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

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Abstract

Grazing of short-term forage crops grown for high quality feed over winter can cause extensive compaction and pugging of soils. This may lead to reduced re-growth of crops and to enhanced N_2O emissions. Modification of management practices may reduce these negative effects, for example decreasing the intensity of tillage used in the establishment of forage crops and restricting grazing when soils are wet.

We designed a replicated field trial to investigate the effects of simulated cattle grazing at three soil moisture contents (< field capacity, field capacity and > field capacity) on N_2O emissions from an autumn sown (March) winter forage crop (triticale) established by three tillage practices: (a) intensive, IT, (b) minimum, MT, or (c) no tillage, NT.

Treading wet soil greatly increased (up to 8 times) the amount of N_2O emitted. The highest cumulative N_2O emissions after 90 days were from IT (14.9 kg N/ha) and MT (12.7 kg N/ha) urine-applied plots treaded at > field capacity. Treading at < field capacity did not affect N_2O emissions (1.5 to 2.4 kg N/ha) where urine was applied. Where urine was not applied, N_2O emissions were negligible (< 0.5 kg N/ha). Soil compaction reduced dry matter production (June to October) by up to 50 % in IT and MT plots treaded at > field capacity. Dry matter production in the NT plots was unaffected by treading.

Key Words

Nitrous oxide, tillage, compaction, urine, forage

Introduction

The grazing of winter forage crops by dairy cows on wet soil can result in soil compaction that may limit crop re-growth. Compaction influences a range of soil physical properties, such as bulk density, soil porosity, and water holding capacity, that are important to maintaining plant growth and environmental quality (Lipiec and Hatano 2003). The effects of pastoral grazing on soil physical condition and pasture performance have received some research attention (Drewry *et al.* 2001; Singleton and Addison 1999). However, the effects of grazing winter forage crops on subsequent dry matter (DM) production are not well understood.

In pastoral systems, grazing by livestock can result in the production of large amounts of nitrous oxide (N_2O), a potent greenhouse gas, because the high nitrogen concentrations in livestock urine stimulate rapid denitrification, especially when soil moisture contents are high (de Klein and van Logtestijn 1994; Oenema *et al.* 1997). Water filled porosity has been identified as a key indicator of N_2O emissions since moisture content will affect diffusion of oxygen through the soil matrix (Linn and Doran 1984). In general, high N_2O emissions from denitrification can occur in a wide range of intensive agricultural systems when water-filled pore space (WFPS) exceeds 60 % (Dobbie and Smith 2003).

The effects of soil compaction on N_2O emissions have been reported for some intensive agricultural systems (Ball *et al.* 1999b; Hansen *et al.* 1993; Ruser *et al.* 1998), and the effects of compaction from stock treading on N_2O emissions suggest that compaction by stock treading could double emissions from pasture (Oenema *et al.* 1997). In New Zealand, soil compaction caused a threefold increase in N_2O emissions from a urine amended dairy pasture (Bhandral *et al.* 2003).

One of the key differences between winter grazing of pasture and forage crops is the use of tillage to establish the latter. Tillage can significantly alter soil structure and thereby increase susceptibility to compaction, especially when soils are wet. While a number of studies have investigated the effects of tillage on soil N_2O emissions, there is a need for information on how the interaction of tillage practices

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and compaction affects N_2O emissions (Yamulki and Jarvis 2002). Some studies have reported higher N_2O emissions from no-tillage than 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 conducted a field trial to test the hypothesis that the use of no-tillage practices to establish forage crops out of pasture will reduce soil compaction, lower emissions of N_2O and increase dry matter production following grazing as compared to conventional and minimum tillage systems.

Materials and methods

The field trial was conducted from March to October 2003 at Lincoln, Canterbury. The soil at the site was a Wakanui silt loam classified as a mottled immature pallic soil (Hewitt 1993). A grass/clover pasture (>15 years old) was sprayed with glyphosate prior to sowing (3 March) a multi-grazing triticale crop (cv. Doubletake). The seedbed was prepared with either (a) intensive (IT: plough to 20 cm depth, maxi-till, roll and harrow), (b) minimum (MT: disc to 10 cm depth, roll and harrow) or (c) no-tillage (NT) practices. These main plots were 9 x 9 m in size, replicated three times. Production of DM was estimated from sub-samples cut from each plots in June, after which the site was mowed to 10 cm height. Six split-plots (3 m x 1 m) were then established within each main tillage plot to determine the effects of soil moisture during grazing, animal treading and urine on soil compaction, N_2O emissions and plant performance (Table 1). A buffer strip of at least 1 m surrounded each split plot.

Table 1: 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	Yes	No
5	FC	No	Yes
6	FC	No	No

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

Simulated grazing

Soil moisture contents for subplots at or above FC (Table 1) were adjusted by applying spray irrigation immediately before grazing. Soil moisture contents <FC (Split plot Treatment 1, Table 1) were achieved by covering subplots with cloche frames during rainfall events from mid-May until simulated grazing. A single grazing event was simulated in June 2003. Treading was 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 treaded 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 treaded. In addition to treading, synthetic urine (Clough *et al.* 1998) was uniformly applied by hand at a rate of 800 kg N/ha. Dry matter production following grazing was calculated by the difference in triticale DM remaining at the time of simulated grazing and DM estimates from sub-samples cut from each subplot at the end of the study.

N_2O measurements

N_2O fluxes were determined using a closed chamber technique (Hutchinson and Mosier 1981). Chambers (10 cm depth) were made from 25 cm diameter PVC pipe with welded lids. 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 water-filled channel at the top of each base produced a gas tight seal with the chamber during measurements. Within each subplot, N_2O concentrations were measured in the chamber headspace at three time intervals (0, 20 and 40 minutes) after chamber closure. Chamber heights were extended during the trial to accommodate the growing triticale. Gas samples were analysed using a gas chromatograph (GC-17A, Shimadzu Corporation, Kyoto) fitted with a ^{63}Ni-Electron capture detector. Measurements were made on 27 occasions over 92 days.

Soil measurements

Soil bulk density was measured at a depth of 0-7.5 cm within 3 weeks of the simulated grazing. On eight occasions during the period of gas sampling, soil mineral N was extracted from soil samples (0-25 cm depth) using 2*M* potassium chloride and analysed using a Rapid Flow Analyser (Astoria-Pacific Inc., Clackamas, Oregon). 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: WFPS = volumetric moisture content/(1-(soil bulk density/soil particle density)). We have assumed that the volumetric moisture content at 0-7.5 cm was similar to that measured by the capacitance probes between 0-10cm. Rainfall, air temperature and soil temperature were also measured at the site.

Statistical analyses

The effects of tillage, treading, soil moisture content at treading and urine on dry matter production following grazing were analysed using split-plot analysis of variance. Contrasts between the various split plots were included in the analysis of variance. Treatment effects on bulk density were analysed using split-split plot analysis of variance. A mixed model fitted using REML (Residual Maximum Likelihood) analysis tested for the effects of tillage, treading, soil moisture content at treading and urine on N_2O emissions, WFPS and mineral N with time. The N_2O flux and mineral N data required log transformation to make the variance more homogeneous; the results presented have been back transformed. Comparison of the N_2O flux and mineral N means between tillage treatments is 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. 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 and discussion

Bulk density

Prior to treading in June, soil bulk density and WFPS were similar at 0-7.5 cm depth (range 1.1–1.2 g/cm^3) for all three tillage systems. At 7.5–25 cm depth, however, bulk density and WFPS were lower under IT than MT or NT (data not shown). Treading at field capacity increased surface soil bulk density (0 to 7.5 cm) in all tillage treatments, the greatest increase occurring under IT (Figure 1). Treading at moisture contents above field capacity (>FC) greatly increased the bulk density and WFPS of surface (0-7.5 cm) soil from IT plots (Figure 1). There was less compaction of surface soil when treading occurred below field capacity (<FC), and bulk density values were similar to the plots that had no treading.

Soil mineral N levels and N_2O emissions

Throughout the trial, soil mineral N contents at 0-25 cm depth remained above 50 kg N/ha in all plots (Figure 2). The application of urine in June resulted in a rapid increase in soil mineral N contents to 400 kg N/ha, which then decreased steadily during the remaining 10 weeks of the trial. There were significant effects ($P < 0.05$) of tillage, moisture content at treading, urine and treading treatments on mineral N (0-25 cm). Mineral N significantly changed over time and there were additional significant interactions between the moisture content at treading and time, and urine and time.

There were significant effects of treading, moisture content at treading and urine ($P < 0.001$) and tillage method on N_2O emissions ($P < 0.05$). Overall, the greatest cumulative N_2O emission was from the IT soil and lowest from the NT soil (Table 2). The highest hourly fluxes of N_2O were associated with high soil moisture and WFPS (Figure 2), following rainfall events, suggesting that the N_2O emissions are largely due to denitrification, as reported in other studies (de Klein and van Logtestijn 1996; Linn and Doran 1984). The highest mean N_2O fluxes and greatest cumulative N_2O emissions were from intensively tilled plots, compacted at moisture contents >FC (Figure 2 and Table 2). The highest mean N_2O fluxes from the IT and MT plots, treaded at >FC with urine applied, were higher than those measured from pasture plots on a moderately drained silt loam in Canterbury (0.7 mg $N/m^2/h$) that had not been treaded, but had urine applied at a rate of 655 kg N/ha (de Klein *et al.* 2003). While, the fluxes from our study are lower than those measured from pasture on a poorly drained silt loam in Otago, (4.9 mg $N/m^2/h$) that had urine applied (592 kg N/ha), but had not been treaded (de Klein *et al.* 2003).

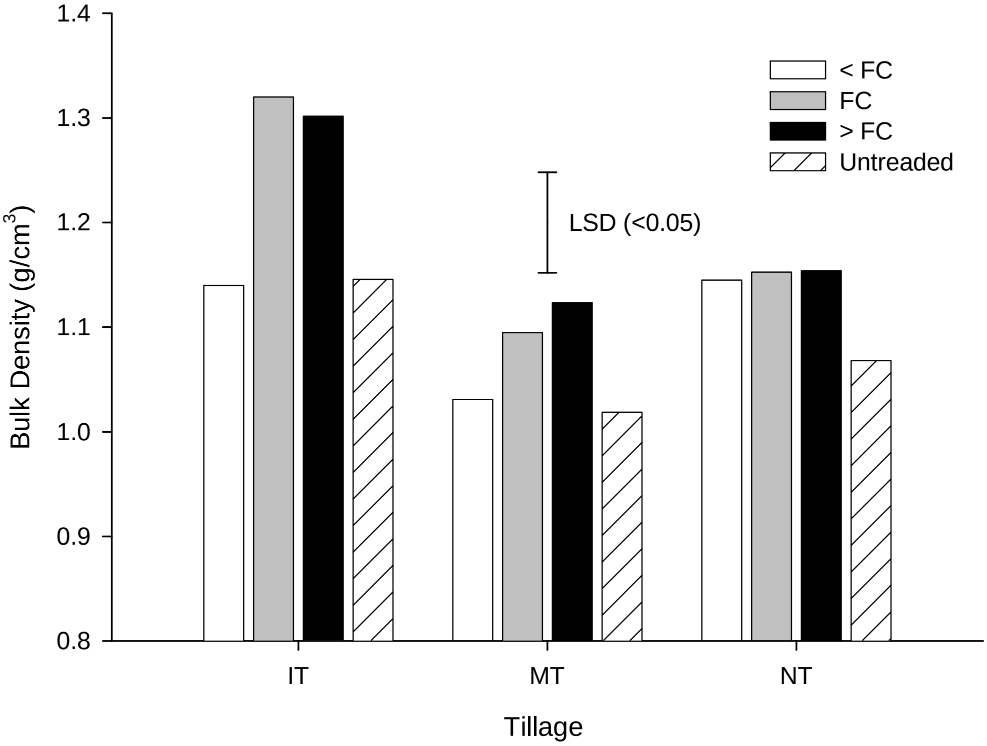

Figure 1. Surface soil bulk density (0-7.5cm) of treaded plots at three moisture contents (< FC, FC and >FC) and untreaded plots at FC (hatched bar) following IT, MT and NT. Data are means of three replicates. The error bar represents the LSD (P < 0.05) for comparisons of the tillage and moisture treatments that were treaded.

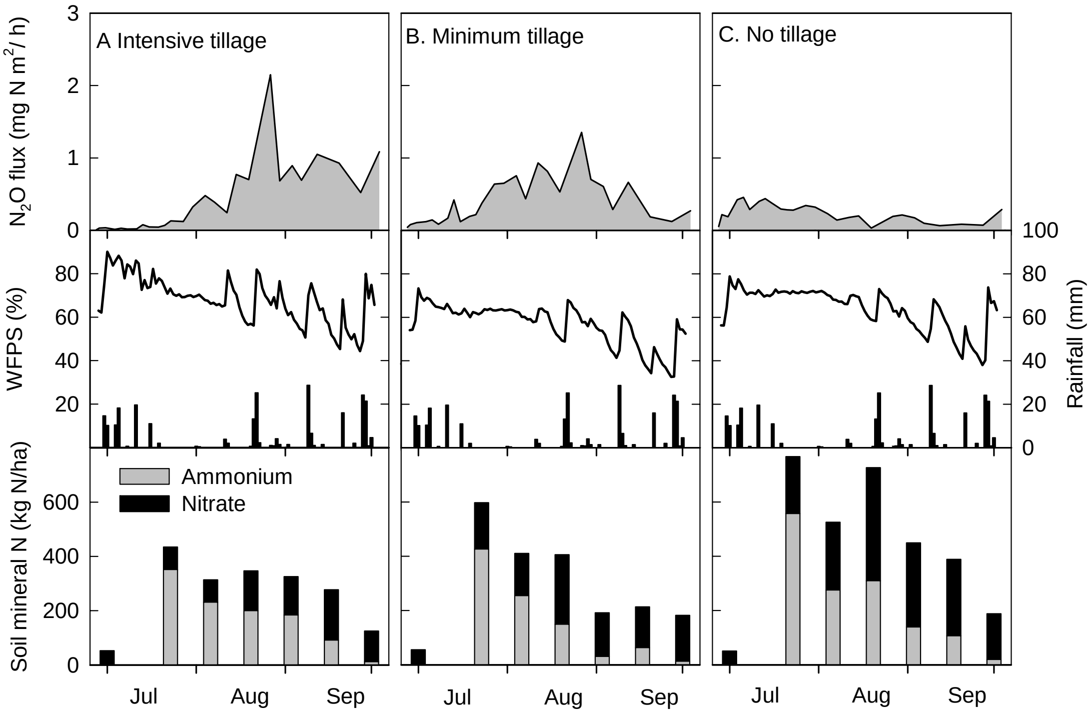

Figure 2. Mean N_2O flux, WFPS (0-7.5 cm) and rainfall, and mineral N (0-25 cm depth) after being compacted when soil was above field capacity and urine had been applied to plots (n = 3) growing triticale following three tillage methods. N_2O and mineral N data are back-transformed from log-transformed data. For comparisons of N_2O flux between different tillage treatments the LSR (P < 0.05) = 2.26. For comparison of mineral N between different tillage treatments the LSR (P < 0.05) = 1.9.

N_2O emissions from compacted soils were up to eight times greater than those of untreaded soil (Table 2). Increased N_2O production due to soil compaction has been observed in several pastoral land-use and other intensive agricultural systems (e.g. Ball *et al.* 1999b; Ruser *et al.* 1998; Yamulki and Jarvis 2002). Bhandral et al. (2003) measured a three-fold increase in cumulative N_2O emissions between tractor-compacted (9.2 kg N/ha) and uncompacted (2.9 kg N/ha) urine amended pasture plots on a Manawatu fine sandy loam soil. In contrast to a number of other studies, we found no significant difference in N_2O emissions between the NT and IT plots that had not been compacted (Table 2). These N_2O emissions were small compared to those from plots that had been compacted when the soil was at or above FC (Table 2).

WFPS and mineral N contents were not good predictors of the amount of N_2O emitted as has been shown elsewhere (Ball *et al.* 1999b; Yamulki and Jarvis 2002). From their study of short-term effects of tillage and compaction, Yamulki and Jarvis (2002) suggested that other factors affecting the production, transport and residence time of N_2O were responsible for differences in N_2O emissions. The key soil properties affected by compaction that may influence the production and transport of N_2O and rate of oxygen diffusion through the soil matrix include macroporosity, soil pore tortuosity and water holding capacity (Ball *et al.* 1999a).

Table 2. Cumulative N_2O emissions for a 90-day period following grazing of intensive, minimum or no tillage triticale plots. Data are means of three replicates.

Split plot treatments			Main plot		
Moisture content	Treading	Urine added	Cumulative N_2O Flux (kg N/ha)		
			IT	MT	NT
<FC	Yes	Yes	1.45	1.87	2.04
>FC	Yes	Yes	14.86	12.68	4.97
FC	Yes	Yes	5.73	3.18	3.0
FC	No	Yes	2.36	1.66	2.07
FC	Yes	No	0.31	0.53	0.37
FC	No	No	0.24	0.28	0.46

Urine application had a strong effect on N_2O emissions in this study. Where urine was not applied, cumulative N_2O emissions were very low (Table 2). In contrast, where urine was applied, N_2O emissions were low during the first month following urine application, as soil mineral N contents were also low during this time, but tended to be higher from August onwards, by which time much of the applied urine had been converted to nitrate (Figure 2). From mid-July onwards, emission peaks were recorded following most rainfall events (Figure 2) and corresponded with an increase in the WFPS of the soil.

Effects on DM production

Dry matter production, before grazing in June, was unaffected by tillage treatment (2400 kg DM/ha). Treading, moisture content at treading and urine application affected the triticale DM production (Figure 3, $P < 0.05$). There was also some evidence to suggest that tillage method was also important ($P = 0.06$ for tillage x split plots interaction effect). As the soil moisture content at treading increased from <FC to >FC, DM production decreased two fold (Figure 3). In contrast, DM production on the NT plots was unaffected by soil moisture content at grazing. The application of urine increased triticale re-growth by up to 50%, this effect being greatest in the NT plots.

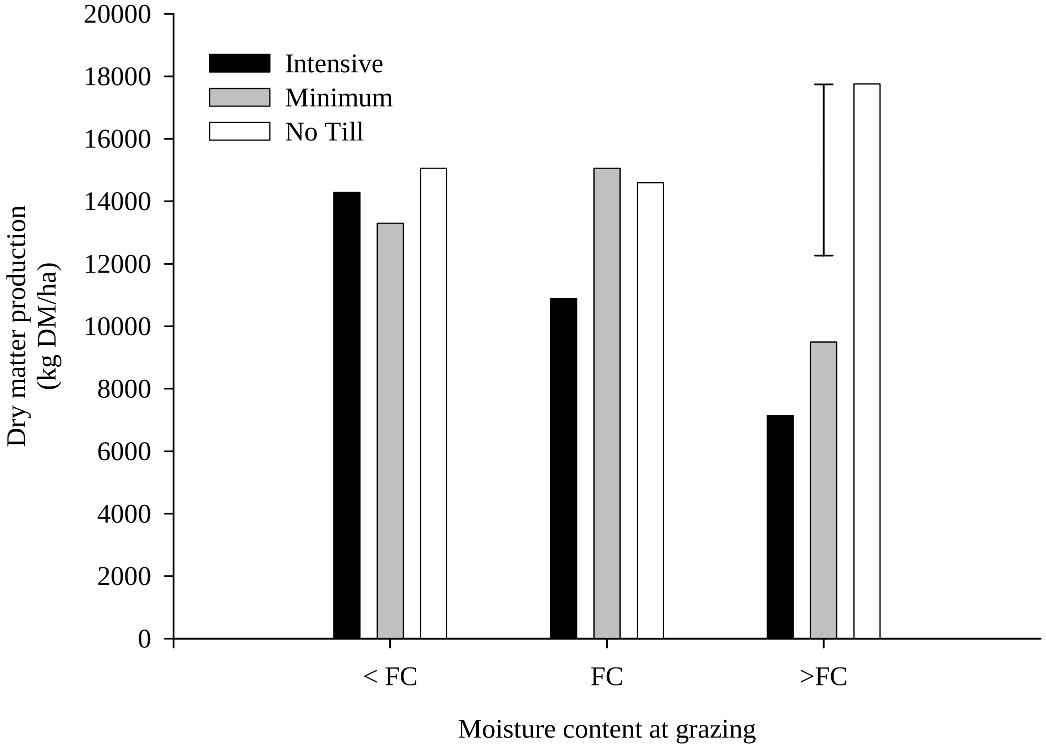

Figure 3. Mean DM production of Doubletake triticale between June and October following simulated grazing at 3 moisture contents (< FC, FC and > FC) established by IT, MT or NT (n = 3). The error bar represents the LSD ($P < 0.05$) for comparison of tillage and moisture treatments.

Conclusions

The use of no-tillage practices to establish a multi-grazing winter forage crop (ex-pasture) had significant benefits over other tillage practices in terms of environmental impacts and forage crop performance. Soil compaction, due to grazing under wet conditions, increased N_2O production and decreased forage crop production. Conventional tillage practices (IT) for establishing winter forage are more likely to result in soil compaction than reduced tillage systems. Hence where these winter forages are grazed, establishment by direct drilling is likely to be an important option for mitigating N_2O emissions, while maintaining high dry matter yields. Restricting grazing when soils are wet will reduce the risk of increasing N_2O emissions and loss of dry matter production.

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