Calvelo Pereira, R., Hedley, M. J., Hanly, J., Hedges, M., Bretherton, M., Beare, M. H., McNally, S.R. Full inversion tillage pasture renewal offers greenhouse gas mitigation options: The Manawatu experience. In: *Nutrient loss mitigations for compliance in agriculture.* (Eds L.D. Currie and C.L. Christensen). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 32. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 11 pages.

FULL INVERSION TILLAGE PASTURE RENEWAL OFFERS GREENHOUSE GAS MITIGATION OPTIONS: THE MANAWATU EXPERIENCE

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Abstract

Increasing soil organic carbon (SOC) stocks has been proposed as one strategy to reduce global atmospheric CO_2 concentrations and slow climate warming. New Zealand's grazed pastures accumulate large amounts of SOC because grasses allocate a high proportion of photosynthate C to root turnover and rhizodeposition. Near-surface rhizodeposition causes the topsoil layers (0–10 cm) to become saturated in SOC, whilst C stocks are often 2 - 4-fold lower in the sparsely rooted, deeper layers (15–30 cm). This vertical stratification of roots and SOC limits the topsoil's capacity to sequester more carbon.

Full inversion tillage at pasture renewal (FIT-renewal) has been proposed as a technique to accelerate SOC storage in pastoral soils showing strong stratification. Using a modified mouldboard plough, full soil inversion (1) transfers carbon-rich topsoil into the subsoil (potentially slowing its decomposition), and (2) exposes the inverted, carbon unsaturated, subsoil to higher C inputs from the new pasture.

During 2016-2018, two trials were established on a Pallic soil in the Manawatu region at Massey University's Dairy 4 farm to assess the effects of FIT on SOC stocks, crop and pasture yields, nitrous oxide emissions, and N leaching. In trial 1, FIT-renewal involved full cultivation of a summer brassica crop followed by autumn re-grassing; in trial 2, full cultivation occurred at autumn re-grassing. Other treatments included pasture renewal by no-till (trials 1 and 2) and shallow till (trial 1), and continuous pasture (trial 2). Plant growth, herbage quality, and nutrient leaching were monitored at both trial sites. Changes in nitrous oxide emissions during pasture renewal and grazing were evaluated for trial 2 only. These field trials complement a similar field trial established in the Canterbury region (McNally et al. 2019, this issue).

The modified plough successfully transferred SOC below the 0–10 cm soil depth. In the crop rotation (trial 1), losses of mineral N during the crop and pasture cycle were lower under FIT, and crop yield was higher. In trial 2, FIT reduced the peak emission of nitrous oxide after urine addition.

FIT-renewal shows potential to maintain crop and pasture yields, whilst reducing net greenhouse gas emissions from grazed pastures.

Introduction

Increasing soil organic carbon (SOC) stocks has been proposed as one strategy to reduce global atmospheric CO_2 concentrations and slow climate warming (Rumpel *et al.*, 2018). New Zealand's grazed pastures accumulate large amounts of SOC (Schipper *et al.*, 2017) because grasses allocate a high proportion of C fixed by photosynthesis to root turnover and rhizodeposition (Rasse *et al.*, 2005; Dignac *et al.*, 2017). Carbon inputs also include those from dung and urine returned to the soil (Soussana and Lemaire, 2014). Carbon losses are from respiration, biomass removed by grazing, dissolved carbon in leaching and erosion (assumed to be negligible for managed grassland on flat land). Near-surface rhizodeposition causes the topsoil layers (0–10 cm) to become saturated in SOC, whilst C stocks are often 2 - 4-fold lower in the sparsely rooted, deeper soil layers (15–30 cm) (Lorenz and Lal, 2005). This vertical stratification of roots and SOC limits the topsoil's capacity to sequester more C. In New Zealand, the topsoil of high producing permanent pastures are close to "saturation" with respect to C content (Beare *et al.*, 2014; McNally *et al.*, 2017), therefore, the scope for additional increases of SOC stocks may be limited (Whitehead *et al.*, 2018).

Grazed-pastures supporting year-round animal production, like those in New Zealand, are under pressure to maintain their output of food, fodder, fuel and fibre (Lal, 2011, 2016) without penalties to the wider environment. Biomass production of mixed ryegrass and clover pastures may decline over the years due to gaps in the sward, pests, weeds or following physical damage to the soil caused by farm operations (Tozer *et al.*, 2013; Whitehead *et al.*, 2018). Pasture renewal every 7-10 years is, thus, actively promoted to farmers to improve pasture performance (species composition and vigour) and animal productivity, particularly when economic return after re-grassing is positive (Dodd *et al.*, 2018). On New Zealand dairy farms, pasture renewal may involve spring cultivation (e.g. Hanly *et al.*, 2017) using tillage of contrasted intensity (either no-till, shallow till or full cultivation), including summer forage cropping and/or direct re-grassing during autumn.

Pasture renewal including full cultivation, often involves shallow (< 15 cm depth) ploughing, which can accelerate short-term SOC losses (Rutledge *et al.*, 2014). However, under proper management, pasture growth replenishes the carbon loss caused by cultivation, particularly when C-rich topsoils are buried by deeper ploughing (i.e. below 25 cm depth; so-called full inversion tillage – FIT) (Alcantara *et al.*, 2016; Alcántara *et al.*, 2017; Calvelo Pereira *et al.*, 2018). In this context, full inversion tillage at pasture renewal (FIT-renewal) has been proposed as a technique to accelerate SOC storage in pastoral soils showing strong stratification. Using a modified mouldboard plough, full soil inversion (1) transfers carbon-rich topsoil into the subsoil (potentially slowing its decomposition), and (2) exposes the inverted, carbon unsaturated, subsoil to higher C inputs from the new pasture. In the context of pastoral soils, FIT must be applied infrequently (every 25-30 years), to avoid carbon losses derived from more frequent ploughing (Conant *et al.*, 2007). Currently no comparative tillage trials, comparing FIT to direct drilling (no till) or shallow tillage at pasture renewal have been conducted. Hence, there is uncertainty surrounding the degree and longevity of any enhanced SOC storage associated with FIT and whether there are other potentially positive or negative effects associated to the establishment of the new sward, such as N loss to water and greenhouse gas emissions.

The objective of this study was to assess the short-term effects of contrasting tillage treatments (either no-till, shallow till or FIT) on pasture renewal of two long-term New Zealand pastoral-based dairy soils. During 2016-2018, two trials were established on a Pallic soil (imperfectly drained) in the Manawatu region at Massey University's Dairy 4 farm. In trial 1, FIT-renewal involved full cultivation of a summer brassica crop followed by autumn re-grassing; in trial 2, full cultivation occurred at autumn re-grassing. Other treatments included pasture renewal by no-till (trials 1 and 2) and shallow till (trial 1), and continuous pasture (trial 2). This article provides a summary of the effects of FIT on SOC stocks, crop and pasture yields, nitrous oxide emissions, and N leaching during year 1 after renewal. This research in the Manawatu region complements a similar field trial established in the Canterbury region (McNally et al., this issue).

Materials and Methods

Trial 1: grass-crop-grass rotation

The trial site was located on Massey University's Dairy 4 farm near Palmerston North, Manawatu (40° 23′ 46.79″ S; 175° 36′ 35.77″ E) on a mole-pipe drained Tokomaru silt loam, a Pallic soil (Hewitt, 2010). Prior to commencement of this trial, all plots were under a mixed pasture of predominantly perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.), which was grazed by dairy cows. Soil fertility at 0–7.5 and 7.5–15 cm soil depths was assessed on 26 October 2016 (Table 1). The initial, pre-renewal, soil fertility status for the pasture site at trial 1 (Table 1) was among the optimum range of ryegrass/white clover-based pasture for the 0–7.5 cm depth (Roberts and Morton, 2012). For the 7.5–15 cm depth, the values of Olsen P and exchangeable K were lower than the target values for supporting optimal crop growth (Table 1) (Roberts and Morton, 2012).

Table 1 Selected soil properties for topsoil (0–7.5 cm depth) and shallow subsoil (7.5–15 cm depth) sampled prior to tillage treatments at the Manawatu region trial sites. Analytical methods are described in Blakemore *et al.* (1987).

Variable	Units	Trial 1		Trial 2	
	Depth (cm)	**0-7.5**	**7.5-15**	**0-7.5**	**7.5-15**
pH	-	6.15	5.81	5.74	5.59
Olsen P	mg/kg	32.7	13.9	31.3	22.7
Sulphate-S	mg/kg	10.6	5.9	11.7	13.7
Exchangeable K	$cmol_c/kg$	0.61	0.26	0.72	0.34
Exchangeable Ca	$cmol_c/kg$	8.96	6.01	6.60	5.40
Exchangeable Mg	$cmol_c/kg$	2.02	1.03	2.09	1.37
Exchangeable Na	$cmol_c/kg$	0.14	0.09	0.21	0.14
CEC	$cmol_c/kg$	15.9	12.1	15.0	12.5

The trial 1 design consisted of three tillage treatments in spring to establish a summer fodder crop followed in autumn by re-sowing permanent pasture by direct drilling into the fodder crop stubble: (1) spray and direct drill-no till (hereafter called NT treatment); (2) spray and shallow (approx. 5 cm depth) rotary hoeing-shallow till (hereafter called ST treatment); and (3) spray and deep ploughing using a mouldboard plough fitted with a disc and skimmer capable of ploughing to 30 cm depth placing the topsoil in the furrow bottom and lifting the subsoil over the topsoil - full inversion tillage (hereafter called FIT treatment). Treatments (NT and FIT, 5 replicates; ST, 4 replicates) were assigned randomly to existing experimental plots (approx. 0.09 ha each).

Following the common practice in that area of the Manawatu region, the pasture on all plots was sprayed with glyphosate on 11 October 2016 and then on late November 2016 a leafy turnip (*Brassica campestris spp rapa*, var Hunter) was sown following the treatments explained above (i.e. NT, ST and TIT). Basal fertiliser was applied during November and December as per the details provided in Table 2. The FIT treatment received higher rates of P and K fertiliser (Table 2) to raise soil P and K status in uplifted subsoil to target soil test values. *Brassica* requirements for boron was additionally met (Table 2). A food grade P fertiliser, Kynofos 21, was used in order to avoid Cd addition to the newly cultivated soil layer.

Table 2 Summary of fertilisers applied to the different tillage treatments at pasture renewal (i.e. no till or NT, shallow till or ST and full inversion till or FIT) for Trial 1.

Date	Fertiliser/Grade	NT	ST	FIT
29 November 2016	Kynofos 21 (21% P)	30 kg P/ha	30 kg P/ha	60 kg P/ha
	Ammonium sulphate (21% N, 24% S)	52 kg N/ha 60 kg S/ha	52 kg N/ha 60 kg S/ha	52 kg N/ha 60 kg S/ha
	Potassium chloride (50% K)	60 kg K/ha	60 kg K/ha	120 kg K/ha
	Sodium borate (15% B)	6 kg B/ha	6 kg B/ha	6 kg B/ha
22 December 2016	Urea (46% N)[A]	148 kg N/ha	148 kg N/ha	148 kg N/ha
5 September 2017	Kynofos 21 (21% P)	30 kg P/ha	30 kg P/ha	30 kg P/ha
	Ammonium sulphate (21% N, 24% S)	30 kg N/ha 34 kg S/ha	30 kg N/ha 34 kg S/ha	30 kg N/ha 34 kg S/ha
	Potassium chloride (50% K)	50 kg K/ha	50 kg K/ha	50 kg K/ha
12 October 2017	Ammo	30 kg N/ha	30 kg N/ha	30 kg N/ha
		14 kg S/ha	14 kg S/ha	14 kg S/ha

[A] urea applied by side-dressing.

At the end January 2017 and on 14 March 2017 the turnip crop on all treatments in the trial area were grazed by dairy cows as part of the farm's grazing rotation. Crop yield was assessed by taking quadrant samples prior to grazing and the herbage was analysed for nitrogen content. On 16 March 2017, the plots were sprayed again to prepare the seed bed for pasture sowing. On 10 April 2017, a mix of perennial ryegrass and white clover was finally sown by direct drilling into the brassica stubble. Following re-grassing, pasture growth was monitored by using a rising plate-meter; all treatments in the trial area were grazed by dairy cows as part of the farm's grazing rotation. At all grazing dates during 2017, grass samples were collected and analysed for total N content.

Each plot had its own internal mole-pipe drainage system. Drainage water from plots was channelled through drainage pipes into individual tipping-bucket flow meters located in sampling pits nearby (Hanly, 2012; Christensen, 2013) and a proportional sub-sample was collected for analysis. Drainage samples were filtered through a 0.45 μm filter within 12 hours of collection and stored frozen until analysis. Filtered samples were analysed for NO_3-N using an Ion Chromatograph.

On 19 October 2016 (i.e. baseline or pre-renewal) and on 17 March 2017 (post-renewal or 5 months after renewal practice and growth of crop), soil cores (0–40 cm depth; 3 cores per plot) were taken from each plot to assess changes in soil carbon. A 43.5 mm diameter percussion corer was used to obtain a representative core to the depth of 60 cm. Soil columns were sliced to obtain representative samples at depth intervals of 0–5, 5–10, 10–15, 15–20, 20–25, 25–30 and 30–40 cm. All samples were air-dried, sieved by 2 mm and stored for elemental analysis after grinding (< 1 mm) a subsample. Total C and N were determined on the samples using a Vario MACRO cube elemental system (Elementar Analysensysteme GmbH, Hanau, Germany). The soil bulk density of each core obtained from each depth interval (i.e. 0–5, 5–10, 10–15, 15–20, 20–25, 25–30 and 30–40 cm depth) was calculated by dividing the sample mass (corrected for the soil mass dried at 105°C in an oven by using a subsample) by the corresponding core volume. Soil C stocks were calculated using an equivalent soil mass approach (Calvelo Pereira *et al.*, 2018).

Trial 2: grass-to-grass rotation

Trial 2 was located on the same farm and with the same soil type as described for trial 1. Prior to commencement of this trial, all plots were under a mixed pasture of predominantly perennial ryegrass and white clover, which was grazed by dairy cows. Soil fertility at 0–7.5 and 7.5–15 cm soil depths was assessed on 12 March 2018 (Table 1). The initial soil fertility status for the pasture site at trial 2 (Table 1) was among the optimum range of ryegrass/white clover-based pasture for the 0–7.5 and 7.5–15 cm depths (Roberts and Morton, 2012).

Trial 2 design consisted of two tillage treatments in autumn and re-sowing of permanent pasture either by: (1) spray and direct drill-no till (NT treatment); and (2) spray and deep ploughing using a mouldboard plough or full inversion tillage (FIT treatment, as described above). A third treatment consisted of continuous pasture (hereafter called CP treatment), which was used as a control treatment. Treatments (NT, FIT, and CP; 4 replicates of each) were assigned randomly to experimental plots (approx. 0.06 ha each).

On 23 February 2018, the plots for NT and FIT treatments were sprayed. On 12 March 2018, the cultivation was done for FIT treatment; rototilling was conducted on 19 March 2019. On 20 March 2018, fertiliser was applied at a rate of 28 kg N/ha, 31 kg P/ha, 28 kg K/ha and 15 kg S/ha using DAP and Potassium Sulphate. A mix of perennial ryegrass and white clover was sown on 27 March 2019 using a direct drill. Following re-grassing, pasture growth was monitored by using a rising plate-meter, and all treatments in the trial area were grazed by dairy cows as part of the farm's grazing rotation. At selected grazing dates during 2018, grass samples were collected, processed and analysed as described for trial 1 (data not shown).

Nitrous oxide measurements

This study measured the emissions of nitrous oxide (N_2O) from the plots in trial 2 at two different periods: period 1, during the pasture establishment phase (March to April 2018), comparing emissions from NT, FIT and CP treatments; and period 2, which was at the time of the third full grazing (September to end November 2018), comparing emissions from NT, FIT and CP treatments after no N addition (0N or control) and after the addition of 600 kg N/ha as artificial urine (Kool *et al.*, 2006) (600N). On August 2018, prior to period 2, selected areas of the plots were excluded from animal grazing.

At each measurement period, static chambers (n = 5 per treatment or combination of treatments considered; 850 mm diameter) were used to measure N_2O emissions, following published methodologies (van der Weerden *et al.*, 2011; Kim *et al.*, 2014). Gas samples were collected three times per week for the first two weeks when possible, and then twice a week, once a week or fortnightly until background levels were reached. Gas sampling frequency was scheduled to correspond with significant rainfall events. Nitrous oxide measurements were carried out between 11 noon and 1 pm at each sampling time. Gas fluxes were monitored after temporarily sealing the cambers using an inflated rubber tube. At each sampling day, three headspace gas samples were taken during a cover period of 120 min, at times 0, 60 and 120 min, from each chamber using syringes, which were used to transfer the gas sample into 12 mL septum-sealed screw-capped glass vials. Gas sample vials were over-pressurised (to obtain a total volume of 25 mL) to ensure sample integrity was maintained; glass vials were previously evacuated in the laboratory. Changes in the gas concentration within the enclosed headspace were determined by gas chromatography and fluxes were calculated using linear regression and the ideal gas law following common practice (Saggar *et al.*, 2009; Giltrap *et al.*, 2014). Soil (water content, mineral N) and climatic parameters (temperature, rainfall) were monitored regularly.

Data analysis and statistics

Statistical analyses were conducted with the Statistica version 8 software package (Stat Soft. Inc., Tulsa, OK, USA). The effect of pasture renewal practice (i.e. NT, ST and FIT in trial 1; NT, FIT and CP in trial 2) on different variables was statistically analysed using a one-way ANOVA test. If a significant ($P < 0.10$) main effect was detected, difference between treatment means was tested using the least significant difference. When depth was included in the statistical analysis, the one-way ANOVA test was calculated independently for each depth considered.

In this study, linear interpolation was used to estimate N_2O loss on the intermediate days between measurements. Total emissions during the period of September 2018 to end November 2018 (i.e. period 2, a total of 70 days) were used to calculate the emission factor for artificial urine and each of the treatments considered (i.e. NT, FIT and CP). Emission factors were calculated from the difference in the total emissions from each urine (600N) treatment and the respective control treatment (0N), divided by the rate of urine N applied and expressed as N_2O-N emitted as % of urine-N applied.

Results and Discussion

Trial 1 monitoring year 1

Dry matter production and nitrogen accumulation and losses

The average turnip crop yield was influenced by the intensity of tillage at pasture renewal, as the average yield in plots was higher ($P < 0.10$) under FIT treatment on average (8957 kg DM/ha) than under NT treatment (6535 kg DM/ha); values of turnip yield under ST (7963 kg DM/ha) were similar ($P > 0.10$) than those under FIT and NT (Figure 1). Following a wet spring during establishment, the turnip in the NT treatment had a poor germination and subsequently the lowest yields (Figure 1). Uptake of N by the turnips was influenced by the higher DM accumulation under FIT treatment, with FIT characteristically showing the highest ($P < 0.10$) accumulation of N during the crop phase (Figure 1b).

Following cultivation, on 23 November 2016, average mineral-N concentrations of drainage water from all treatments increased, including the summer grazing of the turnip (February-March 2017; data not shown). During the period between December 2016 to April 2017 (i.e. drainage corresponding to crop phase), the average loss of nitrate-N was lower ($P < 0.10$) under FIT treatment (on average: 8.6 kg NO_3-N/ha) compared to the NT treatment (on average: 17.3 kg NO_3-N/ha; Figure 1a). During the same period, the average quantity of drainage occurring was 68 mm for the FIT treatment plots and 100 mm for the NT treatment plots (data not shown).

The average pasture herbage accumulated since re-grassing (April 2017) until end of 2017 (four grazing events) was 9798 kg DM/ha, similar ($P > 0.10$) and not significantly different across the renewal treatments (Figure 1a). During the same period, the average amounts of N uptake by the pasture were similar ($P > 0.10$) across all renewal treatments (Figure 1b).

After pasture re-sowing in April 2017, the drainage events increased as a consequence of a wet autumn period, coinciding with the start of the drainage season (May to June 2017). Whilst the FIT treatment continues to have lower N loads in the drainage water during the pasture phase, the N load was similar for all the renewal treatments with no significant difference between each treatment (Figure 1c).

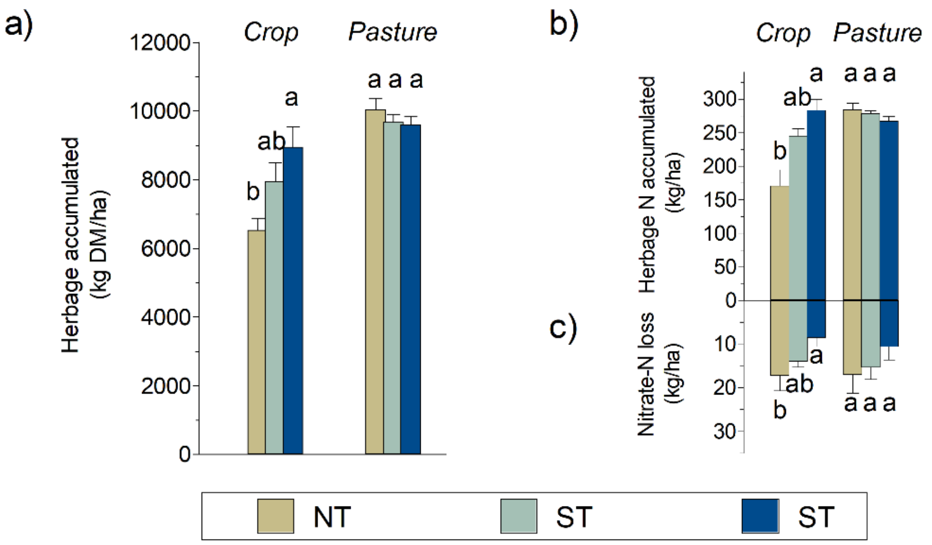

Figure 1 (a) Average herbage dry matter (kg/ha) accumulation; (b) average herbage N (kg/ha) accumulation; and (c) average NO_3-N leached (kg/ha) for trial 1. Data for both main phases of trial 1 during 2016-2017; crop (November 2016 to March 2017) and pasture re-grassing phase (April 2017 to December 2017). For each variable and phase, different letters indicate significant differences between renewal treatments (i.e. NT, ST and FIT) at $P < 0.10$.

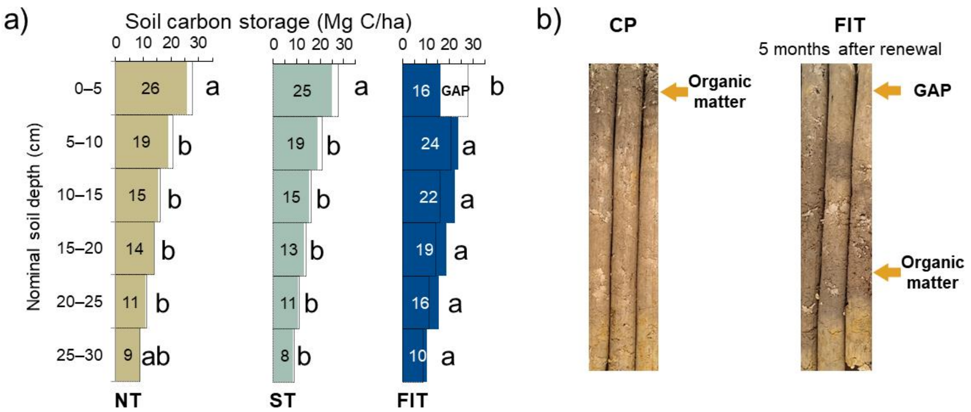

Figure 2 (a) Average soil carbon stocks (Mg/ha) calculated at equivalent soil mass (Mg/ha) per renewal practice 5 months after renewal and growth of crop (March 2017) for trial 1; for each depth, different letters indicate significant differences between renewal treatments (i.e. NT, ST and FIT) at $P < 0.10$. (b) Visual assessment of contrasted organic matter distribution between continuous pasture (CP) and full inversion tillage (FIT) five months after renewal; samples were taken at trial 2; darker colours reflect the presence of organic matter rich areas, as indicated in the figure.

Changes in soil C stocks five months after pasture renewal

At the start of trial 1 (October 2016) the soils showed a distinct stratification of C soil organic matter (data not shown), as expected for long-term pasture. Five months post tillage, at the end of the forage crop grazing, all renewal treatments showed no major differences in total C stocks down to a depth of 30 cm (Figure 2). The NT and ST treatments showed the same SOC stratification as the long-term pasture (Figure 2). Five months after renewal and crop growth, the renewal through cultivation by deep mouldboard ploughing (i.e. FIT treatment) modified the SOC stratification (Figure 2). Carbon stocks in the 0–5 cm nominal depth (on average, 16 Mg C/ha) under FIT treatment was lower ($P < 0.001$) than the C stocks under the NT and ST treatments, which were 26 and 25 Mg C/ha, respectively, on average (Figure 2). The soil profile of the FIT treatment, 5 months after renewal and crop growth, had a higher ($P < 0.05$) C stock than either of the other two treatments, at 5–10, 10–15, 15–20, 20–25, and 25–30 cm nominal depths (Figure 2). These results demonstrate that FIT inverts the topsoil C and, thus, creates an unsaturated C topsoil root zone (i.e. a soil carbon ‘gap’; Figure 2).

Trial 2 monitoring year 1

Nitrous oxide emissions following pasture renewal (period 1: 48 days)

The spraying of the continuous pasture resulted in immediate emissions of N_2O from the topsoil of both the NT and FIT treatments (Figure 3a). Three weeks after spraying, at the time of fertiliser addition, another flush of N_2O emissions was observed for the NT treatment only. Emissions of N_2O from topsoil of the FIT treatment was relatively unaffected by both ploughing and fertiliser addition (Figure 3) and values of N_2O emitted from FIT were similar to those values emitted from CP treatment. The NT treatment showed a higher ($P = 0.002$) quantity of cumulative N_2O-N emitted over 48 days (average: 1.25 kg N_2O-N/ha) compared to the FIT and CP treatments (average of 0.53 and 0.04 kg N_2O-N/ha, respectively; Figure 3).

Nitrous oxide emissions following urine addition (period 2: 70 days)

Five months after re-grassing (equivalent to the third round of grazing of new grass), the addition of artificial urine resulted in emissions of N_2O from the topsoil of all treatments. Emission intensity depended on the renewal practice applied (NT > CP> FIT; Figure 3b). The intensity of the peak emissions was reduced after three weeks. Emissions of N_2O from the topsoil of FIT treatment decreased rapidly two weeks after urine addition, but maintained relatively high values for two more weeks (Figure 3b). After 35 days, emissions of N_2O tended to be reduced to background levels, and emissions were similar between the renewal practices. The average pasture herbage accumulation for the 70-day period after urine deposition was 4469 kg DM/ha, which was similar ($P > 0.10$) across all treatments (data not shown).

After 70 days following urine application, cumulative N_2O emissions from urine on the NT renewal treatment (average of 1.65 kg N_2O-N/ha emitted; EF was 0.24%) was significantly higher than the CP treatment (average of 0.91 N_2O-N/ha emitted; EF was 0.10%) ($P < 0.001$) (Figure 3b). Cumulative N_2O emissions from urine on the FIT renewal treatment (average of 0.71 kg N_2O-N/ha; EF was 0.10%) were similar ($P > 0.10$) to the cumulative N_2O emissions from the CP treatment (Figure 3b). The EF measured for the CP, NT and FIT treatments were in the low range of average EF calculated from urine emissions from other experiments in the the Manawatu region (Singh *et al.*, 2008; Zaman *et al.*, 2009; Kim *et al.*, 2014), which also had ryegrass and clover swards.

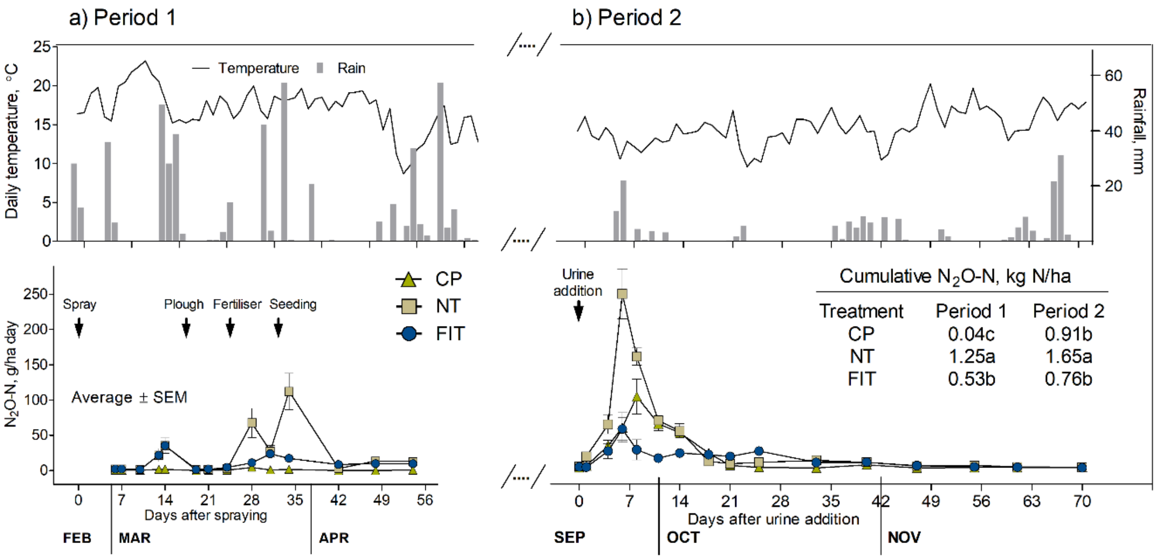

Figure 3 N_2O flux (g N/ha/day; average ± standard error of the mean) during (a) pasture establishment phase (Period 1, March to April 2018; and (b) at the time of the third full grazing (Period 2, September to end November 2018), after the addition of artificial urine. Inset: average cumulative N_2O-N emissions per renewal treatment at the end of each period. For each period, different letters indicate significant differences between renewal treatments (i.e. CP, NT, and FIT) at $P < 0.10$. A summary of main average daily temperature and daily rainfall, as well as main pasture management activities for each period is included.

Summary and conclusion

The modified plough successfully transferred SOC below the 0–10 cm soil depth. In the crop rotation trial (trial 1), losses of mineral N during the crop and pasture cycle were lower under the FIT treatment, and crop yield was higher. In trial 2, the FIT treatment reduced the peak emissions of N_2O after urine addition, compared to the peak emissions from the NT treatment. The FIT treatment has shown that it has potential to maintain crop and pasture yields whilst reducing net greenhouse gas emissions from grazed pastures, at least in the initial phase post-renewal (year 1). Further evaluation of the trial sites over time will help to determine whether FIT can be considered an option to increasing soil carbon storage in pastoral soils and whether it can also mitigate greenhouse gas emissions over the long-term.

Acknowledgements.

The authors would like to thank the following contributes to this research study: M. Osborne, Q. Mai, P. Bishop, A. Bishop, I. Furkert, B. Toes, R. Wallace, M. Cheuyglintase, A. Tumbure, M. Paz, K. Adhikari (Massey University) and J. Dijkstra (The Netherlands) for providing technical support; Massey University’s Dairy 4 farm staff for their contribution to the establishment and management of the two field trail sites. This research has been partially funded by the New Zealand Government to support the objectives of the Livestock Research Group of the Global Research Alliance on Agricultural Greenhouse Gases.

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