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Nitrous oxide emissions in soils cropped with maize under long-term tillage and under permanent pasture in New Zealand

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Abstract

Information on the influence of tillage on nitrous oxide (N_2O) emissions is needed by researchers, policy makers and farmers for assessment of global ramifications of warming potential of greenhouse gas N_2O. This research evaluates the effects of continuous long-term tillage and seasonal changes in N_2O emissions in New Zealand temperate climate. The experiment was conducted in a Kairanga silty clay loam (Eutric Gleysol) where maize (*Zea mays* L.) was grown continuously for either 17 (K17) or 34 (K34) years, with conventional tillage. An adjacent permanent ryegrass (*Lolium perenne* L.) and clover (*Trifolium* sp.) pasture (PP) was used as a control. Mean N_2O emissions under K17 and K34 and PP ranged from 0.04 to 1.35, 0.03 to 1.13, and 0.03 to 0.99 g N_2O-N/ha/h, respectively. Average annual N_2O emissions from K34 were slightly lower than those in the K17 fields although there were no differences in N_2O emissions between PP and K17. Depleted organic C, total N and microbial biomass C in K34 as compared with K17, possibly limited denitrification process and decreased N_2O emissions. Soil water content (SWC) was a key factor controlling N_2O emissions in both pasture and cropped soils. Low emissions occurred when gravimetric SWC content was less than 30%. N_2O emissions from grazed pasture were low during summer (dry) period and increased during winter (wet) season. There were no differences in N_2O between the K17 and K34 during dry season but N_2O emission rates in wet season were lower in the K34. Despite high temporal variability observed in the N_2O emissions, our estimates based on low frequency of measurements over 1 year were in general agreement with those in the literature.

Keywords: Greenhouse gas emissions; Soil organic carbon; Long-term conventional tillage; Seasonal changes; New Zealand

1. Introduction

There is some evidence that intensive tillage practices impact on the nitrogen (N) cycle through loss of organic matter and deterioration of soil structure (Saggar et al., 2001; Shepherd et al., 2001), which could influence the extent of N_2O emissions. It is known that soil disturbance through cultivation decreases N_2O fluxes due to better aeration, while the amounts of fertiliser applied into cultivated soil increase the potential emissions of N_2O (Shepherd, 1992). Mosier et al. (1997) found that changing

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cultivated soils back to grasslands eventually (after 8–50 years) led to N_2O emissions similar to those of native soils of the same texture and parent material. They also found that conservation practices, aimed at reducing harmful effects of extensive conventional practices, contributed to N_2O emissions through improved soil conditions. Increased soil organic matter, higher soil microbial biomass, and water content are conditions that favour emissions of N_2O.

Colbourn (1988) observed denitrification in the undrained ploughed soil as one-fifth of that in drained direct-drilled soil. Tillage restricted denitrification to a greater extent than did drainage. The latter study attributed differences in denitrification to changes in soil structure caused by the tillage. The lack of disturbance in the reduced tillage soils leads to a reduction in large pores, increased soil aggregation and reduced soil aeration, therefore, produced higher denitrification.

Concentrations of biomass carbon (C) and organic C in the soil are highly correlated with denitrification activity (Drury et al., 1991), and there is evidence that increasing C availability decreases the N_2O fraction (Firestone, 1982). Since organic matter in soils is represented by plant debris, crop species have a significant influence on the N_2O emissions (Kaiser et al., 1998). The authors reported that the total N_2O losses during the winter increased with the decreasing dry matter-to-N-content ratio of the plant residues incorporated into the soil by ploughing.

Ineson et al. (1998) demonstrated high levels of N_2O production under elevated CO_2 conditions. Plants growing under elevated CO_2 may be subjected to greater N limitation because of the N being lost through denitrification. Ineson et al. (1998) recorded a 27% increase in N_2O production under elevated CO_2 conditions, and attributed this increase to excess available soil C under elevated CO_2. Plant roots may deplete available inorganic N and alter the soil physical status, resulting in decreased denitrification (Granli and Bockman, 1994). Denitrification rates generally increase with increasing soil water content (SWC). Sitaula and Bakken (1993) obtained a significant increase in N_2O accumulation by increasing the SWC from 35 to 45%. Similarly, Carran et al. (1995) reported low or negligible N_2O emissions in the Manawatu region, New Zealand, when the SWC was less than 35%.

Low N_2O fluxes from grassland compared with cropped tillage systems also contribute to N_2O mitigation with additional benefits of restoration of soil properties (Mosier et al., 1997). On high-class soils in New Zealand (as classified by Webb et al., 1997 from well-defined, topographic, climatic and soil attributes), conversion of pasture for arable cropping is a common practice that generally results in deterioration of soil structure stability, and depletion of soil organic matter and N fertility over time (Saggar et al., 2001; Shepherd et al., 2001). Additional N fertilisers are then applied to compensate for the loss of N fertility and to maintain crop productivity. N fertilisers are considered a major source of N_2O emissions.

In a previous study (Choudhary et al., 2001), we determined the rates of N_2O emissions from plots established in 1995 sown with CT and no-tillage (NT), and with occasionally sheep-grazed permanent pasture (PP). We observed large inherent variations in N_2O fluxes (a mean of coefficient of variation = 119%), probably reflecting natural soil heterogeneity. The N_2O fluxes were substantially higher in CT and NT compared with those of PP, but no differences were found between CT and NT treatments. These plots did not have a long history of continuous tillage nor did the pasture plot represent a regularly grazed pasture common to New Zealand conditions.

Information on N_2O emissions in medium- (17 years) and long-term (34 years) tilled soils may help to interpret the effects of cultivation on N-dynamics. The objective of this study was to determine the impacts of long-term continuous cropping with CT and seasonal changes on N_2O emissions, and compare these with emissions from permanent pasture in temperate New Zealand and estimate annual average N_2O emissions for these soils.

2. Materials and methods

2.1. Experimental site

The experimental site was at Kairanga (40°21′S, 175°39′E) located within the Manawatu region of the North Island of New Zealand. The soil was classified as Eutric Gleysol (FAO), Typic Endoaquept (US), Kairanga silt loam with very poor drainage and soil characteristics (Table 1) as described in Saggar et al. (2001). Three farms at this site representing a regularly fertilised grazed PP sown with introduced grasses

Table 1
Land-use, symbol, soil classification, location, some soil characteristics of Kairanga silty clay loam soil used in this study

Site	Land use	Symbol	Soil classification			Grid reference[a] (NZMS 260)	pH 1:2.5 soil:water	Organic C (g/kg soil)	Total N (g/kg soil)	Microbial C (mg/kg soil)
			NZ	US	FAO					
Kairanga	Permanent	PP[b]	Typic	Typic	Eutric	S24 242 931	5.65 ± 0.0	49.9 ± 3.2	4.7 ± 0.9	1585 ± 5
Silty clay loam[c]	Pasture		Orthic Gley	Endoaquept	Gleysol		1[e]			
	17 years	K17[d]	Typic	Typic	Eutric	S24 229 948	5.58 ± 0.0	33.0 ± 4.9	2.8 ± 0.5	474 ± 11
	Maize		Orthic Gley	Endoaquept	Gleysol		4			
	34 years	K34[d]	Typic	Typic	Eutric	S24 243 093	6.20 ± 0.0	20.3 ± 3.0	1.8 ± 0.9	261 ± 15
	Maize		Orthic Gley	Endoaquept	Gleysol		2			

[a] Specifies the farm easting and westing location on New Zealand Map Series (NZMS).
[b] Site renewed 8 years ago (1989) following a wheat (*Triticum* sp.); before this under long-term ryegrass (*Lolium perenne* L.) and clover (*Trifolium* sp.).
[c] Particle size distribution (g kg^{-1}); Kairanga: sand 90–120, silt 510–530, clay 400–420.
[d] Sites K17 and K34 were under continuous maize (*Zea mays* L.).
[e] Values represent mean ± standard error.

(*L. perenne* L.) and legumes (*Trifolium* sp.); a 17-years conventional cultivation (K17), and a 34-years conventional cultivation (K34) grown maize (*Z. mays*) crop were included in this study. The PP was intensively grazed by dairy stock (160 cows strip-grazed on 1.21 ha sections of the farm for 9 h during the day and 12 h during the night), and was used as a control. Both cropping sites (K17 and K34) were conventionally tilled, up to the 250 mm soil depth using a mouldboard plough followed by levelling and rolling, discing and power harrowing.

Maize was sown at both cultivated farms in late October 1998. The K34 farm received 306.5 kg/ha of (15:10:10:8) fertiliser at sowing and additional 300 kg/ha of urea as side-dressing applied in early December 1998. The maize crop harvested for silage produced 16 Mg DM/ha. The K17 farm received 153 kg/ha (half of K34) of (15:10:10:8) starter fertiliser applied at the end of October and 300 kg/ha of urea side-dressed in early December 1998. The yield of maize grain was 6.9 Mg/ha. Coupled with a dry summer (which followed a very wet October), the fertilisers (especially the urea side-dressing) were not utilised effectively, because of the lack of rainfall and very dry soils. Urea pellets were still visible 2 weeks after application.

2.2. Soil sampling

Within each site, four random locations were chosen, and 25 cores (25 mm dia, 0–10 and 10–20 cm depths) were taken at approximately even spacings in an area of ca 50 m^2 in September 1998, before spring cultivation and sowing. The cores were pooled, field moist soils (−10 kPa) were sieved (<2 mm) soon after collection, and sieved soils stored at 4°C were used for soil microbial biomass C analysis. Subsamples of the sieved soil were air dried and used for pH, C and N analyses.

2.3. Soil analyses

Soil microbial biomass C was determined by a fumigation–extraction method. Fumigated and non-fumigated soils were extracted with 0.5 M K_2SO_4 for 30 min (1:5 soil:extractant ratio), and the extracts analysed for C by TOC 5000 (Shimadzu, Kyoto) analyser. The C obtained from the fumigated samples minus that from the non-fumigated samples was taken to represent the microbial-C flush and converted to microbial-biomass C using the relationship: Microbial C=C flush/0.41.

Air-dried samples were used for the total C and N analyses. Total C in soils was analysed by a combustion method (Induction Furnace, Leco, St. Joseph, MI). Total soil N was determined by semi-micro Kjeldahl digestion followed by NH_4^+-N measurements in the digests by an autoanalyser procedure. Soil pH (1:2.5 water) was determined according to Blakemore et al. (1987).

Soil water content and temperature were measured at 100 mm depth each time during N_2O measurement. Soil samples were collected, weighed, oven-dried to constant mass at 105°C, and weighed again. The final mass M_s, and the difference between fresh and dry masses M_w were used to calculate the gravimetric SWC:

$$\mathrm{SWC} = \left(\frac{M_w}{M_s}\right) \times 100 \quad (1)$$

Soil temperature was measured with a handheld digital thermometer. A temperature probe was inserted into the soil next to each chamber and temperature indications were recorded manually. Particle size distribution was determined by pipette method.

2.4. Nitrous oxide measurements

Monthly, and sometimes fortnightly, N_2O emission measurements included the cropped (October–May) as well as the winter fallow period (June–September). Measurements started in November 1998 and continued until September 1999. During this period a total of 14 measurements were made, although one data set collected on March 31 could not be analysed due to instrument malfunction. Rainfall data for the 3-year period (1996–1999) is shown in Fig. 1. The sites have a temperate humid climate with mean annual air temperatures of 12.1°C. The mean monthly temperature ranged between 15 and 20°C during summer, and between 8.4 and 10.2°C during winter.

Nitrous oxide emissions were measured following the chamber technique developed by Mosier and Hutchinson (1981). Each chamber was inserted 100 mm into the soil. Headspace gas samples were collected using 60 ml polypropylene syringes fitted

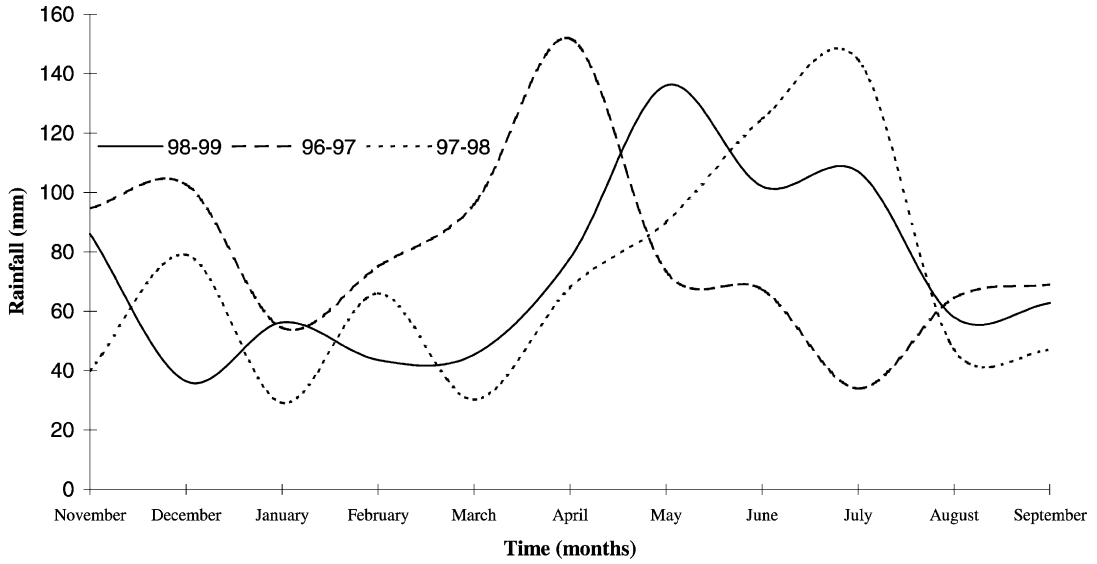

Fig. 1. Monthly rainfall from November 1998 to September 1999, 1996–1997, and 1997–1998.

with 3-way taps. Because of concern over the permeability of polypropylene to N_2O, field samples were analysed as soon as possible after collection, usually within 24 h. Initially, the chambers were left for 3 h with 1 h interval for gas sampling in order to detect any leakage. In later sampling, gas was collected only for 2 h. Analyses were done by gas chromatography (Mosier and Mack, 1980).

2.5. Statistical analysis

Unless otherwise stated, soil chemical and biochemical results were expressed on the basis of the oven-dry (105°C) weight of the material. A general linear model procedure (GLM) was used for analysis of experimental data. An analysis of variance (ANOVA) using a test of least significant difference (LSD) at 5% confidence level was used for comparison of treatments. Correlation of SWC and N_2O fluxes was analysed by mixed model procedure.

3. Results and discussion

3.1. Tillage effect on field N_2O emissions

Initial analysis of data showed significant variability (data not shown), as discussed elsewhere (Choudhary et al., 2001). Because the data were not normally distributed, comparison between treatments was accomplished by log-transformed data. The estimated annual N_2O emissions from the PP, K17 and K34 (calculated as the mean of all individual measurements of the closed cover chamber between November 1998 and September 1999) were similar at 3.24, 3.42 and 2.37 kg N_2O-N/ha/year, respectively (Table 2). Mean emission rates for the PP were within the range reported by Carran et al. (1995) from similar grazed sites on Kairanga soil. The N_2O emissions from the K17 were slightly higher than those from the K34 fields ($P = 0.1$), and were comparable with those recorded by Jacinthe and Dick (1997) for a similar continuous maize system in Ohio, USA. Similar to our recent N_2O flux measurements under CT and NT (Choudhary et al., 2001), spatial variations in N_2O emissions were large. The mean flux rates ranged from 0.175 to 13.32, 0.175 to 16.91 and 0.088 to 30.05 kg N_2O-N/ha/year in PP, K17 and K34, respectively.

Although overall comparison of treatment means did not show any discernible differences between management practices, the trends in data suggested that the K34 had lower emissions ($P = 0.1$) compared with those in the PP (Table 2). During early crop growth (November and December), the management practices had little effect on N_2O emissions (Fig. 2c). During the first 8 weeks of measurements, N_2O fluxes

Table 2
The effects of tillage systems on the means of N_2O emissions from the Kairanga field sites

Treatment	N_2O emissions		
	Per hour (g N_2O-N/ha)	Per day (g N_2O-N/ha)	Per year (kg N_2O-N/ha)
PP[a]	0.37	8.88	3.24
K17[b]	0.39	9.36	3.42
K34[b]	0.27	6.48	2.37
$LSD_{0.05}$	ns[c]	ns	ns

[a] Permanent pasture.
[b] 17 and 34 years of continuous conventional grown maize, respectively.
[c] Not significant.

from the K17 treatment were lower than those in the K34 field, which probably resulted from lower application rate (153 kg/ha) of the starter N fertiliser to the K17 field at sowing. Additional side-dressing of 300 kg/ha of urea in early December did not appear to have had much effect on N_2O emissions. Coupled with the very dry summer (which followed the wet October), the fertiliser added (especially the urea side-dressing) was probably not utilised effectively because of lack of rainfall and resulting dry soils (T.G. Shepherd, pers. commun., 2000). Some urea granules were still visible on the soil surface 2 weeks after application.

In January, the effects of management practices started to show when N_2O emissions in the PP reached the lowest flux (approximately 0.1–0.2 mg N_2O-N/ha/day), due to rapid drying of soil in the December–February summer period (data not shown). On the other hand, N_2O fluxes remained high in the K17 and K34 fields (0.4–1.4 and 0.7–1.4 mg N_2O-N/ha/da, respectively) indicating that during the maize growth period in summer, biological activities remained high.

In February, N_2O emissions decreased in the K17. Similarly, in the K34 field, N_2O fluxes started to drop sharply in March. Rainfall was also low in February and March (Fig. 1). However, the 8.5 mm rain before sampling on March 15, and the 9.5 mm that fell during the day, seemed to have created a burst of N_2O flux from PP: It reached almost 2.4 mg N_2O-N/ha/day,the highest emission rate recorded during the sampling period. The steady decrease of N_2O emissions in the K17 and K34 fields coincided with crop maturation (Fig. 2c). The decrease was more pronounced in the K34 after harvest. Maize in the K34 field was harvested for silage on March 17 and 18. Maize in the K17 resembled that in the K34 field, and was senescent during autumn.

In the cropped soils, N_2O emissions decreased after March, although the PP maintained higher fluxes (Fig. 2c). More frequent rainfall events during April and May (Fig. 1) did not seem to have affected N_2O emissions in the K17 and K34 fields, the emissions remained the lowest (Fig. 2c). There are several likely explanations for this phenomenon. It was probable that little precipitation led to low soil water, thus creating denitrification. Denitrification measured by using acetylene inhibition at the same sites indicated that denitrification rates were high (B.K. Daly, pers. commun., 2000). Alternatively, low soil nitrate levels, low water content in the soil, and low C input through root growth by the senescent crop perhaps slowed down biological activities in the soil, resulting in reduced N_2O emissions.

Grain maize in the K17 was harvested on 19 May, with crop residue left on the soil surface. Also on 19 May sampling was conducted, following a rainfall event (30 mm on 17 May) 2 days before, but the expected flush of N_2O fluxes did not occur (Fig. 2c). To determine if the N_2O fluxes were affected after 4 days, another sampling was carried on 23 May. However, no such differences in nitrous gas emissions were found between the two sampling dates in K17 and K34 (Fig. 2c). This may be due to the unchanged soil conditions: although soil temperature in the K17 decreased moderately (Fig. 2b), SWC in K17 did not differ much due to the surface residue left in the field (Fig. 2a). However, a slight decrease in SWC in the PP led to 41% reduction in N_2O fluxes. This indicates that SWC was a governing factor in N_2O emissions in PP.

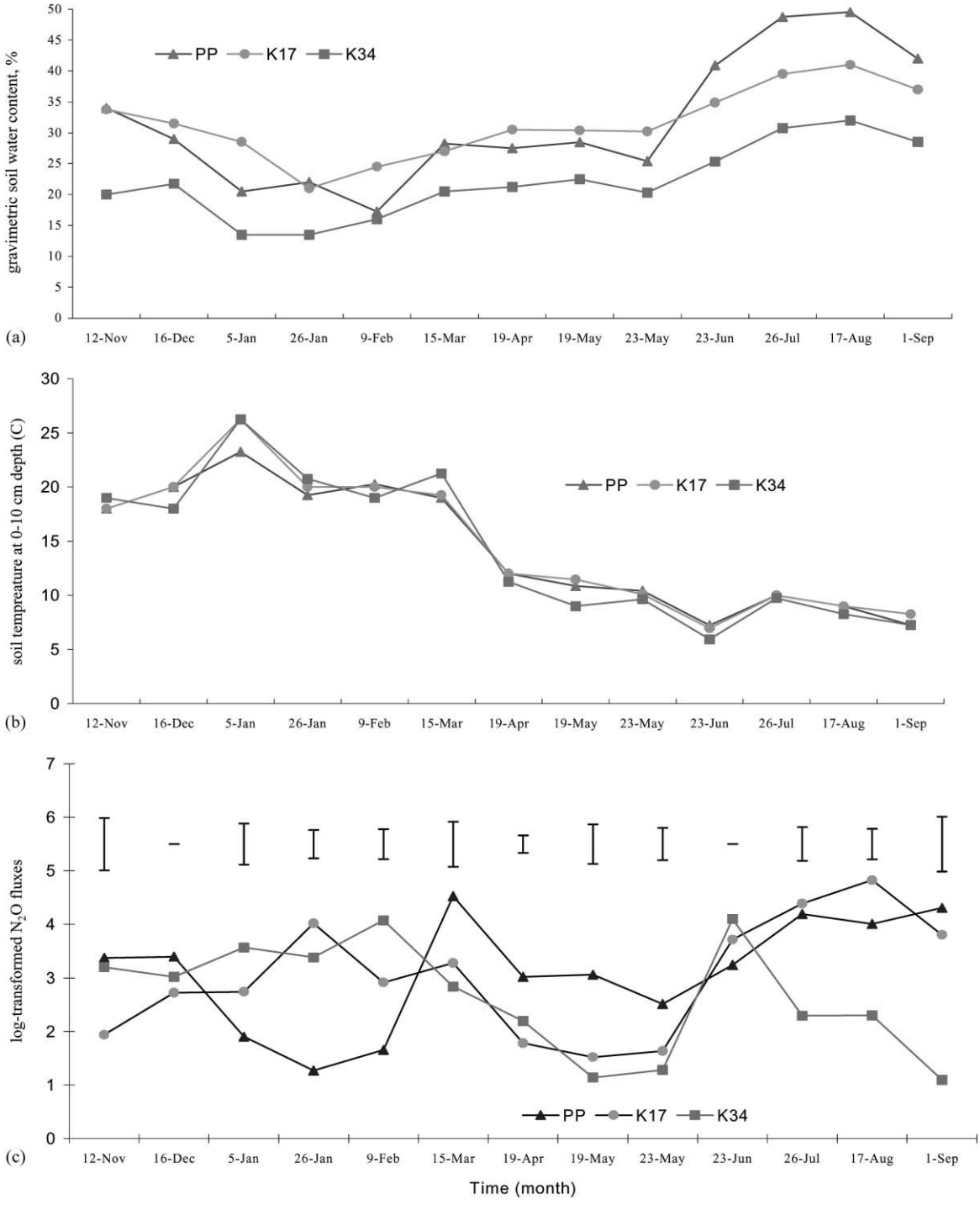

Fig. 2. The effect of PP, 17-year continuous cultivation (K17) and 34-year continuous cultivation (K34) on: (a) SWC; (b) soil temperature; and (c) log-transformed means of N_2O emissions. (vertical bars represent LSDs).

During the fallow in June there was a sudden significant increase in N_2O emissions in both the K17 and K34 fields (Fig. 2c). A more steady increase was observed in the PP. With the onset of winter and a colder period, soil temperature dropped (Fig. 2b), and significant differences became apparent between the treatments. N_2O fluxes declined and returned to rates similar to those observed during autumn in the K34, whereas the PP and K17 field emissions steadily increased. The explanation for such behaviour of soil N_2O fluxes is rather complicated without measurements of additional parameters (such as soil ammonium and nitrate levels, microbial biomass, substrate induced respiration, etc.). Based on the limited available data, low emissions during winter were possibly due to low temperatures (Fig. 2b). On the other hand, interestingly, the highest fluxes measured were during winter, and were 2.7 and 2.2 mg N_2O-N/ha/day in the K34 and K17, respectively. These high N_2O fluxes probably reflected enhanced denitrification due to higher rainfall.

The higher organic C content plus surface residue in the K17 field (Table 1) could indicate that available C limits microbial N_2O production during winter (Kaiser et al., 1998). These authors observed a significant relationship between total N_2O emissions during winter and the ratio of dry matter-to-N content of the incorporated plant residues. The K34 had low soil organic matter content (Table 1) and, as the maize crop was harvested for silage, this left little surface residue input. When considering the N_2O emission rates after harvest in March, with the exception of the N_2O emissions burst in June, it is probable that low soil nitrate levels of applied fertiliser already utilised by the maize in K34, were the determining factors in governing emissions. Moreover, given the favourable SWC (Fig. 2a), the N_2O fluxes were still low despite other researchers reporting high emissions in winter (Kessavalou et al., 1998). This indicates that in this case soil nitrate level may be limiting. However, there is a need to establish the effect of other soil parameters on N_2O emissions.

The N_2O emissions measured from PP were higher than those reported for occasionally sheep-grazed pasture (Choudhary et al., 2001). These relatively high N_2O fluxes appeared to be associated with the pastoral management system used. The PP used in this study was intensively grazed by dairy stock, and could have larger urine returns than the occasionally sheep-grazed pasture reported by Choudhary et al. (2001). Ruz-Jerez et al. (1994) and Williams et al. (1999) have already stressed the influence of grazing animals on input of readily decomposable excreta. Considering that urine is a concentrated N solution (approx. 10 g N/l, of which 80–90% is urea), and the effective rate of application within urine patches is often greater than the equivalent of 500 kg N/ha (Haynes and Sherlock, 1986), denitrification losses could be 30–40% higher (Carran et al., 1982). High N inputs in the form of urine were apparently beyond the ability of plant uptake.

3.2. Effect of SWC on N_2O emissions

Gravimetric SWC and soil temperature measurements from the vicinity of the installed chambers are shown in Fig. 2a and b. The SWC was significantly affected by tillage treatments throughout the year, although there were no differences in soil temperature. The K34 field SWC was 22–52% lower than that in the K17 field. The pattern of SWC changes in K17 closely resembled the pattern in K34. The SWC in the PP was generally higher than that in the K34. There were no marked differences in SWC between the K17 and PP fields during the year except the winter period (June to early September). Winter SWC in the PP was substantially higher compared with the K17 and K34 fields.

The effects of SWC on N_2O emissions in the K17 and PP were different from those in the K34 (Fig. 3). In the K34 field, SMC did not seem to govern fluxes which were more apparent during wet months of April and May. The regression analyses using the measured data revealed no relationship between the SWC and N_2O fluxes in the K34 treatment. Nevertheless, the log-transformed values of N_2O emissions showed a low negative correlation ($r = -0.42$) between the two parameters (Fig. 3). However, N_2O fluxes from PP and K17 appeared to be influenced by SWC ($r = 0.72$ and 0.26, respectively). There is clear indication (Fig. 3) that low emissions occur when gravimetric SWC content is less than 30%. Above this apparent threshold, the upper level of emission values increases with water content, but low values still occur frequently, as observed by Carran et al. (1995). Although N_2O fluxes did not follow the rainfall patterns, regression analysis

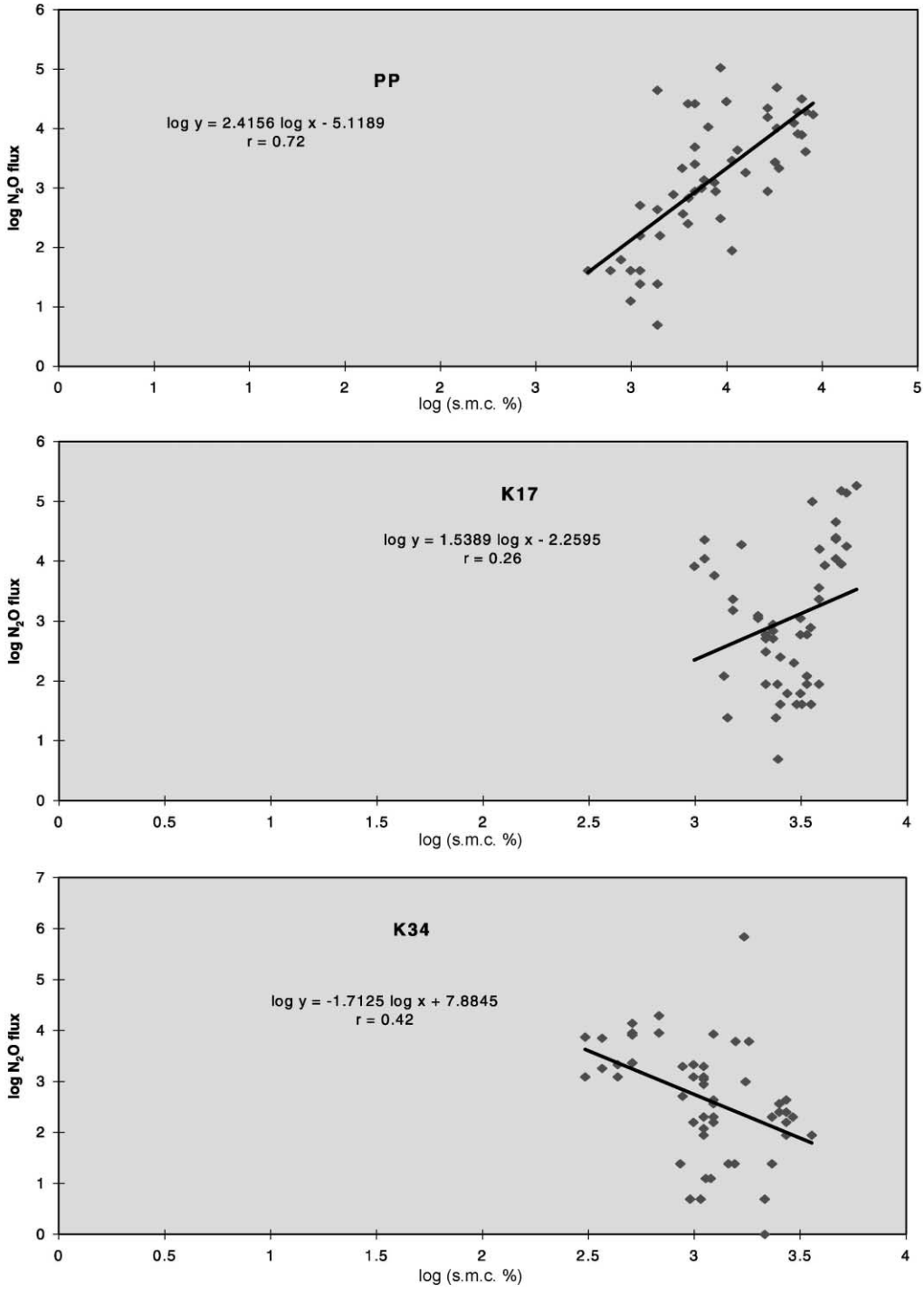

Fig. 3. Regression analysis of log-transformed data between SWC and N_2O emissions in PP, 17-year continuous cultivation (K17) and 34-year continuous cultivation (K34) soils.

Table 3
Seasonal log-transformed field N_2O emissions in the Kairanga field sites[a]

Treatment	Spring (September–November)	Summer (December–January–February)	Autumn (March–April–May)	Winter (June–July–August)	$LSD_{0.05}$
PP[b]	3.91 a	2.27 b	3.46 a	3.81 a	0.64
K17[c]	3.01 b	3.08 b	2.23 c	4.31 a	0.66
K34[c]	2.32 bc	3.53 a	2.09 c	2.90 ab	0.75

[a] Values followed by the same letter in rows show no significant differences ($P < 0.05$).
[b] Permanent pasture.
[c] 17 and 34 years of continuous conventional grown maize, respectively.

using log-transformed data indicated a low but significant relationship with SWC. These results concur with those reported by Kaiser et al. (1998) for arable soils and with Carran et al. (1995) for pasture sites in these soils.

3.3. Effects of seasonal variations on N_2O emissions

General seasonal patterns of N_2O emissions were well defined for the PP, but less pronounced for the K17 and K34 (Table 3). The pattern of N_2O emissions from the PP are consistent with the data of Carran et al. (1995) for the same soil type, and the values for the wet season are similar to those recorded by Ruz-Jerez et al. (1994) in low fertility soils.

Seasonal grouping of monthly log-transformed N_2O emissions showed significant differences in all treatments (Table 3). Summer season N_2O emissions in the PP were lower than those in other seasons, whereas no discernible differences were observed in other seasons. Although N_2O fluxes during spring and summer were similar in the K17 field, they were significantly lower than the winter fluxes, and higher than the autumn ones. There were considerably higher emissions in summer than in autumn in the K34, but seasonal variation between winter and spring was less profound. Mixed N_2O flux response to seasonal variations between treatments makes it difficult to interpret these data. Similar patterns in gas emissions in the K17 and PP during the wet season suggest that SWC is a key factor controlling N_2O emissions in soils. Carran et al. (1995) postulated that the absence of significant emission events while the soil is dominantly aerobic suggest that nitrification or other transformations of urine-derived N do not contribute to overall emissions in an important way. This pattern suggests that denitrification was the primary source of N_2O in the PP.

The onset of wet season can be early, as in 1996–1997, or late as in 1997–1998 (Fig. 1). While wet season fluxes in the K34 were generally low, high rainfall certainly influenced N_2O emissions in the K17 and PP fields. As suggested earlier, losses in N_2O during the wet season may form a major portion of total annual emissions from grazed pasture and cropped fields.

4. Conclusions

Annual N_2O fluxes ranged widely from 0.18 to 13.32, 0.18 to 16.91, and 0.09 to 30.05 kg N_2O-N/ha in the PP, K17 and K34 fields, respectively. Overall average annual N_2O emissions from the K34 (2.37 kg N_2O-N/ha) were lower at ($P = 0.1$) than the K17 fields (3.42 kg N_2O-N/ha). The latter were similar to emissions from pasture (3.24 kg N_2O-N/ha). Depleted total C and N content in the K34, which were low due to continuous intensive cropping, low surface residue (as DM removed for silage), and decreased water holding capacity, as compared with K17, could have limited the denitrification process.

In accordance with previous studies (Ruz-Jerez et al., 1994; Carran et al., 1995), we found N_2O emissions from grazed pasture were low during the summer (dry) period and increased during the winter (wet) season. There were no differences in N_2O between the K17 and K34 during the summer season but N_2O emission rates in winter were lower in the K34.

This study represents the first New Zealand comparison of N_2O emission estimates from long-term

cropped and permanent pasture soils. While the uncertainties associated with these estimates are likely to be large due to high temporal variability observed in the N_2O emissions, our estimates based on low frequency of measurements (13 sampling) over 1 year were in general agreement with those in the literature. Bouwman (1996) showed that N_2O emission estimates from agricultural soils increase as the frequency of measurement increases. Therefore, further prolonged studies with a high frequency of sampling are required to confirm and obtain a robust average yearly value for pasture and cropped soils in New Zealand.

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