear that the slight differences in C:N could fully explain the differences in N response between the two sites.

Conclusions

These findings indicate that farmers on less developed peat have lower base growth but can expect greater yield benefits from larger applications of N fertiliser. Farms with WD soils, similar to those here, can expect efficient pasture yield increases in the spring from rates of 25 kg N/ha. It should be noted that the environmental consequences of increased applications of N fertiliser have not been assessed in this study.

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Soil inorganic nitrogen in spatially distinct areas within a commercial dairy farm in Canterbury, New Zealand

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Abstract

For precision nitrogen (N) fertilisation of grazed dairy paddocks, soil N distribution needs to be quantified. It is expected that farm infrastructure will affect inorganic-N distribution due to its influence on cow grazing behaviour. Surface soil from four spatially distinct areas (main gate, water troughs, non-irrigated and the remaining pasture) was analysed for soil ammonium-N (NH_4^+-N) and nitrate-N (NO_3^--N) from three paddocks (180 soil samples) on an irrigated commercial dairy farm in Canterbury, New Zealand. Variation between paddocks was higher for NO_3^- ($P<0.001$) than for NH_4^+ ($P=0.52$). Differences between spatially distinct areas were detected for NH_4^+ ($P<0.001$) but not for NO_3^- ($P=0.37$), though there was variation in NO_3^- with distance from the gates and troughs. This study demonstrates methods for classifying spatially distinct areas of grazed pasture to quantify their influence on inorganic-N distribution. Further research is required to better understand variability.

Keywords: nitrogen, spatial nitrogen distribution, distinct areas

Introduction

Use of centre pivot irrigation and repetitive mineral N fertiliser applications on grazed paddocks have increased to support the intensification of dairy production in New Zealand (Foote *et al.* 2015). Precision fertilisation can exclude high N areas, reduce fertiliser amounts without sacrificing yields (Diacono *et al.* 2013), and reduce NO_3^- leaching (Foote *et al.* 2015). Strategies for precision fertilisation within cattle-grazed paddocks differ from cropped areas due to heterogeneous grazing behaviours of cattle (Sanderson *et al.* 2010).

Cattle grazing patterns are spatially uneven, as cows can spend ~50% of their time within 13% of the paddock (Hunt *et al.* 2007). Repeated grazing results in spatially random excreta distribution in the paddock (White *et al.* 2001), and rates of soil N accumulation are affected by stocking rate, grazing intensity and rotation (White *et al.* 2001; Hunt *et al.* 2007; Putfarken *et al.* 2008). However, cattle are known to frequent areas around farm infrastructure like water troughs, fences and shelter belts (White *et al.* 2001; Hunt *et al.* 2007; Putfarken *et al.* 2008), which may result in higher soil N in these areas. Identifying spatially distinct areas based on the orientation of farm infrastructures (i.e. water troughs, fences, shelter belts), may provide a way to characterise spatial N distribution around a grazed dairy pasture.

A strategy is needed to quantify the spatial distribution of N within intensively grazed pastures and to related farm infrastructure to develop precision fertiliser schemes. The objective of this paper was to test a methodology to delineate farm infrastructure related spatially distinct areas around a typical New Zealand dairy farm, and to quantify spatial distribution of NH_4^+-N and NO_3^--N.

Materials and methods

Experimental site

The site was an irrigated commercial dairy farm in Rolleston (43.56750°S, 172.32334°E), Canterbury, New Zealand. The soil was a stoneless, free-draining Lismore silt loam (Pallic Firm Brown Soil, Hewitt 2010). The farm stocking density was 3.6 cows/ha for a herd of 630 Friesians. Cows were rotationally grazed on perennial ryegrass (*Lolium perenne*)/ white clover (*Trifolium repens*) pastures. The grazing cycle varied from 26 to 40 days (26, 35 and 40 days for March, April and May, respectively, during 2017) with supplementary feed provided as required. Total broadcast N-fertiliser was 190 kg N/ha from September 2016 to April 2017, including 50 kg/ha of 'SustaiN 25K' (at 23% N) fertiliser after each grazing. Pasture irrigation averaged 3 mm/ha/day from October 2016 to March 2017.

Soil Sampling

Three paddocks (coded 17, 19 and 33), each 5.1-5.5 ha and located in the centre pivot irrigation area, were selected for soil sampling. Each paddock included a main gate, a water trough, and low producing (non-irrigated) area, that were spatially distinct.

Different sampling regimes were used for each distinct area of the paddock to obtain spatially

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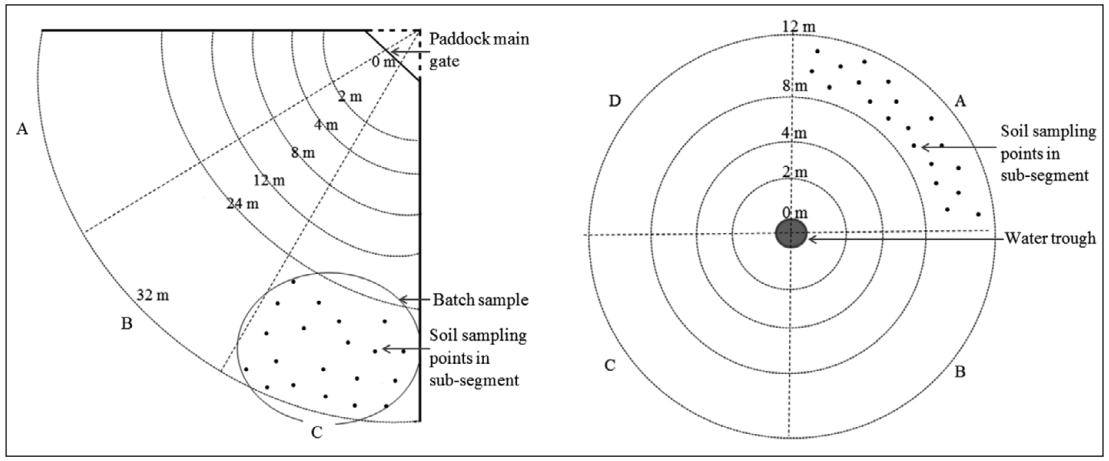

Figure 1 Illustration of sampling procedure at paddock main gate (left) and around water trough (right).

representative samples. Areas around the main gates and water troughs were sub-divided into sampling zones using a radial grid system (Figure 1). Soil samples were obtained at the main gate in an arc divided into three segments, extending from the gate to the main paddock area at increasing distances (Figure 1). Similarly, circular rings divided into four equal segments were subdivided with distances marked at 2, 4, 8 and 12 m from the water trough (Figure 1). The non-irrigated areas were identified as having lower pasture density and an atypical canopy cover compared to the irrigated areas. Using Google Earth images, non-irrigated areas in the paddocks were measured and divided into ten equal segments. The whole paddock area was divided into nine rectangular segments, excluding non-irrigated areas. A 50 m buffer zone (Sanderson *et al*. 2010) was allocated away from the gates, water troughs and non-irrigated areas when sampling the remainder of the paddock.

In April 2017, 15 cm deep soil cores were collected from within each spatially distinct area, 4 to 12 days after grazing and before N fertilisation. Twenty spatially random soil cores were collected within each sub-segment, and were combined into one sample representative of that sub-segment (Figure 1). For each paddock, there were a total of 18 samples taken near the main gate, 16 samples near the water troughs, 10 samples in the non-irrigated and 9 samples from the remainder. Visible urine and dung patches were avoided during soil core collection. All samples were kept in cool storage in-paddock until they were transported to a freezer (0°C) for laboratory storage before analysis.

Soil analysis

To measure soil inorganic-N (NO_3^--N, NH_4^+-N), field-moist soil was sieved (<5 mm) and 5 g (± 0.05 g) subsamples were combined with 25 ml of 2 M KCl and mixed for one hour on a "Ratek" Platform Mixer. The samples were then centrifuged at 4000 rpm for 10 minutes before filtering through 110 mm "Advantec" 5C filter paper. Extracts were analysed colorimetrically using a Flow Injection Analyser (FIAstar 5000 Analyser, FOSS, Centre for Soil and Environmental Research, Lincoln University) within 48 hours of extraction. Extracted samples were stored at 4°C. Gravimetric soil moisture was determined by placing 20 g of field moist soil in a paper container (weight of paper container + moist soil) and oven-drying at 105°C for between 24 to 48 hours. Inorganic-N concentrations were converted to mass of inorganic-N per mass of soil gravimetrically.

Statistical analysis

Analyses were performed using Genstat v16 (VSN International Ltd., UK). Soil NO_3^- and NH_4^+ concentrations were transformed as $\log_{10}(x)$ before analysis, to account for variation between paddocks and unbalanced sampling design. N-concentrations in the different areas were compared using Residual Maximum Likelihood (REML) mixed models, assigning area as a fixed factor and paddock as a random factor. These analyses included all the samples from non-irrigated areas, those samples within 12 m from a gate or trough and the remainder of the paddock. Differences between areas were identified using estimated Least Significance Difference (LSD) pairwise comparisons.

The data describing how N-concentration varied as a function of distance from gates or troughs were examined separately for each paddock, using one-way ANOVA. These analyses also included data from the normal paddock area of each paddock to represent background levels of NO_3^- and NH_4^+. Groups of samples significantly different from the background levels were identified using Fisher's unprotected LSDs ($P<0.05$).

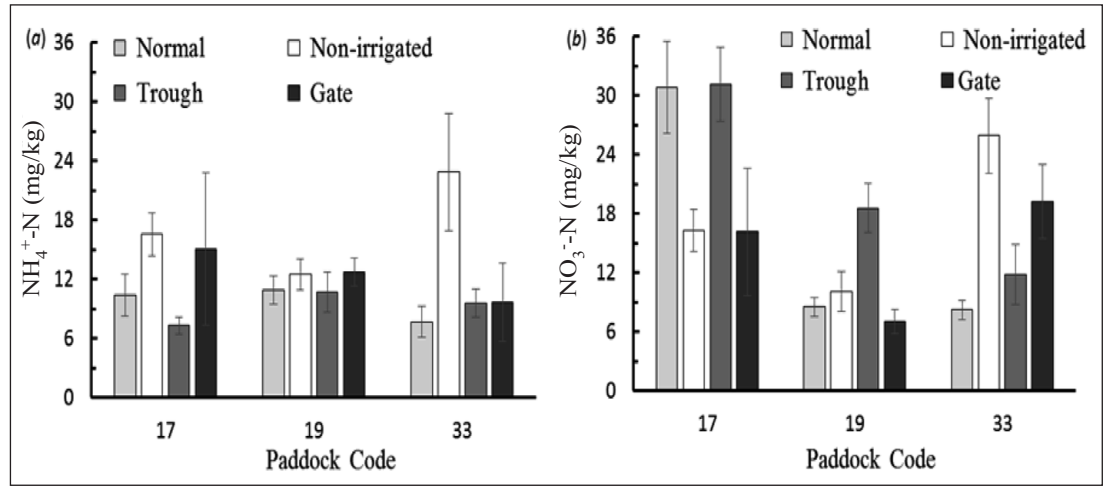

Figure 2 Soil inorganic-N concentration in different areas of the paddocks; (a) NH_4^+-N (mg/kg) (b) NO_3^--N (mg/kg).

Results

General trends of inorganic-N

Both NH_4^+ and NO_3^- concentrations were highly variable across the three paddocks. Overall mean NH_4^+-N concentrations were 11.9 mg/kg soil, but had a 19-fold difference between the minimum (3.5 mg/kg) and maximum value (65.9 mg/kg). Similarly, NO_3^- had a mean concentration of 29.3 mg/kg but a wide (43-fold) range, from 1.3 mg/kg to 54.5 mg/kg.

Distribution of inorganic-N in different areas of the paddocks

When comparing the means between spatially distinct areas within paddocks, there was considerable variation between paddocks for NO_3^- ($P<0.001$), but not for NH_4^+ ($P=0.52$) (Figure 2). One paddock had relatively high NO_3^- concentration in the non-irrigated area (25.9 mg/kg ± 3.8). Overall, there were highly different NH_4^+ concentrations between the distinct areas ($P<0.001$). This was due to the non-irrigated area having higher mean levels than the other three areas (Figure 2a). When comparing overall means, there was no evidence suggesting that NO_3^- differed systematically between different paddock areas ($P=0.37$). However, overall mean NO_3^- concentration recorded in the remaining (normal) paddock area and trough area in one paddock were higher than in all other areas (Figure 2b).

Distances from gates and water troughs

There were no clear patterns in NH_4^+ concentrations with distance from water troughs or the main gates (data not shown). In paddocks 19 and 33, NO_3^- was higher closer to the troughs, and receded to concentrations similar to the normal paddock area by ~8 m from the trough (Figure 3). In paddock 17 and 19, NO_3^- concentrations were lower closer to the gates, and gradually increased at distances away from the gates (Figure 3). In paddock 33, NO_3^- concentrations were high at 2 m from the gates, before quickly decreasing at 4 m and increasing again at 12 m then gradually decreasing again at greater distances from the gates.

Discussion

The low variability in NH_4^+ between spatially distinct areas, and between paddocks (Figure 2), suggests nitrification rates from NH_4^+ to NO_3^- (Sahrawat 2008) were relatively consistent. The one exception was the high mean NH_4^+ in the non-irrigated areas of paddock 33 which was unshaded, unlike paddocks 17 and 19 which were partially shaded by trees. The lack of shade in paddock 33 may have resulted in drier soil, lower nitrification rates, and higher NH_4^+.

Greater soil nutrients from excreta depositions near gates and water troughs have been noted (Wilkinson *et al.* 1989; Franzluebbers *et al.* 2000; Hunt *et al.* 2007; Putfarken *et al.* 2008), but the current study showed that NO_3^- in the gates and trough areas were highly variable (Figure 2). This variability may be related to the trends observed in NO_3^- with distance from gates and troughs (Figure 3). Future studies should reconsider delineation boundaries beyond 8 m around troughs, where NO_3^- was not higher than the surrounding paddock. However, NO_3^- around the gates was different from the normal paddock up until 32 m, suggesting that the affected area may extend beyond the current delineation. The NO_3^- variability may be due to gradients in factors like soil moisture, which affect rates of nitrification and denitrification (Davidson & Verchot 2000), and therefore NO_3^- concentrations.

The studied areas, especially those around gates and troughs, had almost no growth of pasture biomass,

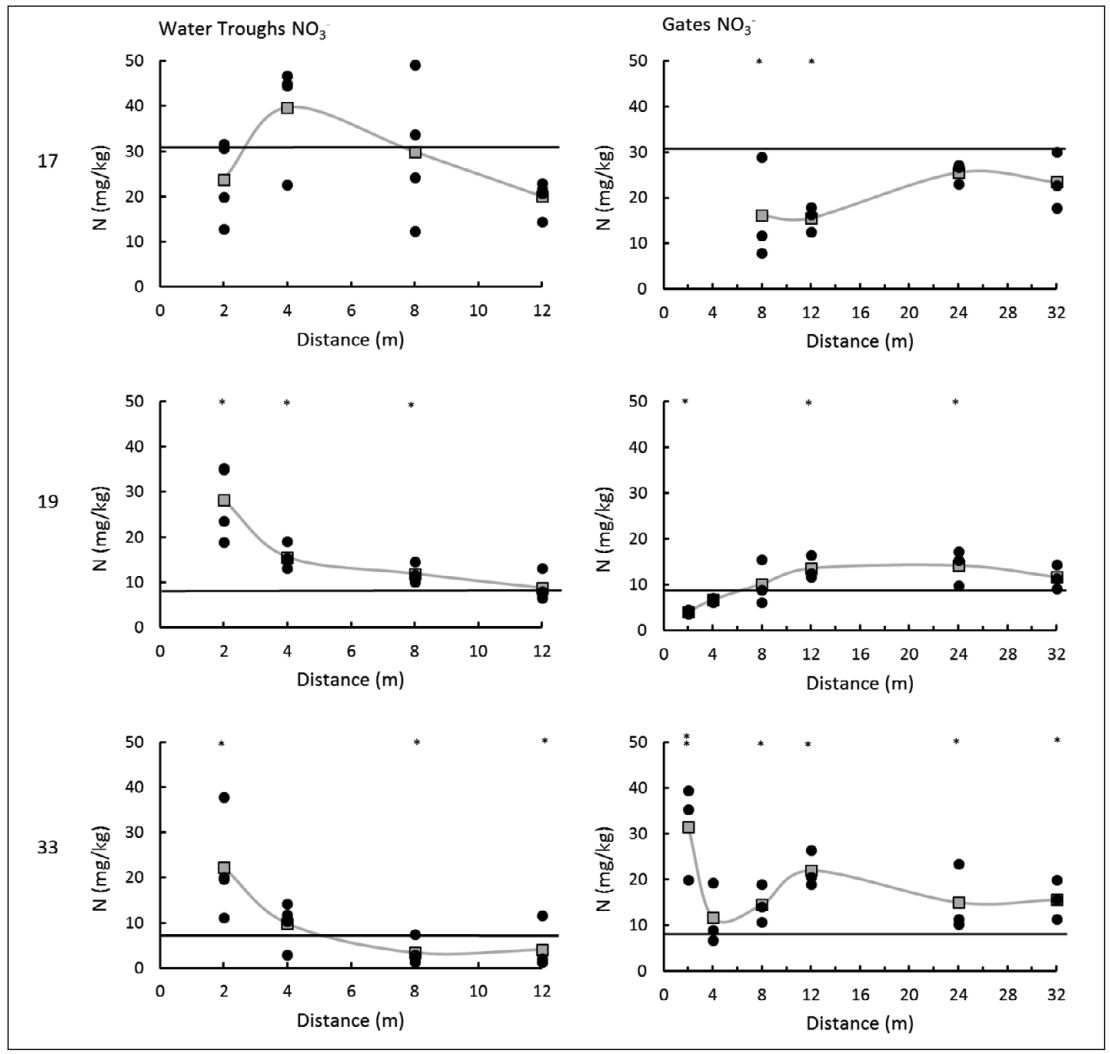

Figure 3 Nitrate (NO_3^-) concentrations (individual samples in black, mean in grey, and a grey smooth line through the means) with the distance from water trough (left) and distance from the main gate (right). The solid black line represents level of N in 'normal' area of paddock (* - LSD indicates significantly different from 'normal' at P<0.05). Nitrate data is not available from the gate in paddock 17 at 2 and 4 m.

likely due to compaction from cattle (Johnson *et al.* 1993; Sheath & Carlson 1998). Inclusion of compaction in future studies may help explain occurrences of inorganic-N variability. As the whole paddock received a uniform N fertiliser application and the studied areas did not show significant differences in the soil N pools, unutilised N fertiliser has to be considered as lost out of these areas. Therefore, this work provides a baseline for the development of a spatially variable rate fertiliser application system, as a system for efficiently evaluating soil N in a grazed paddock will be required. Future iterations of the work can begin to try to couple soil N distribution around farm infrastructure with other factors that are more quickly measured using remote sensors, such as vegetation greenness or density.

Conclusions

Low NH_4^+ variability was observed in all areas expect the non-irrigated areas. High variability in NO_3^- proximate to gates and troughs was observed with variability subsiding at different distances away from the infrastructure. Quantifying inorganic-N spatial variability on irrigated dairy farms may help reduce N fertiliser applications to reduce N lost as pollution, without affecting plant yields. Extended studies are desirable to confirm the influence of spatially distinct areas around farm infrastructure.

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