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REGULAR ARTICLE

Effects of tillage, simulated cattle grazing and soil moisture on N_2O emissions from a winter forage crop

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Abstract Nitrous oxide (N_2O) emissions to the atmosphere from grazed pasture can be high, especially from urine-affected areas. When pastoral soils are damaged by animal treading, N_2O emissions may increase. In New Zealand, autumn-sown winter forage crops are often grown as a break-crop prior to re-sowing pasture. When these crops are grazed in situ over winter (as is common in New Zealand) there is high risk of soil damage from animal treading as soil moisture contents are often high at this time of year. Moreover, the risk of soil damage during grazing increases when intensive tillage practices are used to establish these forage crops. Consequently, winter grazed forage crops may be an important source of N_2O emissions from intensive pastoral farming systems, and these emissions may be affected by the type of tillage used to establish them. We conducted a replicated field experiment to measure the effects of simulated cattle grazing (mowing followed by simulated treading and the application of synthetic urine) at three soil moisture contents (< field capacity, field capacity and > field capacity) on measured N_2O emissions from soil under an autumn (March) sown winter forage crop (triticale) established with three levels of tillage intensity: (a) intensive, IT, (b) minimum, MT, or (c) no tillage, NT. In all treatments, bulk density in the top 7.5 cm of the soil was unaffected by treading when simulated grazing occurred at < field capacity. It was increased in the IT plots by 13 and 15% when treading occurred at field capacity and > field capacity, and by 10% in the MT plots trodden at > field capacity. Treading did not significantly increase the bulk density in the NT plots. Emissions of N_2O from the tillage treatments decreased in the order IT > MT > NT. N_2O emissions were greatest from plots that were trodden at > field capacity and least from plots trodden at < field capacity. Simulated treading and urine application increased N_2O emission 2 to 6-fold from plots that had no treading but did receive urine. Urine-amended plots had much greater emissions than plots that had no urine. Overall, the greatest emission of 14.4 kg N ha^{-1} over 90 days (1.8% of the total urine N applied) was measured from urine-amended IT plots that were trodden at > field capacity. The N_2O emission from urine-amended NT plots that were trodden at < field capacity was 2.0 kg ha^{-1} over 90 days (0.25% of the total urine N applied).

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Decreasing the intensity of tillage used to establish crops and restricting grazing when soils are wet are two of the most effective ways to minimise the risk of high N_2O emissions from grazed winter forage crops.

Keywords Nitrous oxide · Tillage · Compaction · Urine · Forage

Introduction

Agricultural soils are a key source of nitrous oxide (N_2O), a potent greenhouse gas that also interferes with the production and destruction of atmospheric ozone. Nitrification and denitrification are the two major biological processes responsible for N_2O production from soils (Bremner 1997). The relative importance of these processes is strongly dependent on soil moisture, which controls the amount of aeration and oxygen concentration in the soil. Water filled porosity (WFPS) has been identified as a key indicator of N_2O emissions because moisture content will affect diffusion of oxygen through the soil matrix (Linn and Doran 1984). In general, high N_2O emissions mainly from denitrification can occur in a wide range of intensive agricultural systems when water-filled pore space (WFPS) exceeds 60% (Dobbie and Smith 2003).

High N_2O emissions tend to occur in agricultural systems with large nitrogen inputs. Grazed systems have high N from excretal deposits, especially in localised urine patches. Cattle urine patches typically cover about 0.4 m^{-2} and contain between 200 and 800 kg N ha^{-1} (Oenema et al. 1997). Urine applications are known to stimulate rapid denitrification, especially when soil moisture contents are high, producing large amounts of N_2O (de Klein and van Logtestijn 1994; Oenema et al. 1997).

In New Zealand, N_2O emissions from agriculture account for approximately 17% of the national greenhouse gas inventory. Since year-round pastoral farming dominates NZ agriculture, more than 80% of these N_2O emissions come from animal excreta, mostly from cattle urine deposited in autumn and winter (de Klein and Ledgard 2005).

Soil compaction by farm machinery increases N_2O emissions and these effects have been reported for a range of agricultural systems (Ball et al. 1999a; Ball et al. 1999b; Douglas and Crawford 1993; Hansen et al. 1993; Ruser et al. 1998; Sitaula et al. 2000). Compaction influences a range of soil physical properties, such as bulk density, soil porosity, soil tortuosity and water holding capacity, which are important in maintaining plant growth and environmental quality (Ball et al. 1999a; Lipiec and Hatano 2003). In addition, soil compaction can also affect soil biological activity (Torbert and Wood 1992). However, there has been much less focus on the effects of compaction from stock treading on N_2O emissions. In their review, Oenema et al. (1997) postulated that compaction by stock treading could double emissions from pasture, using supporting evidence from Douglas and Crawford (1993), who measured two-fold increases in nitrous oxide emissions under wheel traffic on a grassland soil. In New Zealand, Bhandral et al. (2007) observed a three-fold increase in N_2O emissions from a urine-amended dairy pasture following soil compaction caused by a tractor.

Much research has been done on the physical effects of grazing pastures on soil physical conditions (e.g. Drewry et al. 2001; Menneer et al. 2005b; Singleton and Addison 1999). The risk of treading damage is great when the soil moisture content is high (i.e. near or above the soil's plastic limit). Severe treading damage can have long-lasting effects (>18 months) on physical soil characteristics such as hydraulic conductivity, aggregate size, total porosity, pore size distribution, and bulk density (Singleton et al. 2000). Treading damage can significantly decrease pasture plant growth (Drewry et al. 2001; Drewry and Paton 2005a; Menneer et al. 2005b) and greatly increase denitrification (Menneer et al. 2005a).

There have been relatively few measurements of N_2O emissions from urine patches during and following grazing. Most measurements from urine patches have been made with cattle excluded, so do not include the effects of animal treading. All of the published work on N_2O emissions from grazing and excreta has been from pasture systems and not other forage systems. The grazing of winter forage crops by dairy cows on wet soil can result in soil compaction that may limit subsequent crop re-growth. There has been little attention paid to the physical effects of treading on grazed forage crops (Drewry and Paton 2005b).

One of the key differences between winter grazing of pasture and forage crops is the short-term nature of the latter, with intensive cultivation practices widely used to them as part of the pasture renewal process. Tillage and compaction can significantly alter soil structure and water content, both of which affect soil gas diffusivity (Ball et al. 1997). Several studies have investigated the effects of tillage on soil N_2O emissions, but there is a need for information on how the interaction between tillage practices and compaction affects N_2O emissions (Yamulki and Jarvis 2002). Some studies have reported higher N_2O emissions from no-tillage than from conventional tillage soils (Ball et al. 1999b), as a result of increased soil moisture content, water conservation and lower soil gas diffusivity, whereas other studies report no significant effects of tillage on N_2O emissions (Elmi et al. 2003; Yamulki and Jarvis 2002).

To address some of these uncertainties we designed a factorial field experiment to test the hypothesis that the type of tillage practice used to establish forage crops out of pasture will affect the extent of soil compaction and emissions of N_2O after simulated grazing.

Materials and methods

The field trial ran from March to October 2003 at Lincoln, Canterbury, New Zealand (lat. 43°40′ S, long. 172°28′ E, elevation 5 m). The soil at the site was a Wakanui silt loam classified as a mottled immature pallic soil (New Zealand Soil Classification, Hewitt 1993) or Udic Dystochrept (USDA Taxonomy). Some of the initial properties of the topsoil are shown in Table 1. A grass/clover pasture (>15 years old) was sprayed with glyphosate prior to sowing (3 March) of a multi-grazing triticale crop (cv. Doubletake). The seedbed was prepared with either (a) intensive tillage (IT: plough to 20 cm depth, maxi-till, roll and harrow), (b) minimum tillage (MT: disc to 10 cm depth, roll and harrow) or (c) no-tillage (NT) practices. These main plots were 9×9 m in size and were arranged in a Latin square design, replicated three times. Six split-plots (3 m×1 m) were then established within each main tillage plot to determine the effects of soil moisture (<, =, > field capacity) during grazing, animal treading (yes/no) and urine application (yes/no) on soil compaction and N_2O emissions (Table 2). A buffer strip of at least 1 m surrounded each split plot. Granular fertiliser was applied to the field plots 10 days after sowing at rates of 22.5, 15, 15 and 11.5 kg ha^{-1} of nitrogen, phosphorus, potassium and sulphur, respectively.

Table 1 Initial soil properties at the field site

Depth (cm)	Bulk density ($g\ cm^{-3}$)	Total C (%)	Total N (%)	pH
0–7.5	1.17	3.4	0.29	5.8
7.5–15	1.32	2.6	0.22	5.7
15–25	1.46	1.9	0.16	5.6

Simulated grazing

Soil moisture contents for subplots at or above field capacity (FC, Table 2) were adjusted by applying spray irrigation immediately before grazing using overhead mini-sprinklers. Soil moisture contents <FC (Split plot Treatment 1, Table 2) were achieved by covering subplots with cloche frames during rainfall events from mid-May until simulated grazing. A single grazing event was simulated in all treatments in June 2003. At this time, all the plots were mown to a height of about 10 cm. Treading was then simulated using a mechanical cow hoof that applied a pressure of 220 kPa to the soil surface, representing the treading impact of an adult Friesian cow (Di et al. 2001). The soil was trodden by placing the mechanical hoof on the soil surface, then pneumatically pressing the hoof in to the soil. This procedure was repeated on the adjacent soil surface until the whole plot had been trodden. Once the plots had been trodden, synthetic urine was applied. The synthetic urine was made to a recipe described by Clough et al. (1998) and was uniformly applied using watering cans at a rate of 800 kg N ha^{-1}.

N_2O measurements

N_2O fluxes were determined using a closed chamber technique (Hutchinson and Mosier 1981). The sam-

Table 2 Split plot treatments imposed at simulated grazing

Split plot treatment	Soil moisture content	Treading	Urine application
1	<FC[a]	Yes	Yes
2	FC	Yes	Yes
3	>FC	Yes	Yes
4	FC	No	Yes
5	FC	Yes	No
6	FC	No	No

[a] FC (field capacity)=35% *v*/*v*; <FC=27%; >FC=40%

pling method we used is similar to that described by de Klein et al. (2003). Chamber tops (10 cm depth) were made from 30 cm diameter PVC pipe with gas-tight lids made from PVC plate welded on to the pipe. Polystyrene and closed–cell foam was attached to the tops to prevent temperature and pressure fluctuations within the chamber. Chamber bases (15 cm depth), made from the same diameter PVC pipe, were inserted into the soil (5 cm depth) to enable gas fluxes to be measured at the same position within each plot. A channel made from PVC and welded to the top of each base was water-filled to produce a gas-tight seal with the chamber top during measurements. Prior to installing the chamber tops on to their bases, a 25 mm diameter rubber septum was removed from the chamber lid, to prevent a pressure difference between the chamber headspace and the surrounding air as the chamber was being installed. The septum was reinserted about 1 minute after the chamber was installed.

Headspace gas was sampled through the septum at 0, 20 and 40 min after chamber closure using a 20 mL gas tight syringe with a hypodermic needle. To help mix the headspace gas in the chamber, and provide a representative sample, three syringe volumes of the chamber headspace were slowly flushed through the syringe before a 12 mL volume was injected and stored (over-pressurised) into evacuated 6 mL Exetainers (LabCo Ltd., UK) prior to analysis. N_2O flux was calculated assuming a linear change in concentrations corrected for sampling temperature based on in previous studies (e.g. de Klein et al. 2003) and checks during the experiment. The chamber heights were extended during the trial to accommodate the growing triticale by adding PVC rings 30 cm diameter and 30 cm tall to the chamber tops. The first extension was added 57 days after the urine was applied (26 August) and the second was added on day 86 (24 September) giving a total headspace height of 80 cm (volume of 57 L). Samples were taken on 27 occasions over 92 days. Cumulative N_2O fluxes were calculated assuming a linear change in N_2O fluxes between sampling dates. Gas samples were analysed within 72 h of sampling using a gas chromatograph (GC-17A, Shimadzu Corporation, Kyoto) equipped with a Porapak Q (80/100 mesh) column and fitted with a ^{63}Ni-Electron capture detector (ECD) heated to 320°C. Oxygen free nitrogen was used as a carrier gas (30 mL min^{-1}) and argon with 10% methane was used as a make-up gas (5 mL min^{-1}) for the ECD to improve sensitivity.

Soil and weather measurements

Before the tillage treatments were imposed in March, soil bulk density was measured at depths of 0 to 7.5, 7.5 to 15 and 15 to 25 cm from six cores (50 mm diameter) from each tillage block. Following simulated grazing bulk density was measured at the same depths from three cores taken from each plot within 3 weeks of the simulated grazing. On eight occasions during the period of gas sampling, soil mineral N was extracted from sieved, field moist soil samples (4 mm sieve, 0–25 cm depth) taken from each plot using 2 M potassium chloride and analysed for NO_3^- and NH_4^+ using a Rapid Flow Analyser (Astoria-Pacific Inc., Clackamas, Oregon). Soil samples were stored at 4°C until they were analysed (within 2 days of sampling). Volumetric soil moisture content (0–10 cm) was measured hourly in each plot using ECH_2O capacitance probes (Decagon Devices Inc., Pullman, Washington) connected to a datalogger and multiplexers (Campbell Scientific Inc., North Logan, Utah). WFPS (0–7.5 cm) was estimated by the calculation: WFPS=volumetric moisture content/(1−(soil bulk density/soil particle density)). Particle density was calculated to be 1.54 g cm^{-3}, accounting for the density of soil organic matter. In our calculations of WFPS, we used the bulk density for 0–7.5 cm and the volumetric moisture content measured by the capacitance probes between 0–10 cm. Rainfall, air temperature and soil temperature at 5 cm depth (measured in one of the three replicates) were automatically recorded at the site using the datalogger.

Statistical analyses

Bulk density

The effects of tillage, treading, soil moisture content at treading and urine application on bulk density were analysed using split-split plot analysis of variance with tillage as the main factor with depth as the split–split plot factor. Contrasts between the various split plots were included in the analysis of variance.

Mineral N

The treatment effects on soil mineral N (split into NO_3^- and NH_4^+) after simulated grazing were analysed using split-split plot analysis of variance with tillage as the main plot factor and date as the split-split plot. It was necessary to log-transform the data before analysis due to heterogeneous variances. Comparison of means between treatments was made using the least significant ratio (LSR). The LSR is the smallest ratio between two back-transformed means (largest mean/smallest mean) such that the larger mean is significantly greater than the smallest mean. The results presented have been back-transformed.

WFPS

A mixed model fitted using Residual Maximum Likelihood (REML) analysis (Verbyla et al. 1999) tested for the effects of tillage, treading, soil moisture content at treading and urine on N_2O emissions, WFPS and mineral N with time.

N_2O fluxes

The effects of treatments on the cumulative N_2O fluxes were analysed using split-plot analysis of variance with tillage as the main-plot factor. The variance for cumulative N_2O data was homogenous. To investigate the effects of treatments on N_2O emissions with time, a mixed model was fitted using REML. Since, daily flux data from the IT >FC and MT >FC treatments were considerably more variable than from other treatments, some of which had small negative fluxes, the mixed model was modified to estimate separate residual variances for the IT >FC and MT >FC treatments and a common residual variance for the rest. This means that the least significant difference (LSD) for comparing IT >FC or MT >FC with other treatments is larger than the LSD for comparing among other treatments.

For all the statistical analyses a significance level of 5% was used to test for treatment effects. Analyses were performed using the GenStat (version 7) software package.

Results

Rainfall and soil temperature

Data for rainfall and soil temperature are shown in Fig. 1. A total of 248 mm of rain fell during the 3 months following the treading treatment. The highest daily rainfall amount recorded was 29 mm. Over the same period, the daily average soil temperature at 5 cm was 6.8°C, the maximum daily average was 10.6°C and the minimum was 3.1°C. We did not observe appreciable differences in daily average soil temperatures between treatment plots, although the lowest temperature was recorded in the wettest plot and most compacted plot (IT>FC) in early July (winter) soon after the urine had been applied. Soil temperatures tended to increase from early July until the end of the measurements in early spring (Fig. 1).

Tillage and treading effects on bulk density

The initial soil bulk densities measured before cultivation are shown in Table 1. Surface disturbance

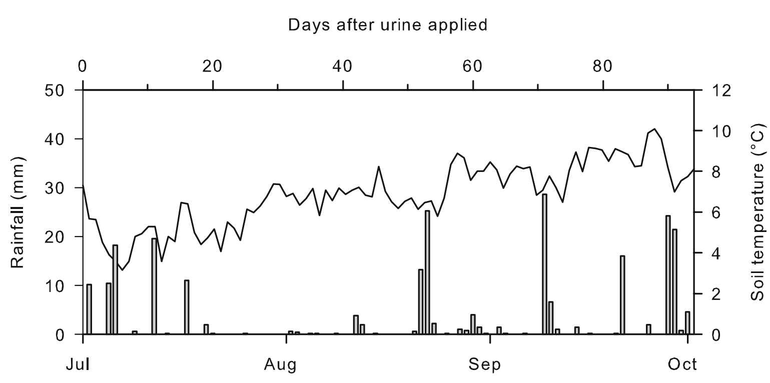

Fig. 1 Rainfall (*bars*) and daily mean temperature (*line*) for the field site

by the seed drill reduced the bulk density in NT to 1.07 g cm^{-3} in the top 0–7.5 cm depth but did not affect the soil below this (Tables 1 and 3, "untrodden plots"). In the MT plots the cultivation by discs to 10 cm reduced the bulk density for the 0–7.5 cm depth by 13% to 1.02 g cm^{-3} and by 7% for the 7.5–15 cm depth, but the cultivation had no effect on the soil below this depth (Tables 1 and 3 "untrodden plots"). Ploughing to 20 cm greatly reduced the bulk densities at both the 7.5–15 and 15–25 cm depths by 15% and 14% respectively, but did not change the bulk density at the 0–7.5 cm depth.

Measurements of soil bulk density at 0–7.5, 7.5–15 and 15–25 cm depths following treading are shown in Table 3 ("trodden plots"). Treading increased bulk density in IT and MT plots in the 0–7.5 cm depth when the soils were wet. The highest bulk densities (1.3 and 1.32 g cm^{-3}) and greatest increase (13 to 15%) were measured in the IT plots in the 0–7.5 cm depth when trodden at both FC and >FC, but there was no effect of treading at <FC. In the MT plots, treading at >FC bulk density (1.12 g cm^{-3}) was increased by 10% in the 0–7.5 cm depth. Differences in bulk density in the 0–7.5 cm depth following treading of the MT plots at FC were not statistically significant. Simulated treading in the NT plots at all moisture contents did not significantly increase bulk density at any of the measured depths.

WFPS

The highest WFPS values (>80%) were recorded in the IT plots trodden at FC and >FC immediately following treading and the application of urine (Fig. 2). Changes in WFPS responded rapidly to rainfall. There were a number of rainfall events in the 20 days following the urine application that maintained high levels of WFPS in all the treatments. Marked changes in WFPS did not occur in any of the plots until about day 40 following the urine application (Fig. 2) and soon after rainfall events increased WFPS to high values. WFPS tended to decline more rapidly towards the end of the experiment as day length and temperatures increased (Fig. 1). Over the study duration, mean WFPS tended to be higher in the IT > NT > MT plots (Fig. 2). The lowest WFPS was measured in the MT plots (<20%) close to the end of the experiment.

Soil mineral N contents

The application of 800 kg N ha^{-1} greatly increased ($P<0.05$) the amount of soil mineral N (0–25 cm) in the plots. There were significant interactions of urine and soil moisture content at the time of treading over time. Tillage did not significantly affect soil mineral N.

Table 3 Soil bulk density (g cm^{-3}) measurements at 0 to 7.5 and 7.5 to 15 cm for untrodden plots and plots trodden at three different moisture contents

	Tillage treatment								
	IT			MT			NT		
Soil depths (cm)	0–7.5	7.5–15	15–25	0–7.5	7.5–15	15–25	0–7.5	7.5–15	15–25
Moisture content at treading									
Trodden									
<FC	1.14[a]	1.11	1.33	1.03	1.31	1.45	1.15	1.31	1.45
FC	1.32	1.15	1.28	1.09	1.29	1.46	1.15	1.29	1.42
>FC	1.30	1.18	1.32	1.12	1.29	1.46	1.15	1.30	1.44
Untrodden									
FC	1.15	1.12	1.25	1.02	1.23	1.46	1.07	1.29	1.42

Measurements were made soon after simulated treading occurred.

[a] For comparisons between different tillage treatments LSD=0.10 (*df*=110). For comparisons of same tillage treatment LSD=0.09 (*df*=127).

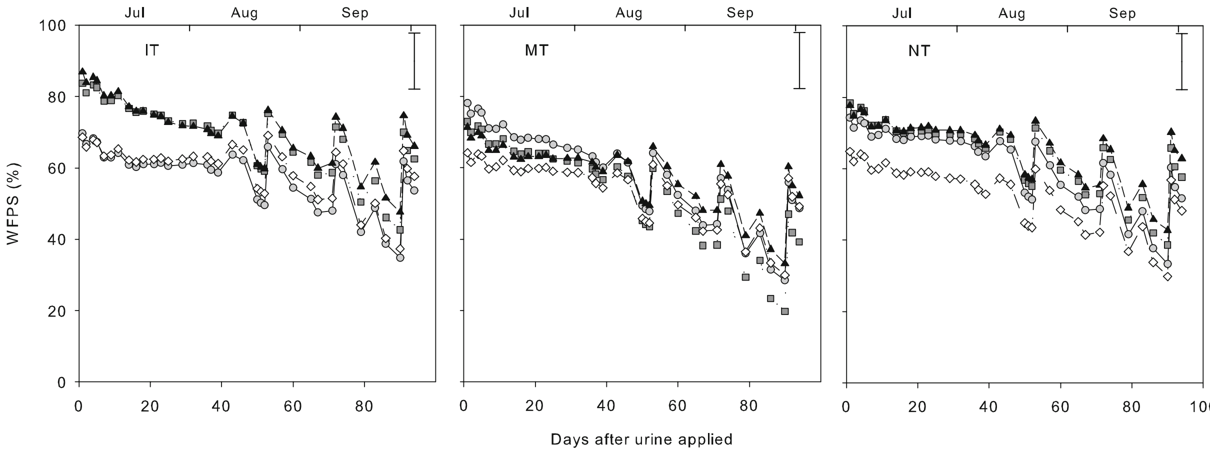

Fig. 2 Mean water-filled pore space (*WFPS*) from plots growing triticale established following **a** intensive tillage (*IT*), **b** minimum tillage (*MT*) and **c** no-tillage (*NT*) following simulated grazing (treading and urine applied) at three different moisture contents: <field capacity (<FC, *filled circles*), field capacity (FC, *filled squares*), >field capacity (>FC, *filled triangles*) and field capacity without treading (*empty diamonds*). *Error bar* is the LSD (n=3)

The application of urine in July (day 0) resulted in a rapid increase in soil mineral N contents in the soil. Changes in ammonium (NH_4^+) and nitrate (NO_3^-) content followed a similar pattern in both trodden and untrodden plots. This pattern is represented in Fig. 3 for plots trodden at FC. Three weeks after urine was applied, the soil mineral N (0–25 cm) ranged from 440 kg N ha^{-1} in the IT plots trodden at >FC to

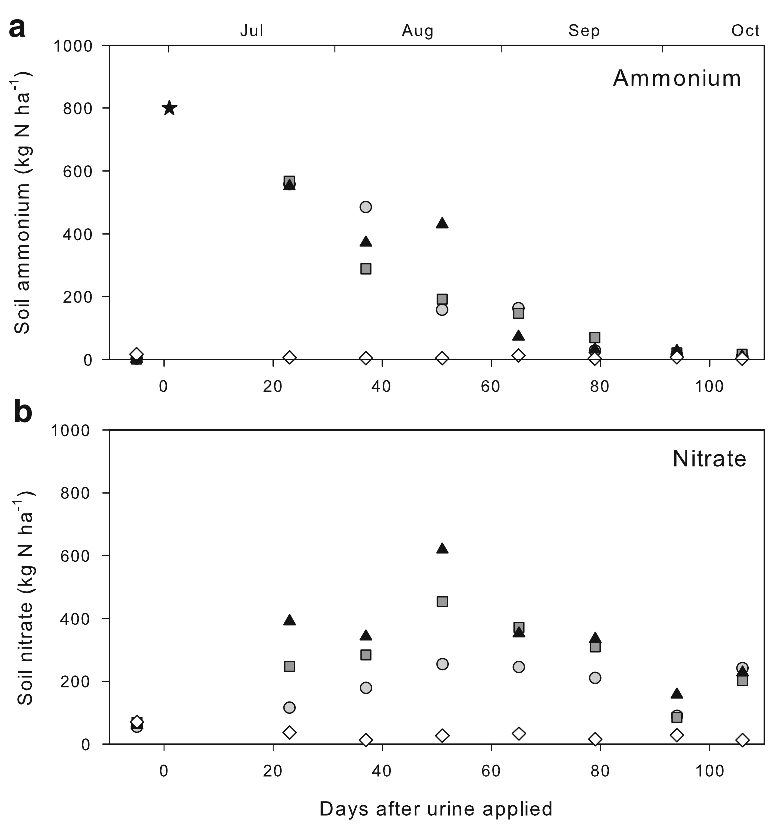

Fig. 3 Mean soil **a** NH_4^+ and soil **b** NO_3^- (0–25 cm) before and after simulated grazing (treading + urine) at field capacity for *IT* (*filled circles*), *MT* (*filled squares*) and *NT* (*filled triangles*), and for ungrazed (no treading, no urine) for *NT* (*empty diamonds*) plots (n=3). Data have been log back-transformed. Urine was applied at a rate of 800 kg N ha^{-1} (*stars*). For treatment comparisons the LSR's for NH_4^+ and NO_3^- data are 1,260% and 188%, respectively

923 kg N ha^{-1} in the IT plots trodden at <FC. Mineral N contents decreased steadily during the remaining 10 weeks of the trial (Fig. 3). Maximum NH_4^+ concentrations will have occurred soon after urine application following rapid urea hydrolysis. A large proportion of this NH_4^+ had been nitrified to NO_3^- by the time of the first sampling 22 days after urine application (Fig. 3). The NO_3^- contents had peaked by about 50 days after urine was applied. After about 65 days after the urine had been applied, the amounts of NH_4^+ were no longer significantly greater than plots that had no urine applied (Fig. 3).

Throughout the trial, soil mineral N contents at 0–25 cm depth remained above 50 kg N ha^{-1} in all plots that had urine added. At the end of the study mineral N contents at 0–25 cm depth ranged between 91 and 227 kg N ha^{-1} in the urine-amended plots. By this stage, most or, in some plots, all of the mineral N remaining in the soil was in the form of NO_3^-.

The average mineral N contents in the plots that had no urine added (with and without treading), decreased steadily from a range of 39–52 kg N ha^{-1} in the IT plots and 50–75 kg N ha^{-1} in the NT plots, to less than 16–28 kg N ha^{-1} in all plots by the end of the study (data not shown). Throughout this period most of the mineral N in the non-urine plots was in the form of NO_3^-.

Tillage, treading and urine effects on nitrous oxide emissions

Cumulative N_2O emissions over the study period were affected by treading, the moisture content at treading and urine ($P<0.001$). Greatest emissions occurred from the plots that had been trodden when the soil had been wet (i.e. at FC and >FC) and had urine applied (Table 4). The tillage method alone did not significantly affect N_2O emissions ($P=0.559$), but there were strong interactions between treading, the moisture content at treading and urine and the tillage practice on N_2O emissions. Cumulative N_2O emissions from the IT and MT plots trodden at >FC were 14 and 8 times greater, respectively, than the plots that were trodden at <FC. For all tillage treatments treading when the soil was at FC without urine added had little or no effect on N_2O emissions, which remained low.

Table 4 Cumulative N_2O emissions for a 90 day period following grazing of intensive, minimum or no tillage triticale plots

Split plot treatments		Main plot		
Moisture content	Urine added	Cumulative N_2O emission (kg N/ha) over 90 days		
		IT	MT	NT
Trodden				
<FC[a]	Yes	1.02[b]	1.59	1.74
FC	Yes	5.13	2.98	2.60
>FC	Yes	14.41	12.66	3.98
FC	No	−0.21	0.43	0.14
Not trodden				
FC	Yes	2.05	1.39	1.84
FC	No	−0.21	−0.10	0.17

Data are means of three replicates.

[a] FC (field capacity)= 35% *v*/*v*; <FC=27%; >FC=40%

[b] For comparisons between different tillage treatments LSD ($P<0.05$)=1.30, except for comparisons with IT>FC (LSD=5.32) or MT>FC (LSD=6.60). For IT>FC compared to MT>FC the LSD=8.38. For comparisons within tillage treatments, LSD ($P<0.05$)=1.1, except for comparisons with IT>FC (LSD=5.28) or MT>FC (LSD=6.57)

Looking at patterns over time (Figs. 4 and 5), the highest N_2O fluxes were measured from the IT and MT plots that were trodden at >FC and received urine. These emission peaks were measured in August following 27 mm of rainfall 3 to 4 days earlier (days 53 and 54), when the soil moisture content and WFPS had been close to maximum values (Fig. 2). Relatively high N_2O fluxes were observed within 1–2 days of the urine application across many of the plots (Fig. 4). In the most disturbed and compacted plots (IT >FC) the N_2O fluxes remained low for about 30 days followed by higher fluxes, despite high WFPS and high mineral N contents (Figs. 2 and 3). In the compacted MT plots (>FC) and the IT plots trodden at FC the pattern was not as pronounced with small peaks occurring within the first 20 days of the urine application, followed by higher emissions (Fig. 4). Typically N_2O emissions peaks for all treatments occurred when WFPS was high, although high WFPS did not necessarily result in high N_2O emissions, and the magnitude of N_2O peaks varied greatly. In the NT plots the highest emissions in the

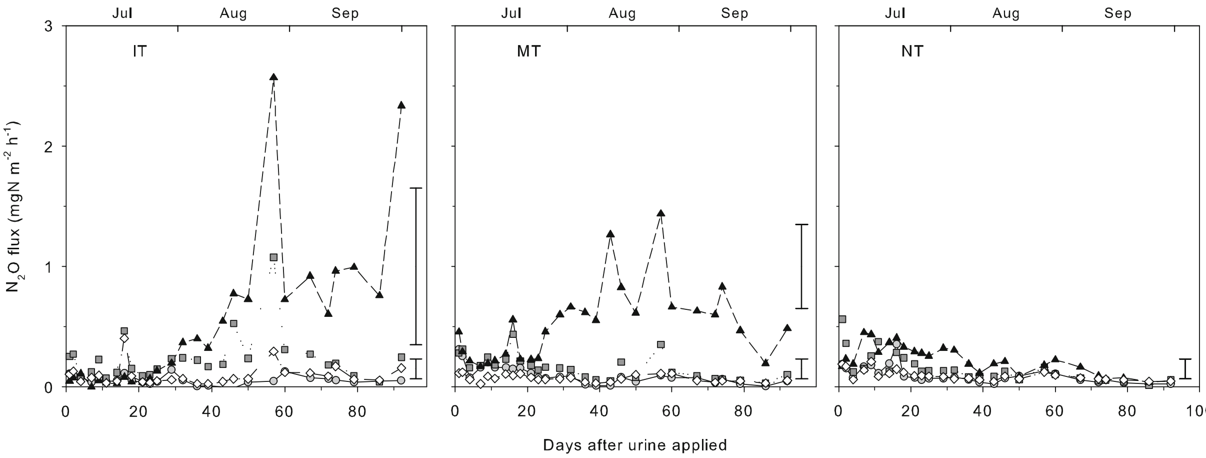

Fig. 4 Mean daily N_2O flux from plots growing triticale established following **a** intensive tillage (*IT*), **b** minimum tillage (*MT*) and **c** no-tillage (*NT*) following simulated grazing (treading and urine applied) at three different moisture contents: <field capacity (*<FC*, *filled circles*), field capacity (*FC*, *filled squares*) and >field capacity (>FC, *filled triangles*) and field capacity without treading (*empty diamonds*). *Error bar* is 2× SED (*n*=3). Where there are *two error bars*, the *wider upper bar* is for comparing >FC with other treatments, and the *lower bar* is for comparisons between other treatments

FC and >FC plots that were trodden occurred soon after the urine application (within the first 20 days) and then tended to decline to very low levels at the end of the study.

An increase in N_2O fluxes in many of urine-amended plots was observed in September (spring) at the end of the trial, when WFPS had increased following rainfall. The increase was greatest in the plots that had been trodden at FC and >FC. Urine greatly increased N_2O emissions. Cumulative N_2O emissions were very low from plots that had no urine applied (Fig. 5 and Table 4).

Discussion

Tillage effects on initial soil properties

The tillage treatments we used provided a range of cultivation intensities and levels of soil disturbance. They also represent cultivation practices currently used to establish forage crops in New Zealand. The IT treatment (ploughing, maxi-till and harrow and rolling) extensively modified the topsoil, resulting in bulk density values in the 0–7.5 and 7.5–15 cm layers that were initially less than those in the MT plots and the

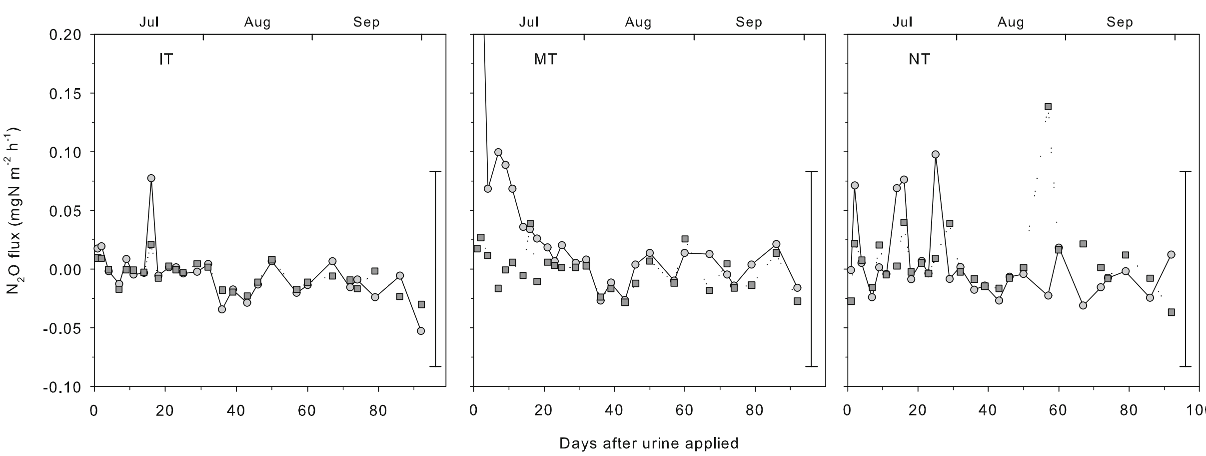

Fig. 5 Mean N_2O flux from plots growing triticale established following **a** intensive tillage (*IT*), **b** minimum tillage (*MT*) and **c** no-tillage (*NT*) from plots trodden at field capacity (*filled circles*) and untrodden plots (*filled squares*). These plots received no application of urine. *Error bar* is 2×SED (*n*=3)

NT plots. When bulk density changes the total pore volume must change too; hence a reduction of soil bulk density results in an increase in total soil porosity. In the IT plots, ploughing inverted the top 20 cm of the soil, affecting the soil to twice the depth of the minimum till plots that were cultivated to 10 cm depth using discs.

Typically, a long-term pasture soil will have high macroaggregate stability due to the high amounts of organic matter, microbial biomass and fungal hyphae (Tisdall 1994) and this provides a relatively high soil bearing capacity. Intensive and minimum tillage will have resulted in changes to soil physical properties including the physical fragmentation of soil aggregates, soil compression and sheering, resulting in loose, structurally unstable aggregates that are susceptible to collapse and reduced soil structural strength (Or and Ghezzehei 2002). Soil inversion by ploughing will have brought poorly aggregated subsoil to the surface. Furthermore, cultivation may stimulate the release of organic matter that binds micro-aggregates together to form macro-aggregates, resulting in an increased proportion of micro--aggregates in the soil (Six et al. 2000).

Effects of treading on soil properties

We found that simulated animal treading caused the greatest compaction and reduction in total porosity in the plots that had the most intensive and deepest cultivation when the soil was at or above field capacity (bulk density increased by 13% to 15%). Compaction was only observed in the minimum tillage plots when soil was trodden when very wet, above field capacity (bulk density increased by 10%), whereas, there was no change in soil bulk density following treading in the uncultivated NT plots. It is not surprising that greatest compaction occurred in the wettest plots. Soil moisture is the most important factor influencing soil compaction processes; increasing soil moisture reduces the internal soil strength (Hamza and Anderson 2005), and the ability of the soil to resist the pressure exerted by animal hooves. Tillage will have increased the risk of compaction by reducing soil strength and aggregate stability. Therefore the IT plots were most likely to compact. Whereas compaction from grazing is least likely when soils are below FC, but this would not have been achievable for long periods of the trial. Indeed, for many regions of New Zealand, soils are likely to be at or above field capacity for several months each year. In this study, the soil moisture contents were equal or greater than field capacity for about 40 days after the simulated grazing event.

Treading of wet soils by animals can result in plastic deformation, or plastic flow around the hoof, this is known as poaching. This can result in compaction deeper in the soil than after grazing when the soil is below the plastic limit (Drewry and Paton 2005a; Scholefield et al. 1985). There was some visual evidence of this on the soil surface in the IT>FC plots, and small (not significant) increase in bulk density at the 7.5–15 cm depth.

The amount of soil damage due to treading also depends on the hoof pressure of the animal. The cow hoof that we used delivered a hoof pressure of about 220 kPa (Di et al. 2001). However, in reality hoof pressures vary and will depend on factors including the type and size of the animal, and whether the animal is moving or stationary. The pressure also differs between front and hind legs. Cattle hoof pressures of up to 300 to 400 kPa have been reported for walking cows (Scholefield et al. 1985), whereas sheep hooves exert a pressure of about 50–125 kPa (Bhandral et al. 2007). Moreover, the effects of treading can vary across small distances. Drewry and Paton (2005b) found that physical conditions varied between hoof prints and the “hump” areas next to hoof prints. They found that bulk density, macroporosity and air permeability were reduced in the hoof print areas.

Effects of compaction from treading on N_2O emissions

Although there are no other published studies of the effects of compaction from grazing of winter forages, the two- to seven-fold increases in N_2O emissions from plots following treading and urine application are similar to a number of studies where compaction has been observed. Some of the cumulative N_2O emissions we have estimated over the relatively short measurement period of 90 days are very high (14.4 and 12.7 kg N_2O–N ha^{-1} for the IT and MT plots trodden at >FC). In a New Zealand study by Bhandral et al. (2007), cumulative N_2O emissions from a pasture measured over a similar period (about 90 days) during spring and early summer following urine application were three times greater from a sandy loam soil that was compacted by tractor wheels (9.17 kg N ha^{-1}) than from uncompacted pasture (2.94 kg N ha^{-1}). The tractor traffic (630 kPa pressure) increased soil bulk density by 11%. The N_2O–N lost in the compacted treatment was 1.5% of the urine applied and 0.5% in the uncompacted treatment. Two studies in the Netherlands measured similar ranges of increases of N_2O emissions following compaction. In a laboratory incubation study (103 days at 16°C), compaction of a sandy soil (bulk density increased from 1.07 to 1.22 g cm^{-3}) and the application of urine increased N_2O emissions six-fold, from 0.9% to 4.9% of the applied urine (van Groenigen et al. 2005a). Under field conditions and the same soil type, N_2O emissions increased an average of 2.2-fold (ranging from 1.3 to 2.9-fold) following simulated treading and urine applications in summer and autumn; treading was simulated using a large wooden hammer that increased bulk density by about 4% (from 1.54 to 1.60 g cm^{-3}) (van Groenigen et al. 2005b).

This range of N_2O increase following treading is supported by emissions following compaction in non-grazed fertilised grassland systems, where compaction by tractor wheel traffic increased N_2O emissions two-fold (Douglas and Crawford 1993; McTaggart et al. 1997). Ball et al. (1999a) found that reduced soil gas diffusivity and air-filled porosities increased N_2O emissions following heavy tractor compaction. Increased emissions have also been measured from compaction in arable crops including cereals (Ball et al. 1999b) and row crops (Ruser et al. 2006; Ruser et al. 1998), and Menneer et al. (2005a) showed that denitrification was stimulated by three to six times following moderate and severe treading of a New Zealand pasture soil.

In our study, tillage without the effect of compaction or urine did not have a significant effect on N_2O emissions. This is a similar finding to the short-term investigation of the effects of tillage and compaction on greenhouse gas emissions by Yamulki and Jarvis (2002), who showed that compaction increased N_2O emissions by 3.5-fold, whereas tillage did not significantly affect N_2O emissions. This differs from a number of studies in which greater N_2O emissions have been reported for no-till than tilled soils (Ball et al. 1999b; Vinten et al. 2002). Under no-tillage systems, diffusion of air into and out of the soil is often reduced and soil water contents tend to be greater. In Scotland, N_2O emissions from cereals established without tillage on an ex-grass clover pasture had greater emissions than from ploughed soils (Ball et al. 1999b; Skiba and Ball 2002). The researchers concluded that ploughing had improved the aeration of the soil. Measured air-filled porosities and gas diffusivities were lower in the no-till plots than the ploughed plots, and soil moisture contents and WFPS were greater in the no-till plots (Ball et al. 1999b). In our study, N_2O measurements were made over the winter period when soil moisture contents tended to be high in all tillage treatments. The effects of no tillage on emissions may have been greater in autumn and spring periods when changes in soil water content are greater and plant oxygen consumption greater.

Seasonal changes in daily N_2O emissions following simulated grazing

Applying synthetic urine had a large positive effect on N_2O emissions that was enhanced by compaction. There were no differences in N_2O emissions between trodden and untrodden plots that had no urine applied, which is consistent with the findings of van Groenigen et al. (2005a). It appears that these plots were limited by low soil mineral N contents. On a number of sampling occasions N_2O appears to have been consumed (mainly in IT and MT plots; Fig. 5) and based on our measurements we have estimated that over this period that there was net N_2O consumption (Table 4). This has been observed in several studies and mainly on unfertilised grasslands occurring when soil temperatures were below 10°C and when WFPS were high, although it was also observed during summer months (Flechard et al. 2007; 2005). Why this happens is poorly understood, although it is assumed that it is through biological denitrification of N_2O to N_2. It is probable that the consumption occurs very close to the soil surface, possibly at microsites that are anaerobic where oxygen diffusion occurs at a lower rate than consumption by respiration (Neftel et al. 2007).

The pattern of N_2O production was affected by the severity of compaction. Initially N_2O productions was very low in the plots where the greatest compaction occurred when the soil moisture contents was high. A delay in N_2O production followed by higher N_2O fluxes has been observed in a few other studies (e.g.

Bhandral et al. 2007; van Groenigen et al. 2005a). N_2O emissions during this initial period are likely to have been inhibited by highly anaerobic conditions. Following compaction and poaching a large proportion of the soil pores will have been saturated due to the reductions in the overall pore volume and hydraulic conductivity. Rainfall and WFPS data indicate that the soil remained in a saturated condition for a number of days following the treading and urine addition. The small air volume in the soil pores will have had low oxygen contents while gas diffusivity will have been reduced.

These highly anaerobic conditions will have been conducive to denitrification, while a lack of oxygen will have inhibited nitrification. In urine patches, nitrification is usually inhibited for at least a week because of the high concentration of NH_4^+, increased pH and the high salt concentration (Williams et al. 1998). Our soil measurements indicate that there was a reasonable supply of NO_3^-. Hence, early N_2O emissions are most likely to be from the denitrification of the NO_3^- in the soil before urine was applied. Although, the initial N_2O emissions from the highly compacted plots were low, it is probable that mainly soil-derived NO_3^- was being denitrified but mainly to N_2, i.e. a high N_2 to N_2O ratio. Denitrification of N_2O to N_2 may be enhanced where soil compaction reduces the soil gas diffusivity increasing the residence time of N_2O in the soil pores (Yamulki and Jarvis 2002). Based on Denitrification Enzyme Assays, Simek et al. (2006) found that the greatest N_2 to N_2O ratios were measured from severely trodden areas. They suggest that the severity of treading provided more conducive conditions for denitrification, while high excretal inputs increased soil pH which could increase the N_2 to N_2O ratio. In a laboratory incubation study, van Groenigen et al. (2005a) found that N_2O emissions were low for 10–15 days after urine was applied to compacted soils followed by strong peaks. N_2O production was further delayed when dung was applied with the urine.

In this study, WFPS and mineral N contents were positively related to N_2O emissions. Müller and Sherlock (2004) estimated that about 75% of N_2O emissions from temperate pasture in New Zealand and Germany occurred when WFPS was greater than 60%. They calculated that approximately 70% of the emissions from synthetic urine patches were due to denitrification associated with WFPS of about 80%. We observed the largest N_2O emissions when the soil was wet (at WFPS of 60% to 80%). However, high WFPS was not always associated with high N_2O emissions, and the patterns of emissions varied across treatments in this relatively short-term study, as has been found in some other studies where soils have been compacted (Ball et al. 1999b; Yamulki and Jarvis 2002). We found that there was large variability in the calculated values of WFPS within the treatments (Fig. 2) and that relatively high N_2O emissions occurred from individual plots over a wide range of our measured WFPS from 50% to 90% (data not shown). In situations were soils are damaged by treading, WFPS may not be a good indicator of N_2O emissions since it does not take account of changes in soil diffusivity that result from physical changes to the soil that are not directly associated with changes in the total porosity of the soil. Furthermore, the depth used for calculating WFPS may not reflect the sites in the soil that are involved in N_2O production. In our study we estimated WFPS from the average soil moisture content over a depth of 10 cm. Van Groeningen et al (2005a) concluded from their incubation study that anaeorobicity caused by compaction and urine volume and carbon availability (from dung and urine compounds) rather than the amount of N was more important in controlling N_2O emissions. This was largely supported by field experiments designed to confirm the laboratory findings, although they found that in field conditions urine volume did not affect N_2O emissions (van Groeningen et al 2005b).

Given that emissions of N_2O were still high in some of the plots that contained reasonably high soil mineral N contents at the end of our study period (Fig. 4), it is reasonable to expect that N_2O emissions from the urine would have continued beyond the 90 day study period. The amount of these N_2O emissions would be largely influenced by WFPS or aeration (affected by rainfall), the continued availability of soil mineral N and rising soil temperatures (Dobbie and Smith 2003). We would expect the soil mineral N levels and WFPS to decline as the rate of uptake of N and water by the plants increased over the spring period. Even so it can take a long time before N_2O emission rates reduce to background levels. De

Klein et al. (2003) found that it took 18 months for N_2O emissions from a urine patch to return to background levels; their study site was located close to ours.

By the end of the measurement period, the cumulative amount of N_2O emitted from the MT and IT plots trodden when wet was 1.6 to 1.8% of the amount of urine applied, whereas the N_2O emissions from urine patches that were not trodden was only about 0.2% of the urine applied. Our use of synthetic urine may have also led to higher N_2O emissions than if we had used real urine (de Klein et al. 2003; van Groenigen et al. 2005a). These values are below the default Intergovernmental Panel on Climate Change (IPCC) emission factor of 2% of the N excreted ($EF_{3PR\&P}$ IPCC 1997). New Zealand has a country-specific value of 1% (New Zealand Climate Change Office 2003).

Although large increases in N_2O emissions may occur from urine patches following compaction as we found in this study and others have found from compaction of dung and urine patches (Bhandral et al. 2007; van Groenigen et al. 2005a; van Groenigen et al. 2005b), the combined effects of compaction and excreta are not currently addressed in IPCC guidelines. Furthermore, the effect of the overlap of urine and dung patches that are extremely heterogeneous from single and repeated grazings has had limited attention (Hutchings et al. 2007; van Groenigen et al. 2005b). Simulated N_2O emissions from spatially heterogenous, overlapped excretal patches from repeated grazings were lower than if patches were distributed homogenously across the field (Hutchings et al. 2007). The effect of compaction was not included in the simulations.

Winter forage cereal crops are typically intensively grazed by cattle and sheep in New Zealand either with large animal mobs or grazed in strips. They are grazed at heights and dry matter contents much greater than pasture. Field observations of soil compaction, reductions in total porosity and air permeability have been measured following grazing of winter forage brassica crops (Drewry and Paton 2005b). The triticale cultivar (Doubletake) we used in our study is recommended to be grazed more than once and then left for cut silage. The intensive nature of the grazing is likely to result in treading and excreta covering large proportions of the area in a short period of time when soil water contents during winter are likely to be high. Consequently there is a significant risk of soil compaction and poaching of areas where excreta has been deposited.

Conclusions

The risk of soil damage from grazing forage crops in winter is high especially when intensive cultivation practices have been used to establish forage crops. During winter, soils can remain wet for long periods and under these conditions grazing of forage crops is likely to result in soil damage by animal treading causing compaction and changes to soil porosity, soil gas diffusion and soil moisture conditions that are likely to enhance N_2O emissions from grazed crops, notably under urine patches. The findings from this study supported our hypothesis that the use of no-tillage practices to establish winter forage crops out of pasture reduces soil compaction by grazing. This results in lower emissions of N_2O from urine patches compared with forage crops established with conventional and minimum tillage systems where livestock treading occurs. Hence where winter forages are grazed, establishment by direct drilling is likely to be an important option for mitigating N_2O emissions. Restricting grazing when soils are wet will reduce the risk of increasing N_2O emissions.

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