Plant Soil (2008) 309:227–237
DOI 10.1007/s11104-007-9444-9

REGULAR ARTICLE

# Effects of dairy farming intensification on nitrous oxide emissions

**J. Luo · S. F. Ledgard · C. A. M. de Klein · S. B. Lindsey · M. Kear**

Received: 25 July 2007 / Accepted: 5 October 2007 / Published online: 20 October 2007


**Abstract** A dairy farm system trial was conducted between September 2003 and August 2005 to evaluate the effect of integration of maize silage forage on nitrous oxide ($N_2O$) emissions. Potentially, the integration of low-protein forage (e.g. feeding cows with maize silage) to reduce dietary-nitrogen (N) concentration can mitigate environmental N emissions and increase N use efficiency. The dairy farm systems consisted of a maize supplementation system with a stocking rate of 3.8 cows $ha^{-1}$ of grazed pasture with maize silage brought in and a control system with a stocking rate of 3.0 cows $ha^{-1}$ of grazed pasture. Direct and indirect $N_2O$ emissions from all components of the farm systems were either measured using a closed chamber technique or calculated using the New Zealand IPCC inventory methodology. Annual average $N_2O$ emissions were slightly lower on the maize supplementation pasture than on the control pasture. Annual total $N_2O$ emissions from the "whole" farm systems (including direct and indict emissions from the grazed pastures, maize growing land, N fertilizer use and associated land application of farm effluent) were 7.71 and 8.00 kg $N_2O$–N $ha^{-1}$ of dairy farm on the control and maize supplement farm systems, respectively. The corresponding annual milk production was 13,437 and 17,925 kg $ha^{-1}$. Therefore, the $N_2O$ emission per kg of milk production from the maize supplementation was 22% lower than that from the control system. This was due to the much greater efficiency of N use from low-protein maize silage than from pasture. The results suggest that the integration of low-protein forage can be an effective management practice to mitigate adverse environmental effects of increasing stocking rates in the New Zealand dairy farm systems, in terms of $N_2O$ emissions per unit of milk production.

**Keywords** Dairy farm · Nitrous oxide · Grazed pasture · Maize supplement · New Zealand

Responsible Editor: Per Ambus.

J. Luo (✉) · S. F. Ledgard · S. B. Lindsey · M. Kear
Land and Environmental Management,
AgResearch Ruakura,
Private Bag 3123,
Hamilton, New Zealand
e-mail: Jiafa.luo@agresearch.co.nz

C. A. M. de Klein
Land and Environmental Management,
AgResearch Invermay,
P.O. Box 50034,
Invermay, New Zealand

## Introduction

In grazed pasture soils, $N_2O$ gas is mostly generated from N present in the dung and urine of grazing animals and fertilizer N (de Klein and Ledgard 2005;

Oenema et al. 2005). Nitrous oxide is an intermediate product of the soil processes of nitrification (biological oxidation of soil ammonia to nitrite and nitrate) and denitrification (biological reduction of soil nitrate to gaseous N compounds) (Firestone and Davidson 1989). These processes are affected by a number of soil factors, such as soil oxygen and moisture contents, temperature, mineral N content, available soil carbon and pH (Tiedje 1988). Weather conditions, such as rainfall, can affect soil moisture and oxygen contents, and consequently affect $N_2O$ production (Eckard et al. 2003).

Estimates indicate that $N_2O$ emissions in 2004 from New Zealand agriculture produced 39,980 t of $N_2O$ annually (Ministry for the Environment 2006), which represents 16.5% of national greenhouse gas ($CO_2$-equivalent) emissions. New Zealand's target for 2008–2012 under the Kyoto Protocol is to reduce greenhouse gas emissions to 1990 levels. However, the estimated emissions of $N_2O$ in 2004 were about 25% higher than in 1990 (Ministry for the Environment 2006). The increase has been associated with livestock farming intensification, particularly dairy intensification (Ledgard et al. 2002). Production on dairy farms in New Zealand has been steadily increasing over time (Livestock Improvement 2003). This has occurred through several factors including increased stocking rates, increased feed supply and increased supplementary forage feeds.

There are a number of possible management options that can reduce $N_2O$ emissions from dairy farms. These options include using restricted grazing regimes (de Klein et al. 2006), using nitrification inhibitors (Di et al. 2007), applying fertilizers at an optimum times (Eckard et al. 2003), and using low-N feed supplements as an alternative to using N-rich pasture. Integration of the fertilizer N-boosted pasture with low-protein maize silage could reduce dietary-N concentrations, reduce environmental N emissions and consequently increase N use efficiency (e.g. Jarvis et al. 1996; Ledgard et al. 2004; Misselbrook et al. 2005; Oenema et al. 1997). There is little information available on the effects of such management practices on total $N_2O$ emissions from whole farm systems. Thus, a field study was carried out between September 2003 and August 2005 to evaluate the effect of integration of maize silage forage on $N_2O$ emissions. In this paper we summarise $N_2O$ emission data obtained from several components (grazed pastures, maize-growing land and land application of farm effluent) of the dairy farm system. The impact of this farm system on environmental efficiency in terms of $N_2O$ emissions per unit of milk production is also assessed.

## Materials and methods

### Experimental site

The experimental site was located in the Waikato Region in New Zealand and contained white clover (*Trifolium repens* L.) and perennial ryegrass (*Lolium perenne* L.) pasture on Te Kowhai silt loam soil (Typic Ochraqualf, Soil Survey Staff 1990). The soil was poorly drained with compact subsoil and slow permeability. Soil properties of the upper 75 mm of the soil profile are: total N of 0.45%, total C of 5.0%, organic matter of 8.6%, pH of 6.4, bulk density of 0.94 Mg $m^{-3}$, and cation exchange capacity of 17 me/100 g. The site had an annual rainfall of about 1,200 mm and mean annual temperature of 14°C. Winter and spring at the study site were relatively wet with cool temperatures, whereas summer and early autumn were dry and warm.

### Farm systems

A Resource Efficient Dairy (RED) farmlet system trial had been established at the experimental site to evaluate intensive dairy farm systems involving treatments with integration of N fertilizer, maize silage and winter management strategies (Clark 2003). The trial had six experimental farmlets. Feed varied from 15 to 40 t dry matter (DM) $ha^{-1}$ $year^{-1}$, with stocking rates, ranging from 2.3 cows $ha^{-1}$ to 6.9 cows $ha^{-1}$. The treatment design was based on achieving the same comparative stocking rate of about 85 kg live weight $t^{-1}$ DM across all treatments. There were 21 Holstein–Friesian cows on each farmlet with farmlet size varying from 3 to 9 ha. Milk yield was measured by weekly herd tests, with samples analysed to determine crude protein and N concentrations. Detailed information on the animal management regime, pasture composition and external inputs to these dairy systems has been previously published (Jensen et al. 2005). $N_2O$ emissions from two of the farm systems in the RED farmlet system trial were evaluated. These systems were:

- Control: Typical white clover/perennial ryegrass pasture with an average stocking rate of 3.0 cows ha$^{-1}$ and a normal rotational pasture grazing regime (i.e. cows grazed on a paddock for a day and were then moved to fresh paddocks to allow pasture to regrow). The stocking rate is a common stocking rate for dairy farms in the Waikato Region in New Zealand. The pasture received 175 kg urea–N ha$^{-1}$ year$^{-1}$, in 5 split applications throughout the year. The farmlet was estimated to grow 17.5 t DM ha$^{-1}$ year$^{-1}$, and no external feed was brought in.
- Maize supplement: Maize supplementation to cows on pasture with an average stocking rate of 3.8 cows ha$^{-1}$. The same rotational grazing regime was used, and the pasture also received 175 kg urea–N ha$^{-1}$ year$^{-1}$, in 5 split applications throughout the year. The farmlet was estimated to grow 17.5 t DM ha$^{-1}$ year$^{-1}$. Maize silage (5.6 t DM ha$^{-1}$) was brought in annually and was generally fed in autumn and winter when pasture growth was slow. Maize growing was carried out on nearby land and the annual yield was 21 t DM ha$^{-1}$. The maize growing field was cultivated from previous pastureland in October 2003, and maize was then sown. N fertilizer was applied at a rate of 40 kg N ha$^{-1}$ at the time of sowing. In December 2003, N fertilizer was again applied as a side dressing at a rate of 138 kg urea–N ha$^{-1}$. Maize

**Table 1** Nitrous oxide measurement on grazed pastures, animal grazing information, and soil water-filled pore space (WFPS) (0–75 mm depth) for each measured occasion

| Farmlet | Measurement period | Average grazing intensity (cows ha$^{-1}$ day$^{-1}$) | Seasons represented | Number of grazing events in the season | WFPS (%)[a] |
|---|---|---|---|---|---|
| Control | Nov–Dec 2003 | 63 | Spring/early summer (Sep–Dec 2003) | 5.8 | 69 (5.0, $n$=9) |
| | Mar–Apr 2004 | 84 | Summer/autumn (Jan–Apr 2004) | 4.3 | 44 (1.6, $n$=8) |
| | Jun–Jul 2004 | 336 | Late autumn/winter (May–Aug 2004) | 1.1 | 91 (1.5, $n$=11) |
| | Oct–Nov 2004 | 63 | Spring/early summer (Sep–Dec 2004) | 5.8 | 81 (2.4, $n$=6) |
| | Feb–Mar 2005 | 84 | Summer/autumn (Jan–Apr 2005) | 4.3 | 32 (3.7, $n$=4) |
| | Jun–Jul 2005 | 294 | Late autumn/winter (May–Aug 2005) | 1.3 | 83 (1.3, $n$=10) |
| Maize supplementation | Nov–Dec 2003 | 63 | Spring/early summer (Sep–Dec 2003) | 7.3 | 59 (4.2, $n$=9) |
| | Mar–Apr 2004 | 84 | Summer/autumn (Jan–Apr 2004) | 5.4 | 41 (1.6, $n$=8) |
| | Jun–Jul 2004 | 336 | Late autumn/winter (May–Aug 2004) | 1.4 | 89 (1.0, $n$=11) |
| | Oct–Nov 2004 | 63 | Spring/early summer (Sep–Dec 2004) | 7.3 | 78 (2.5, $n$=6) |
| | Feb–Mar 2005 | 84 | Summer/autumn (Jan–Apr 2005) | 5.4 | 32 (1.9, $n$=4) |
| | Jun–Jul 2005 | 336 | Late autumn/winter (May–Aug 2005) | 1.4 | 87 (1.2, $n$=10) |

Numbers in parenthesis indicate the standard errors of the mean and numbers of samples.

[a] Soil water-filled pore space (WFPS) at "field capacity" was 65%.

was cut and silage was made at the end of March 2004.

### Measurement of $N_2O$ and statistical analysis

Nitrous oxide emissions were measured both on the grazed pasture and on the maize-growing land. Detailed measurements of $N_2O$ emitted from the control and maize supplementation pastures were made within one or two grazing intervals on two replicated paddocks during three typical grazing patterns/seasons in each year between September 2003 and August 2005 (Table 1). Measurements were generally made on one occasion 1 or 2 days before the grazing events, and subsequently on a number of occasions before commencement of the next grazing event. The measurements always occurred at least one month after urea fertilizer application, so direct emissions from the application of urea should not affect these measurements (Luo et al. 2007a). A separate study on direct emission of $N_2O$ from application of N fertilizer was conducted on the same pasture in the same seasons as the current study (Luo et al. 2007a). The $N_2O$ emission factor for fertilizer N obtained from that study was used to calculate the direct emissions from the application of urea on this pasture when calculating the emissions from the whole farm system.

Measurements of $N_2O$ on the maize-growing land were made during the year 2003/2004. The measurements were made on one occasion in October 2003, 5 days before the annual ryegrass ungrazed-paddock was ploughed for maize growing, and on 15 occasions over the 5-month maize-growing period. Direct emissions of $N_2O$ from application of N fertilizer were included in these measurements on the maize-growing land.

A closed chamber technique was used to measure $N_2O$ emissions, and the methodology was based on that of Saggar et al. (2004) and the NzOnet studies on excreta $N_2O$ emissions (de Klein et al. 2003). We determined coefficients of variation (CVs) of $N_2O$ emissions from the grazed pasture using this chamber technique in a preliminary study. Using the obtained CVs and considering the likely difference between the $N_2O$ emissions from the control and maize supplement pastures, we calculated that about 12 replicates of measurement would be required to determine if there was any difference at $P=0.05$. Therefore, 12 replicate chambers were used for both the grazed pasture and the maize growing land and these were randomly placed in the field. Details of sample collection, analysis and calculation of $N_2O$ emission rates have previously been presented (Luo et al. 2007a). Briefly, the hourly emissions were integrated over time, for each chamber, to estimate the total emission over the measurement period for both grazed pastures and maize growing land. The geometric means of these integrated emissions were then calculated. Seasonal emissions from the grazed pastures were estimated by multiplying the geometric means of the $N_2O$ emissions over one grazing interval by the number of the grazing events during the season (Table 1). Annual emissions were then calculated by adding all the seasonal emissions. The integrated emissions per chamber were log-transformed and an ANOVA analysis was performed to identify differences between treatments.

### New Zealand IPCC calculations

The New Zealand IPCC inventory methodology was used to calculate $N_2O$ emissions from sources that were not included in the field measurements (Ministry for the Environment 2006). These sources consisted of leached N, land-applied effluent N and volatilised ammonia N. In these calculations, measured data for the amount of N leached were used (Ledgard et al. 2006). The New Zealand IPCC inventory methodology assumes that 5% of total excreta is collected as effluent under a normal rotational pasture grazing regime. The New Zealand IPCC inventory methodology also assumes that 20% of the excreta and effluent N and 10% of the fertilizer N are lost by ammonia volatilisation (Ministry for the Environment 2006). The emission factor for direct emissions from applied effluent N is 1%, and the emission factors for indirect emissions from leaching N and volatilising N are 2.5% and 1%, respectively (Ministry for the Environment 2006).

### Soil water contents

Four replicate soil samples [with 6 soil cores (25 mm diameter) for each replicate] were taken (0–75 mm depth) from the control and maize supplementation pastures and maize growing land on most of the gas sampling days. The gravimetric soil water content (SWC) was measured in the soil samples and soil volumetric SWC calculated using bulk density data for the site (Luo et al. 2007a). Soil particle density was assumed to be 2.65 Mg $m^{-3}$ (Danielson and Sutherland 1986). Total porosity was calculated for the soil, according to the following equation:

$$\text{Total pore space}(\%) = 100 \times [1 - (\text{bulk density}/\text{particle density})] \quad (1)$$

Water-filled pore space (WFPS) was calculated as the ratio of the volumetric SWC to the total pore space.

## Results

### Nitrous oxide emissions from grazed pastures

#### *Measured hourly $N_2O$ emission fluxes*

Nitrous oxide fluxes were generally similar between the control and maize supplement pastures before grazing events in all measured seasons (Fig. 1a–f). After grazing, $N_2O$ fluxes generally increased in most measured seasons, reaching maxima from 1 to 14 days after grazing. After this, fluxes declined to levels similar to those measured prior to grazing. The increases in $N_2O$ fluxes following grazing were significant ($P<0.05$) in both late autumn/winter seasons, but the increases were marginal (not statistically significant at $P=0.05$) in the

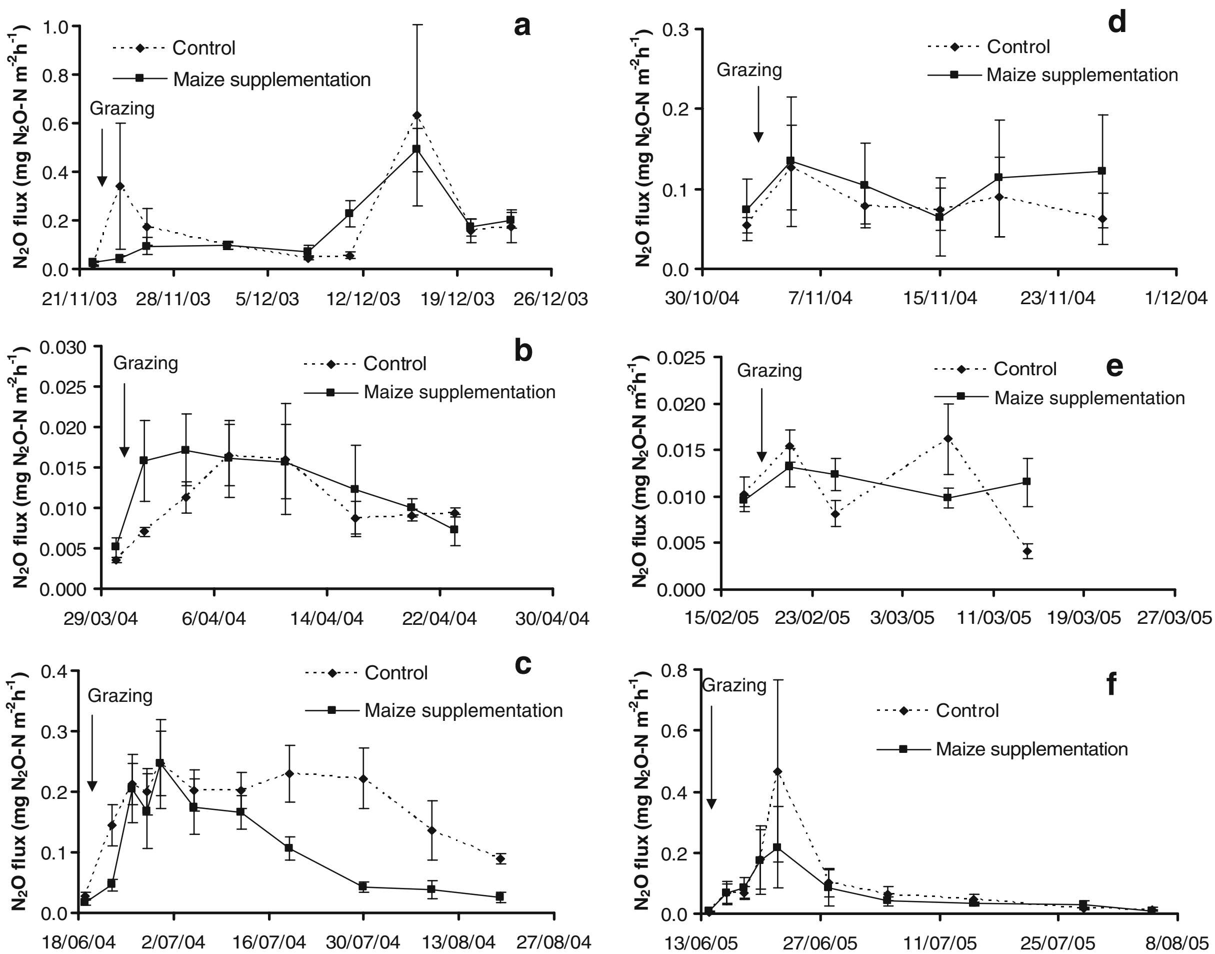


**Fig. 1** **a**–**f** Nitrous oxide emissions following grazing events (*bars* represent SE, $n=12$). Note the differences in scale between seasons. For each panel, the *arrow* indicates the grazing day

other seasons. The magnitude of the $N_2O$ fluxes was high during the late autumn/winter and early spring seasons but was extremely low during the late summer and autumn. Generally, the measured hourly $N_2O$ fluxes from the pastures in different seasons were in the following order: late autumn/winter ≥ spring/early summer > late summer/early autumn.

The patterns of $N_2O$ fluxes following the grazing events were not always consistent among the pastures. Over the measurement periods in the spring, summer and autumn seasons, the magnitudes of $N_2O$ fluxes on the maize supplementation pasture were generally similar to those on the control pasture on most sampling occasions. On several sampling occasions following grazing events during the winter sampling seasons, the $N_2O$ fluxes on the maize supplementation pasture were lower (but not always significantly at $P<0.05$) than those on the control pasture.

### *Total nitrous oxide emissions*

Generally, on both control and maize supplementation pastures the $N_2O$ emissions measured in the summer/early autumn seasons (Jan–Apr) were lower ($P<0.05$) than in the spring/early summer seasons (Sep–Dec) and were also lower ($P<0.05$) than in the late autumn/winter seasons (May–Aug) (Table 2). This applied to both study years. Therefore, the $N_2O$ emission rate on both control and maize supplementation pastures, calculated over the whole summer/early autumn seasons (Jan–Apr), were substantially lower ($P<0.05$) than the emissions in the other seasons. Generally, the whole-seasonal $N_2O$ emission rates from the pastures in different seasons were in the following order: spring/early summer ≥ late autumn/winter > summer/early autumn. On both control and maize supplementation pastures, the calculated overall yearly $N_2O$ emission rates were higher ($P<0.05$) during the first study year (Sep 2003–Aug 2004) than those during the second study year (Sep 2004–Aug 2005) (Table 2).

Due to large variability, no significant ($P>0.05$) differences in the total annual $N_2O$ emission rates between the control and maize supplementation pastures were found. However, in the two study years there was a clear trend of lower $N_2O$ emission rates (but not always statistically significant at $P=0.05$) per grazing interval from the maize supplementation pasture than from the control pasture in most of the measured seasons. Although not statistically significant, there was a trend for the yearly average $N_2O$ emission rates to be lower for the maize supplementation pasture (4.03 kg $N_2O$–N $ha^{-1}$) than for the control pasture (4.67 kg $N_2O$–N $ha^{-1}$) (Table 2).

### *Soil water*

Soil WFPS values are presented in Table 1. The field capacity of the study sites was at a WFPS value of about 65%. In the late autumn/winter study periods, soil moisture was consistently above field capacity on all pastures. Throughout the spring/early summer, soil WFPS values were close to or higher than the field capacity on most sampling days. However, during late summer/autumn, the soil remained very dry, with soil WFPS being much below the field capacity.

**Table 2** Calculated nitrous oxide emission rates on grazed pastures

| Season | Rate over one grazing interval (kg $N_2O$–N $ha^{-1}$ grazing interval$^{-1}$) | | Estimated rate per season (kg $N_2O$–N $ha^{-1}$ season$^{-1}$) | |
|---|---|---|---|---|
| | Control | Maize supplement | Control | Maize supplement |
| Sep–Dec 2003 | 0.48 | 0.47 | 2.74 | 3.26 |
| Jan–Apr 2004 | 0.08 | 0.06 | 0.32 | 0.33 |
| May–Aug 2004 | 2.72 | 1.40 | 2.99 | 1.94 |
| Sep 03–Aug 2004 | | | 6.05 | 5.53 |
| Sep–Dec 2004 | 0.31 | 0.16 | 1.79 | 1.18 |
| Jan–Apr 2005 | 0.07 | 0.05 | 0.28 | 0.30 |
| May–Aug 2005 | 0.97 | 0.75 | 1.22 | 1.05 |
| Sep 04–Aug 2005 | | | 3.29 | 2.53 |
| Average annual rate | | | 4.67 | 4.03 |

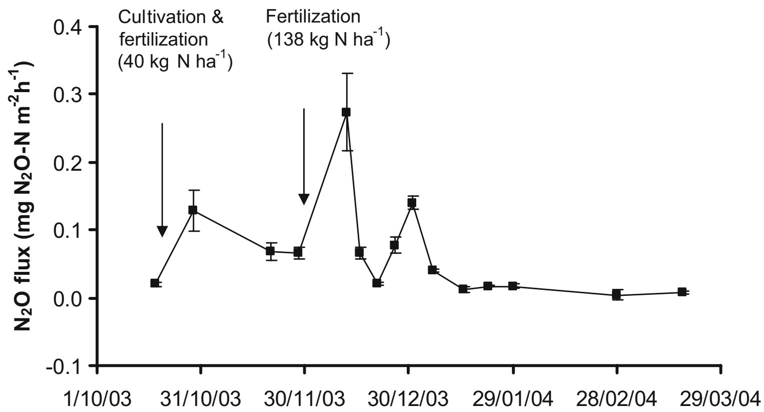


**Fig. 2** Nitrous oxide emissions during maize growing period (*bars* represent SE, $n$=12)

## Nitrous oxide emissions from maize-growing land

After soil was cultivated and fertilised (40 kg N ha$^{-1}$) in October 2003, $N_2O$ fluxes increased on the maize growing land (Fig. 2). The highest $N_2O$ flux (0.28 mg $N_2O$–N m$^{-2}$ h$^{-1}$) was observed in December 2003, 2 days after application of urea fertilizer at 138 kg N ha$^{-1}$. Integration of the measured $N_2O$ over the maize growing period of 5 months resulted in total $N_2O$ emissions of 2.1 kg $N_2O$–N ha$^{-1}$ from the maize growing land.

As the maize silage yield was about 21 t DM ha$^{-1}$, it was calculated that about 0.10 kg $N_2O$–N was emitted per tonne of maize silage DM produced. Since 5.6 t of maize silage DM was brought in per hectare of grazed pasture, the maize production contributed 0.56 kg $N_2O$–N ha$^{-1}$ of pasture to the whole maize supplement dairy system.

**Table 3** Intake and excreta N in the trial (average between 2003/2004 and 2004/2005)

| Farm system | Control | Maize supplement |
|---|---|---|
| Intake (kg N ha$^{-1}$ year$^{-1}$)[a] | 499 | 547 |
| Milk (kg N ha$^{-1}$ year$^{-1}$)[a] | 79 | 103 |
| Excreta (kg N ha$^{-1}$ year$^{-1}$)[b] | 419 | 443 |
| Excreta to farmlet (kg N ha$^{-1}$ year$^{-1}$)[c] | 398 | 421 |
| Excreta to effluent (kg N ha$^{-1}$ year$^{-1}$) | 21 | 22 |

[a] Data from the RED trial annual reports (Lancaster and Leydon-Davis 2005).

[b] From “Intake N – Milk N”.

[c] Adjusted for 5% transfer to effluent.

## Total $N_2O$ emissions from whole farm systems

For the whole farm calculations, we estimated N intake and excreta N for the years 2003/2004 and 2004/2005 (Table 3). The New Zealand IPCC inventory methodology assumes that under normal rotational grazing (e.g. the control and maize supplementation pastures) 95% of cow excreta N would be deposited to grazed pastures, while the remaining 5% would be deposited on lanes or collected as dairy farm effluent in dairy yards. It was calculated that annual amounts of effluent N would be 21 and 22 kg N ha$^{-1}$ from the control and maize supplement dairy systems, respectively (Table 3).

In addition to the measuring $N_2O$ emissions from grazed pastures and maize growing land, we calculated $N_2O$ emissions from sources that were not included in these field measurements (Table 4). The annual direct emissions of $N_2O$, which would result from land application of the effluents, would be 0.21 and 0.22 kg $N_2O$–N ha$^{-1}$, using NZIPCC emission factor for effluent of 1%, from the control and maize supplement dairy systems, respectively. Annual nitrate leaching rates were 32 and 34 kg N ha$^{-1}$ from the control and maize supplementation grazed pastures in 2004/2005, respectively. These data demonstrate that the maize supplementation pasture slightly increased annual nitrate leaching losses by 6% compared to the control farm. Using these data, annual indirect $N_2O$ emissions from N leached from dairy farms were calculated at 0.80 and 0.85 kg $N_2O$–N ha$^{-1}$ from the control and maize supplement dairy systems, respectively. Therefore, any measures taken to reduce N leaching from pastures can also reduce indirect $N_2O$ emissions. Indirect $N_2O$ emissions from the N, which

**Table 4** Estimates of total annual $N_2O$ emissions for whole farm systems (kg $N_2O$–N $ha^{-1}$ dairy pasture land)

| Source | Emission factor (%) | Control | Maize supplement |
|---|---|---|---|
| Direct emission | | | |
| Fertilizer to dairy farm | 0.56 – (Luo et al. 2007a, b) | 0.98 | 0.98 |
| Grazed pasture | | 4.67 | 4.03 |
| Maize-growing land (including fertilizer use) | | | 0.56 |
| Effluent N applied to dairy farm | 1 – NZIPCC | 0.21 | 0.22 |
| Sub-total (direct) | | 5.86 | 5.80 |
| Indirect emission | | | |
| Leached N from dairy farm and application of fertilizer | 2.5 – NZIPCC, using measured leached N data | 0.80 | 0.85 |
| Leached N from land application of dairy effluent | 2.5 – NZIPCC | 0.03 | 0.03 |
| Leached N from maize-growing land and application of fertilizer | 2.5 – NZIPCC, using measured leached N data | | 0.22 |
| Volatilised $NH_3$ from fertilizer (dairy farm) | 1 – NZIPCC | 0.18 | 0.18 |
| Volatilised $NH_3$ from fertilizer (maize-growing land) | 1 – NZIPCC | | 0.04 |
| Volatilised $NH_3$ from grazed farm | 1 – NZIPCC | 0.80 | 0.84 |
| Volatilised NH3 from land application of dairy effluent | 1 – NZIPCC | 0.04 | 0.04 |
| Sub-total (indirect) | | 1.85 | 2.20 |
| Total | | 7.71 | 8.00 |
| Reduction in $N_2O$ emission compared to control (%) | | | −4 |

was leached as a consequence of application of effluent from dairy yards and from the maize growing site, were generally low, so their contributions to the total emissions were small (Table 4). Indirect $N_2O$ emissions for volatilised ammonia N from several sources, including fertilizers, cow excreta on pastures and effluent, were included in our calculations. There were relatively high contributions to the total $N_2O$ emissions from ammonia volatilised from the grazed pastures (Table 4). When all possible sources contributing to emissions of $N_2O$ were included, we estimated total annual emissions of 7.71 and 8.00 kg $N_2O$–N $ha^{-1}$ of grazed pasture under the control and maize supplement farm systems, respectively (Table 4).

## Discussion

### Nitrous oxide emissions from grazed pastures

The observed seasonal variation in $N_2O$ emissions from the grazed pastures (Fig. 1, Table 2) can largely be explained by corresponding seasonal variations in soil water content (Table 1). High $N_2O$ emissions in the late autumn/winter or spring/early summer seasons were observed when the WFPS was close to or above "field capacity". This indicates that formation of anaerobic sites in the soil, in addition to excreta N return to the soil, both fundamental requisites for denitrification, was mainly responsible for these high $N_2O$ fluxes (Luo et al. 2007b). Several other field studies have also shown increased denitrification rates and $N_2O$ emissions associated with restricted soil aeration at high soil water content in grazed pasture systems in New Zealand and south-eastern Australia (e.g. Eckard et al. 2003; Ledgard et al. 1996; Luo et al. 1999b, 2000; Menneer et al. 2005). Higher grazing intensities on the control and maize supplementation pastures during the late autumn/winter measurement period than in the other seasons (Table 1) could also provide higher amounts of available N to the soil (data not shown), and this could have influenced the emission rates (Table 2). Grazing also causes more anaerobic environments, particularly in the late autumn/winter, as a consequence of soil compaction caused by animal treading (Luo et al. 1999a; Oenema et al. 1997; Simek et al. 2006).

Slightly lower $N_2O$ emission rates on the maize supplementation pasture than on the control pasture (Table 2) may have been caused by a reduction of the N concentration in urine patches resulting from the supplemental feed of low N maize silage (Jarvis et al. 1996; Oenema et al. 1997). The amount of excreta N deposited on the maize supplementation pasture was only slightly higher than that on the control pasture (Table 3), although the stocking rate was 3.8 cows $ha^{-1}$ on the maize supplementation pasture compared to 3.0 cows $ha^{-1}$ on the control pasture. It is generally thought that $N_2O$ emission factors from dung patches are lower than from urine patches (van Groenigen et al. 2005). Therefore lower $N_2O$ emission rates on the maize supplementation pasture may have been also due to a higher proportion of N being excreted in dung than in urine as a consequence of the low N maize silage supplementary feed (Ledgard et al. 2000). The grazing on the maize supplementation pasture may have encouraged production of $N_2$ instead of $N_2O$ in the denitrification process by supplying more available carbon (Bolan et al. 2004) due to higher carbon concentrations in excreta resulting from the addition of maize silage. Also the higher stocking rate on the maize supplementation pasture may have caused a more anaerobic soil environment as a consequence of soil compaction, and anaerobic conditions generally favour production of $N_2$ from denitrification (Barton et al. 1999; Bolan et al. 2004).

## Nitrous oxide emissions from maize-growing land

As $N_2O$ emissions from soil are due to complex biological, chemical and physical processes (Bolan et al. 2004), it is likely that short-term changes in soil properties associated with land use changes between pasture and arable cropping influence $N_2O$ fluxes. Cultivation practices during land use change can hugely affect soil properties, such as soil structure, porosity and microbial activity (Reicosky et al. 1997), which in turn may influence $N_2O$ emissions. Conversion of pasture to arable cropping can also result in depletion of soil organic matter and soil N fertility over time (Saggar et al. 2001) and application of additional N fertilizer is required to compensate for the loss of organic N reserves. The addition of N fertilizer can significantly affect $N_2O$ emissions (Luo et al. 2007a; Smith et al. 1997). Overall, the land use change from pasture to maize cropping in this study significantly influenced the $N_2O$ fluxes. During the early maize growth period (October to early January), management practices in the maize growing land resulted in increased $N_2O$ fluxes (Fig. 2). The higher emission rates from the maize growing land were probably due to higher nitrate–N levels (data not shown), which were associated with the 2 applications of N fertilizer. The increased nitrate–N levels may have also been due to increased mineralisation and nitrification activity, caused by cultivation, which increased soil porosity and consequently increased diffusion of $O_2$ into the soil. In maize-growing land the root distribution is not as dense as under typical dairy pastureland, and therefore the uptake of N by maize may not be as efficient as by pasture. The combination of these factors could have lead to higher substrate N levels available in the soil for $N_2O$ production. However, the low soil moisture contents during the maize growing period in late spring and summer in the study area (Table 1) may have limited $N_2O$ emission rates.

## Total $N_2O$ emissions and milk production

The use of maize increased the total $N_2O$ emissions per hectare of grazed pasture by about 4%, compared to the control farm, despite the reduction in the measured emission on the maize supplementation pasture, because production of maize silage also

**Table 5** Average milk production and whole dairy system efficiencies

| | Control | Maize supplement |
|---|---|---|
| Milk (kg $ha^{-1}$ $year^{-1}$)[a] | 13,437 | 17,925 |
| Efficiency indices (kg excreta N $tonne^{-1}$ milk) | 31.2 | 24.7 |
| Efficiency indices (kg $N_2O$–N $tonne^{-1}$ milk) | 0.57 | 0.45 |
| Gain in efficiency in terms of kg $N_2O$–N $tonne^{-1}$ milk compared to control (%) | | 22 |

[a] Data from the RED trial annual reports (Lancaster and Leydon-Davis 2005).

emitted $N_2O$ (Fig. 2, Table 4). So when the maize-growing land is considered as part of the whole farm system, use of maize supplementation slightly increased the overall total $N_2O$ emissions in terms of emission rates per hectare of the grazed pastureland.

Average milk productions were 13,437 and 17,925 kg ha$^{-1}$ year$^{-1}$ from the control and maize supplement farm systems, respectively (Table 5). Total amounts of excreta N between the two systems were similar (Table 3). Thus, less N was excreted per tonne of milk produced from the maize supplement farm system compared to the control farm system (Table 5). The much higher milk production per kg N intake (Table 5) was due to the much greater efficiency of N use from low-protein maize silage than from pasture (Jarvis et al. 1996; Ledgard et al. 2003; Oenema et al. 1997).

It was calculated that the total $N_2O$ emissions were 0.57 and 0.45 kg $N_2O$–N for producing 1 t of milk from the control and maize supplement dairy farm systems, respectively (Table 5). So the emissions from the maize supplement dairy system were 22% lower than from the control system. This calculation indicates that the adverse environmental effects of increasing stocking rates in order to increase milk productivity in the dairy farm system can be mitigated, in terms of $N_2O$ emissions per unit of milk production, by using maize silage as a feed supplement.

## Conclusions

Nitrous oxide emission rates from the grazed pastures exhibited marked seasonal variation. Generally, the seasonal $N_2O$ rates varied in the following order: spring/early summer ≥ late autumn/winter > summer/early autumn. The annual average $N_2O$ emission rates were slightly lower on the maize supplementation pasture than on the control pasture. The total annual $N_2O$ emissions from the whole maize supplement farm system (including maize growing land) were slightly higher than the control farm system. However, the use of maize silage decreased the total $N_2O$ emission per tonne of milk produced by 22%, due to high conversion of N in low-protein maize into milk and relatively low excreta N compared to that from the control dairy system. These results suggest that feeding cows with low-protein maize silage to reduce the concentration of N in excreta can be a successful management practice to reduce direct and indirect $N_2O$ emissions from dairy farms.

**Acknowledgements** The authors wish to thank Dr. Dave Clark and other Dexcel staff for the RED farmlet system trial and management, the New Zealand Pastoral Greenhouse Gas Research Consortium (PGGRC) for funding this work, Dr. Surinder Saggar and Dr. Andrea Donnison for the valuable advice and the New Zealand Landcare Research for the $N_2O$ analysis.

## References

Barton L, McLay CDA, Schipper LA, Smith CT (1999) Annual denitrification rates in agricultural and forest soils: a review. Aust J Soil Res 37:1073–1093

Bolan NS, Saggar S, Luo J, Bhandral R, Singh J (2004) Gaseous emissions of nitrogen from grazed pastures: processes, measurements and modelling, environmental implications, and mitigation. Adv Agron 84:37–120

Clark D (2003) RED trial measures the effect of feed and management. Dexcelink (Spring 2003). Hamilton, New Zealand, pp 1–16

Danielson RE, Sutherland PL (1986) Porosity. In: Klute A (ed) Methods of soil analysis, part 1: physical and mineralogical methods. American Society of Agronomy, Madison, pp 443–461

de Klein CAM, Ledgard SF (2005) Nitrous oxide emissions from New Zealand agriculture – key sources and mitigation strategies. Nutr Cycl Agroecosyst 72:77–85

de Klein CAM, Barton L, Sherlock RR, Li Z, Littlejohn RP (2003) Estimating a nitrous oxide emission factor for animal urine from some New Zealand pastoral soils. Aust J Soil Res 41:381–399

de Klein CAM, Smith LC, Monaghan RM (2006) Restricted autumn grazing to reduce nitrous oxide emissions from dairy pastures in Southland, New Zealand. Agric Ecosyst Environ 112:192–199

Di HJ, Cameron KC, Sherlock RR (2007) Comparison of the effectiveness of a nitrification inhibitor, dicyandiamide, in reducing nitrous oxide emissions in four different soils under different climatic and management conditions. Soil Use Manage 23:1–9

Eckard RJ, Chen D, White RE, Chapman DF (2003) Gaseous nitrogen loss from temperate perennial grass and clover dairy pastures in south-eastern Australia. Australian Journal of Agricultural Research 54:561–570

Firestone MK, Davidson EA (1989) Microbiological basis of NO and $N_2O$ production and consumption in soil. In: MO Andreae, DS Schimel (eds) Exchange of trace gases between terrestrial ecosystems and the atmosphere. Wiley, Chichester, pp 7–21

Jarvis SC, Wilkins RJ, Pain BF (1996) Opportunities for reducing the environmental impact of dairy farming managements: a systems approach. Grass Forage Sci 51: 21–31

Jensen RN, Clark DA, Macdonald KA (2005) Resource efficient dairy trial: measurement criteria for farm systems over a range of resource use. Proc N Z Grassl Assoc 67:47–52

Lancaster J, Leydon-Davis C (2005) RED trial annual report

Ledgard SF, Sprosen MS, Brier GJ, Nemaia EKK, Clark DA (1996) Nitrogen inputs and losses from New Zealand dairy farmlets, as affected by nitrogen fertilizer application: year one. Plant Soil 181:65–69

Ledgard SF, de Klein CAM, Crush JR, Thorrold BS (2000) Dairy farming, nitrogen losses and nitrate-sensitive areas. Proc N Z Soc Anim Prod 60:256–260

Ledgard SF, Clark H, de Klein CAM (2002) Improved estimation of nitrous oxide emissions using upgraded pasture intake data for grazing animals. Report to MAF prepared by AgResearch

Ledgard SF, Finlayson JD, Gavin J, Blackwell MB, Carran RA, Wedderburn ME, Jollands NA (2003) Resource use efficiency and environmental emissions from an average Waikato dairy farm, and impacts of intensification using nitrogen fertiliser or maize silage. Proc N Z Grassl Assoc 65:185–189

Ledgard SF, Luo J, Carran RA, Wedderburn ME (2004) Environmental effects of dairy farm intensification. In: Zhu Z, Minami K, Xing G (eds) Proceedings of the 3rd International Nitrogen Conference, Nanjing, China, pp 46–49

Ledgard SF, Sprosen MJ, Judge AA, Lindsey SB, Jensen R, Clark DA, Luo J (2006) Nitrogen leaching and whole-system efficiency as affected by dairy intensification and mitigation practices in the Resource Efficient Dairying Trial. In: Currie LD, Hanly JA (eds) Proceedings of the Workshop on Implementing Sustainable Nutrient Management Strategies in Agriculture, Massey University, Palmerston North, New Zealand, pp 263–268

Livestock Improvement (2003) Dairy statistics 2001–2002. Livestock Improvement Corporation, Hamilton, New Zealand, pp 1–45

Luo J, Tillman RW, Ball PR (1999a) Grazing effects on denitrification in a soil under pasture during two contrasting seasons. Soil Biol Biochem 31:903–912

Luo J, Tillman RW, Ball PR (1999b) Factors regulating denitrification in a soil under pasture. Soil Biol Biochem 31:913–927

Luo J, Tillman RW, Ball PR (2000) Nitrogen loss through denitrification in a soil under pasture in New Zealand. Soil Biol Biochem 32:497–509

Luo J, Ledgard SF, Lindsey SB (2007a) Nitrous oxide emission from urea application. NZ J Agric Res 50:1–11

Luo J, Lindsey SB, Ledgard SF (2007b) Nitrous oxide emissions from animal urine application on a New Zealand pasture. Biol Fertil Soils (in press)

Menneer JC, Ledgard SF, McLay C, Silvester W (2005) Animal treading stimulates denitrification in soil under pasture. Soil Biol Biochem 37:1265–1629

Ministry for the Environment 2006. New Zealand's Greenhouse Gas Inventory 1990–2004. The National Inventory Report and Common Reporting Format, April 2006. New Zealand Climate Change Office, Wellington, New Zealand. Available online at: http://www.climatechange.govt.nz

Misselbrook TH, Powell JM, Broderick GA, Grabber JH (2005) Dietary manipulation in dairy cattle: laboratory experiments to assess the influence on ammonia emissions. J Dairy Sci 88:1765–1777

Oenema O, Velthof GL, Yamulki S, Jarvis SC (1997) Nitrous oxide emissions from grazed grassland. Soil Use Manage 13:288–295

Oenema O, Wrage N, Velthof GL, van Groenigen JW, Dolfing J, Kuikman PJ (2005) Trends in global nitrous oxide emissions from animal production systems. Nutr Cycl Agroecosyst 72:51–65

Reicosky DC, Dugas WA, Torbert HA (1997) Tillage-induced soil carbon dioxide loss from different cropping systems. Soil Tillage Res 41:87–104

Saggar S, Yeates GW, Shepherd TG (2001) Cultivation effects on soil biological properties, microfauna and organic matter dynamics in Eutric Gleysol and Gleyic Luvisol soils in New Zealand. Soil Tillage Res 58:55–68

Saggar S, Andrew RM, Tate KR, Hedley CB, Rodda NJ, Townsend JA (2004) Modelling nitrous oxide emissions from dairy-grazed pastures. Nutr Cycl Agroecosyst 68:243–255

Simek M, Brucek P, Hynst J, Uhlirova E, Petersen SO (2006) Effects of excretal returns and soil compaction on nitrous oxide emissions from a cattle overwintering area. Agric Ecosyst Environ 112:186–191

Smith KA, McTaggart IP, Tsuruta H, Smith K (1997) Emissions of $N_2O$ and NO associated with nitrogen fertilization in intensive agriculture, and the potential for mitigation. Soil Use Manage 13:296–304

Soil Survey Staff (1990) Keys to soil taxonomy. SMSS Technical Monograph No. 19. Virginia Polytechnic Institute and State University, USA

Tiedje JM (1988) Ecology of denitrification and dissimilatory nitrate reduction to ammonium. In: Zehnder AJB (ed) Biology of anaerobic microorganisms. Wiley, New York, pp 179–244

van Groenigen JW, Velthof GL, van der Bolt FJE, Vos A, Kuikman PJ (2005) Seasonal variation in $N_2O$ emissions from urine patches: effects of urine concentration, soil compaction and dung. Plant Soil 273:15–27