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Effect of nitrogen fertilizer management and waterlogging on nitrous oxide emission from subtropical sugarcane soils

D.E. Allen [a,b,*], G. Kingston [c], H. Rennenberg [d], R.C. Dalal [b], S. Schmidt [a]

[a] University of Queensland, St Lucia 4072, Brisbane, Australia
[b] Department of Environment and Resource Management, Indooroopilly 4068, Australia
[c] BSES Limited, Bundaberg 4670, Australia
[d] Albert-Ludwigs-Universität Freiburg, 79085 Freiburg, Germany

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ABSTRACT

Considerable potential for N_2O emission from Australian sugarcane systems exists from high N fertilizer application rates and periodic waterlogging. To determine N_2O emissions, 2 experiments were conducted on ratooned sugarcane grown under field conditions. In the first experiment, crops received 0, 100 or 200 kg N ha^{-1} as single or split application. In the second experiment, a sub-set of the single N application plots was subjected to waterlogging. Higher N_2O emissions (350 μg–17 mg N_2O m^{-2} h^{-1}) occurred during warm and wet months (November–February) and coincided with high availability of mineral N in top soil (10–500 mg N kg^{-1} soil). Lower emissions (<350 μg N_2O m^{-2} h^{-1}) were detected in cool and dry months (March–October) coinciding with availability of low mineral N (<10 mg N kg^{-1} soil). Regression analysis showed significant positive correlations between N_2O emissions and soil temperature, water-filled pore space and mineral N (ammonium and nitrate) content. N_2O emissions, soil mineral N content and crop yield followed N application rates ($0 < 100 < 200$ kg N ha^{-1}) and waterlogging amplified N_2O emission. Split application of N fertilizer reduced annual N_2O emissions in the 200 kg N ha^{-1} treatment. We estimate, using the IPCC Tier 1 approach that between 1.0% and 6.7% of applied N fertilizer was emitted as N_2O. Our study demonstrates that immediate reduction of N_2O emissions can be achieved by avoiding high levels of soil mineral N pools and waterlogging through appropriate fertilizer rates and time of application and soil management.

1. Introduction

Nitrous oxide (N_2O), a long-lived atmospheric tracer of human induced changes to the global N cycle, is a major greenhouse gas contributing to global warming (Denman et al., 2007; Forster et al., 2007). N_2O sources are increasingly scrutinised and mitigation options to reduce anthropogenic N_2O emissions are sought. Agricultural soils are the most significant anthropogenic sources of N_2O, with the largest N_2O sources occurring from terrestrial landscapes at subtropical latitudes (Stehfest and Bouwman, 2006). Humid tropical soils generally favour large production of gaseous N oxides, including N_2O (Weitz et al., 2001), although the magnitude of emissions depends on the interactive effects of soil type, climate and farm management, which govern microbial processes and diffusion of gaseous N_2O to the atmosphere (Granli and Bøckman, 1995; Weitz et al., 2001).

In 2005, Australia's National Greenhouse Gas Inventory (NGGI) reported that ~68% (53 Gg) of Australia's annual N_2O emissions originated from agricultural soils (Department of Climate Change, 2009), however, there are large uncertainties associated with this estimate (AGO, 2007). Dalal et al. (2003) note that uncertainties in N_2O estimates from Australian agriculture are due to numerous contributing factors, including the comparatively low number of empirical studies, spatial and seasonal aggregations, lack of information on specific on-farm practices, as well as diverse soils, climates and cropping systems throughout the continent. Regardless of these uncertainties, N_2O flux from soil generally increases with increasing N fertilization rates and intensive cropping (Mosier et al., 2004; McSwiney and Robertson, 2005). Therefore, attention has focused on a range of mitigation options, including fertilizer type, and timing and application of N fertilizer to meet actual plant demands (Dalal et al., 2003; Wassman and Vlek, 2004).

Sugarcane cropping in Australia occupies ~500 000 ha in subtropical and tropical coastal regions with a total N fertilizer use of 71–96 Gg N per year, around 10% of the total N fertilizer use in Australia in the last decade (Chudleigh and Simpson, 2001; Dalal et al., 2003; Meier et al., 2006). Weier (1998) reported a total estimated N_2O production in Australia of 2.1 and 2.4 Gg N_2O-N per

* Corresponding author at: Department of Environment and Resource Management, 80 Meiers Road, Indooroopilly 4068, Brisbane, Australia.
Tel.: +61 7 38969307; fax: +61 7 38969623.
E-mail address: Diane.Allen@derm.qld.gov.au (D.E. Allen).

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year from trash-blanketed and uncovered soils, respectively, noting that further measurements were needed to provide quantifiable data for inventory purposes. Research activity in the Australian sugarcane industry over the last decade has focussed on improved understanding of N losses (including N_2O in some studies) under a range of current management practices, including trash blanketing, N fertilizer management and irrigation (Weier, 1999; Pratersak et al., 2002; Thorburn et al., 2003a,b; Meier et al., 2006; Robertson and Thorburn, 2007; Denmead et al., 2006, 2007, 2008; Wang et al., 2008; Macdonald et al., 2009), although how recommended practices to reduce N may affect cane yield remains unclear (Kingston et al., 2008).

The objective of this study was to assess the impact of environmental variables (temperature, rainfall and soil moisture), and N management on N_2O fluxes in ratoon sugarcane plantations to gain insight into causalities of N_2O relations and to aid future recommendations for reducing N_2O emissions from sugarcane farming. Two experiments were established at the site, to consider (i) N application rate and type of application (N fertilizer experiment) and (ii) simulated waterlogging conditions (waterlogging experiment). In the N fertilizer experiment, treatments consisted of 3 N fertilizer rates, applied as either a single sub-surface application, or as a split application (sub-surface and broadcast application). N_2O flux and soil parameters, including temperature, moisture and mineral N content, were monitored over a 12-month period on a sub-set of the N fertilizer plots. In the second experiment, irrigation water was applied to half of the N fertilizer sub-plots to simulate waterlogged conditions, which regularly occur in sugarcane fields in Australia. On a sub-set of the waterlogged and non-waterlogged plots, N_2O flux was measured on days 1, 2, 4, 7, 11 and 19 after waterlogging. In both experiments, sampling was undertaken within and between cane-rows to identify main biophysical drivers of N_2O emissions. We also estimated annual N_2O emission as a proportion of applied in fertilizer, according to the IPCC Tier 1 method of reporting.

2. Materials and methods

2.1. Experimental site

The field experiment was carried out on a sugarcane farm near Jacobs Well, approximately 45 km south east of Brisbane, Australia (27°43′S, 153°16′E). The site was cropped for over 10 years with sugarcane (*Saccharum* sp.). Farm management consisted of 2–3 years ratoon rotations followed by a sugarcane plant crop. Annual applications of liquid urea [$CO(NH_2)_2$] fertilizer were applied at approximately 15 cm soil depth from a stool splitting applicator (~160 kg N ha^{-1}) and Dunder (distillery waste) applied at the soil surface as a potassium source. We studied 3rd and 4th ratoon rotation (2003–2005) of sugarcane, which was planted in July 2002, with 2nd ratoon cane (*Saccharum officinarum* L. cv Q155) harvested in July 2003. Mean daily summer and winter temperatures are 28.4 and 8.6 °C, respectively, and mean annual rainfall is 1017 mm (Bureau of Meteorology, Site 040854, Brisbane). For selecting the site, and prior to setting up the experiment, initial assessment was undertaken by BSES Ltd., whereby 6–8 composite cores, sampled across the field, were analysed by a commercial soil testing laboratory (Incitec Pivot, Ltd.). Main soil properties determined from site selection analysis are shown in Table 1. Field texture and colour were determined using Northcote and Munsell colour chart methods, respectively. Soil pH, organic carbon, nitrate-N, sulphur and electrical conductivity were determined as per Haysom (1982). Bulk density was determined as per Campbell and Henshall (2002). The soil is a Hydrosol (Isbell, 2002) of medium clay content (Table 1). Jarosite was observed in some sub-soil cores; therefore, the site was classified as having potential acid-sulphate activity. Site-specific management commenced in 2003; the site was divided into 40 sub-plots (each 13 m × 30 m), containing 9 rows (1.5 m spacing) with a 5 m guard area along rows between plots. Pre-survey of the site identified variable sub-surface electrical conductivity at the site (Table 1), therefore, a sub-set of plots at the northern end of the experimental site, which had negligible salt influence (0.21 ± 0.05 dS m^{-1} and 0.42 ± 0.13 dS m^{-1}, $n = 8$, at 0–25 cm and 25–50 cm soil depths, respectively), was selected for sampling of N_2O and soil properties.

Table 1
Soil properties of sugarcane cropping experimental site, subtropical Queensland, Australia.

Soil characteristic	Soil depth	
	0–25 cm	25–50 cm
Texture and colour	Medium grey-brown clay	
Textural analysis (%)		
Sand	28	21.5
Silt	26	25.5
Clay	46	53
pH (water)	4.7–5.3	4.3–4.6
Organic carbon (%C)	3.0	1.1
Nitrate-N (mg kg^{-1})	3.8	0.8
Sulphur (MCP) (mg kg^{-1})	259	803
Electrical conductivity (dS m^{-1})	0.21–0.31	0.43–0.75
Bulk density	0.95–1.09 cane-row 1.19 between-row	

2.2. Experimental design and treatments

Five experimental treatments were applied during 3rd and 4th ratoon cropping cycles (2003–2005) according to a randomized block design (8 sub-plots per treatment, Table 2). The experimental site was part of a sugarcane farm which had been managed according to industry standard (~160 kg N ha^{-1} $year^{-1}$ with trash blanket retained after harvest; Table 2). Application of N fertilizer occurred in the form of liquid urea, applied to the row mound using a stool splitting applicator at approximately 15 cm depth from the soil surface. Additional fertilizer for the split application treatments was applied as broadcast fertilizer (Nitram), producing effective rates of 98 kg and 195 kg N application for 50 + 50 N and 100 + 100 N treatments, respectively. The chosen N application rate here reflects current industry average application rates and recommended N application rates (Thorburn et al., 2003a,b; Schroeder et al., 2005).

Irrigation was used to simulate soil waterlogging in a sub-set of N fertilizer plots during 3rd ratoon crop growth at 106 and 107 days after harvest (DAH). Water was applied to the southern end of the site from an adjacent dam using 17.8 cm plastic irrigation fluming, with sugarcane trash at the distal end of the experiment bunded to allow a waterlogging period of 24 h. Inundation occurred to the top of the cane-row and standing water (~15 cm) remained for approximately 24 h, subsiding over several days. A sub-set of 0N, 100N and 200N treatments were selected for N_2O flux measurement, since irrigation was applied ~4 weeks before the second application of fertilizer for the split N treatments. N_2O flux was measured intermittently for ~3 weeks after the irrigation event in 3 sub-plots each of waterlogged and non-waterlogged N fertilizer treatments as follows:

(a) zero N fertilizer added (0N and 0N + W);
(b) single application of 100 kg N ha^{-1} (100N and 100N + W);
(c) single application of 200 kg N ha^{-1} (200N and 200N + W).

Biomass and N accumulation throughout the growing period, as well as cane and sugar yields were also assessed for all N application experimental plots for 3rd and 4th ratoon crops (for

Table 2
Site management and experimental design for the sugarcane cropping experimental site, subtropical Queensland, Australia.

Farm management	Years 1–3 (planting of crop to 2nd ratoon crop) July 2000–2003	Year 4 (3rd ratoon crop) 27/07/2003–21/07/2004	Year 5 (4th ratoon crop and plough out) 21/07/2004–21/08/2005
Fertilizer experiment	Site managed as single plot. 160 kg N ha^{-1} urea, applied at ∼15 cm soil depth from a stool splitting applicator as liquid urea	Start of fertilizer experiment. Crop divided into 40 sub-plots with 5 fertilizer treatments (8 sub-plots per treatment): (1) zero fertilizer (0N); (2) 100 kg N ha^{-1} (urea) (100N); (3) 200 kg N ha^{-1} (urea) (200N); (4) 50 kg N ha^{-1} (urea), 48 kg N (NH_4NO_3) (100N split); (5) 100 kg N ha^{-1} (urea), 95 kg N (NH_4NO_3) (200N split). 100N and 200N fertilizer treatments applied as a single application (applied at ∼15 cm soil depth from a stool splitting applicator as liquid urea) 72 days after 2nd ratoon harvest (DAH). Split fertilizer treatments (100N split, 200N split) applied 127 DAH as surface application. Soil N_2O flux measured for 12 months commencing November 2003	Continuation of fertilizer experiment as per year 4 experimental set-up. 100N and 200N fertilizer treatments applied as a single application (liquid urea applied at ∼15 cm soil depth) 74 days after 2nd ratoon harvest (DAH). Split application treatments (100N split, 200N split) applied at surface 129 DAH
Flooding experiment	None applied	Start of flooding experiment. 40 sub-plots (from fertilizer experiment) divided as follows: (1) flood irrigation applied at 102–103 DAH for 24 h (4 sub-plots per N fertilizer treatment; 20 sub-plots total); (2) no flood irrigation applied (4 sub-plots per N fertilizer treatment; 20 sub-plots total). Soil N_2O flux measured intermittently for ∼3 weeks after the irrigation event in 3 sub-plots each of waterlogged and non-waterlogged N fertilizer treatments as follows: (1) zero fertilizer (0N and 0N + W); (2) single application of 100 kg N ha^{-1} (urea) (100N and 100N + W); (3) single application of 200 kg N ha^{-1} (urea) (200N and 200N + W)	None applied
Tillage	Disc plough < 10 cm (year 1 only); mulching thereafter		
Weeding	Spray; 1/year	Spray; 2/year	Spray; 1/year

detailed results see companion paper by Kingston et al., 2008). In brief, cane yields (t cane ha^{-1}) ranged from 67 to 98 (3rd ratoon) and from 53 to 81 (4th ratoon); 0N treatments had significantly lower yields than other treatments for both ratoons, although significant differences between 100N and 200N application rates, were observed in the 3rd ratoon crop only. Split N fertilizer application did not significantly affect cane yields for either 3rd or 4th ratoon years.

2.3. N_2O sampling and analysis

For N_2O flux measurements, 10 chambers for N_2O flux measurement were placed in each of the sub-plots, representing each N application treatment (a total of 50 chambers for N fertilizer experiment; total of 60 chambers for waterlogged experiment). Chambers consisted of polyvinyl chloride base collars (23.5 cm diameter, 30 cm length, 0.043 m^2 surface area) inserted approximately 5 cm into soil, enclosing a volume of 10.8 l. Chamber lids were fitted with a teflon septum port and vent tube through which gas samples were taken using a gas-tight syringe (Hamilton, Australia). Within each sub-plot, chamber collars were placed between cane stalks within the mounded cane-row (n = 5) and in between-row space (n = 5). During farm management operations (fertilization and final harvest), collars were removed and re-installed in the same location immediately afterwards.

For the N fertilizer experiment, soil N_2O fluxes were sampled over 1 year period (November 2003–2004) at 3–7 days intervals for the first 4 months, then fortnightly thereafter. During the short-term waterlogging experiment, N_2O flux was measured on 1, 2, 4, 7, 11, and 19 days after the irrigation event. Gas was sampled between 9 and 11 h; lids were placed on the chamber collars for 60–80 min, with a gas sample collected from the dark chamber initially at the chamber closure, then 2–3 additional samples were collected during the closure period at approximately 20–30 min intervals, depending on closure period. Ten millilitres of gas samples were collected in pre-evacuated Exetainers (Labco Limited, USA), transported under cool conditions to the laboratory and analysed within 24 h using gas chromatography (Auto-system, Perkin-Elmer (PE), USA) as described by Allen et al. (2007). Gas fluxes were calculated as rates of observed linear least-square fit ($R^2 > 0.98$) of the time series of gas concentrations.

Representation of N_2O flux on a unit surface area of the cropping system is described by Allen et al. (2008). In brief, weighted contributions of the area of mounded cane-row (38.8%) and between-row (61.2%) were used to represent N_2O flux on a per hectare basis for each treatment. Hourly fluxes were scaled up to daily fluxes (hourly rate × 24), since soil temperature during the measurement period did not significantly differ from mean daily temperature. Wang et al. (2008) detected similar daily mean soil N_2O emissions (measured using automatic chamber and micrometeorological methods) to N_2O emissions measured manually between 9:15 and 10:45 am AEST, suggesting that the manual sampling measurements could be used to estimate daily emission rates without correction for diurnal variation in N_2O emissions. Annual cumulative estimates of N_2O were calculated by linear interpolation between sampling events. N_2O emission factor was calculated as 100 × [(cumulative N_2O-N emission from fertilized field − cumulative N_2O-N emission from unfertilized field)/N application] (Granli and Bøckman, 1995), in accordance with IPCC (2006) Tier 1 approach.

2.4. Soil sampling and analysis

Soil temperature and gravimetric moisture were measured at hourly intervals between November 2003 and May 2004 at

Table 3
Seasonal mean (log-transformed) N_2O emissions ($\mu g \ln N_2O\, m^{-2}\, h^{-1}$) measured during November 2003–2004 period in 3rd and 4th ratoon sugarcane crop, subtropical Queensland, Australia[a].

	0N	50 + 50N	100N	100 + 100N	200N
Summer					
Cane-row	3.7 ± 0.2^a	5.7 ± 0.3^b	5.9 ± 0.2^{bc}	6.4 ± 0.3^c	7.4 ± 0.2^d
Between-row	4.1 ± 0.2^a	5.0 ± 0.2^b	4.6 ± 0.2^b	4.9 ± 0.2^b	5.6 ± 0.2^c
Autumn					
Cane-row	3.3 ± 0.4	3.5 ± 0.3	2.2 ± 0.5	3.4 ± 0.3	3.4 ± 0.3
Between-row	3.7 ± 0.3	4.0 ± 0.3	3.3 ± 0.4	4.2 ± 0.4	4.5 ± 0.3
Winter					
Cane-row	2.9 ± 0.3	2.2 ± 0.5	3.4 ± 0.3	2.2 ± 0.5	3.4 ± 0.3
Between-row	2.8 ± 0.3	2.1 ± 0.3	2.2 ± 0.4	1.8 ± 0.3	2.0 ± 0.3
Spring					
Cane-row	3.4 ± 0.2^a	4.8 ± 0.2^b	5.8 ± 0.3^{bc}	4.6 ± 0.2^b	5.3 ± 0.2^d
Between-row	3.6 ± 0.2	3.8 ± 0.2	3.7 ± 0.3	3.7 ± 0.2	3.7 ± 0.2

[a] Differences at $P < 0.05$ level of significance between N fertilizer treatments or each season in cane-row and between-row positions are highlighted by letters. Seasonal mean N_2O emissions calculated for summer (December–February), autumn (March–May), winter (June–August) and spring (September–November).

1, 5, and 10 cm depths in cane-row and between-row positions at 4 locations in the northern end of the field. Logged data of gravimetric moisture was converted to volumetric moisture content (θ_v) based on bulk density measurements of cane-row and between-row locations. Bulk density was measured for each sub-plot in cane-row ($n = 5$) and between-row ($n = 5$) positions, and calculated as weight of dry sample at 105 °C/total volume of soil sample. Total porosity (TP) of cane-row and between-row positions was estimated as 1 − (bulk density/particle density), where particle density was taken as 2.65 g cm^{-3} (Carter and Ball, 1993). Water-filled pore space (%WFPS) was calculated as $(\theta_v/\text{TP}) \times (100)$.

Fresh soil from the top 10 cm depth was sampled intermittently to determine mineral N (NO_3^- and NH_4^+) content. Soils were stored cool at 4 °C and extracted within 48 h of collection with 2 M KCl (1:10), shaken for 1 h, and filtered through a 0.45 μm membrane filter. Solution was analysed for nitrate (NO_3^-) according to Rayment and Higginson (1992) and ammonium (NH_4^+) according to Baethgen and Alley (1989). Redox potential (E_h) was recorded at 5 min intervals during the waterlogging event, using a platinum electrode and a silver/silver chloride reference electrode (ORP300; Greenspan technology Pty Ltd., Australia). E_h was measured at 10 cm depth in between-row positions during flooding and at 3 cm depth during drying phase.

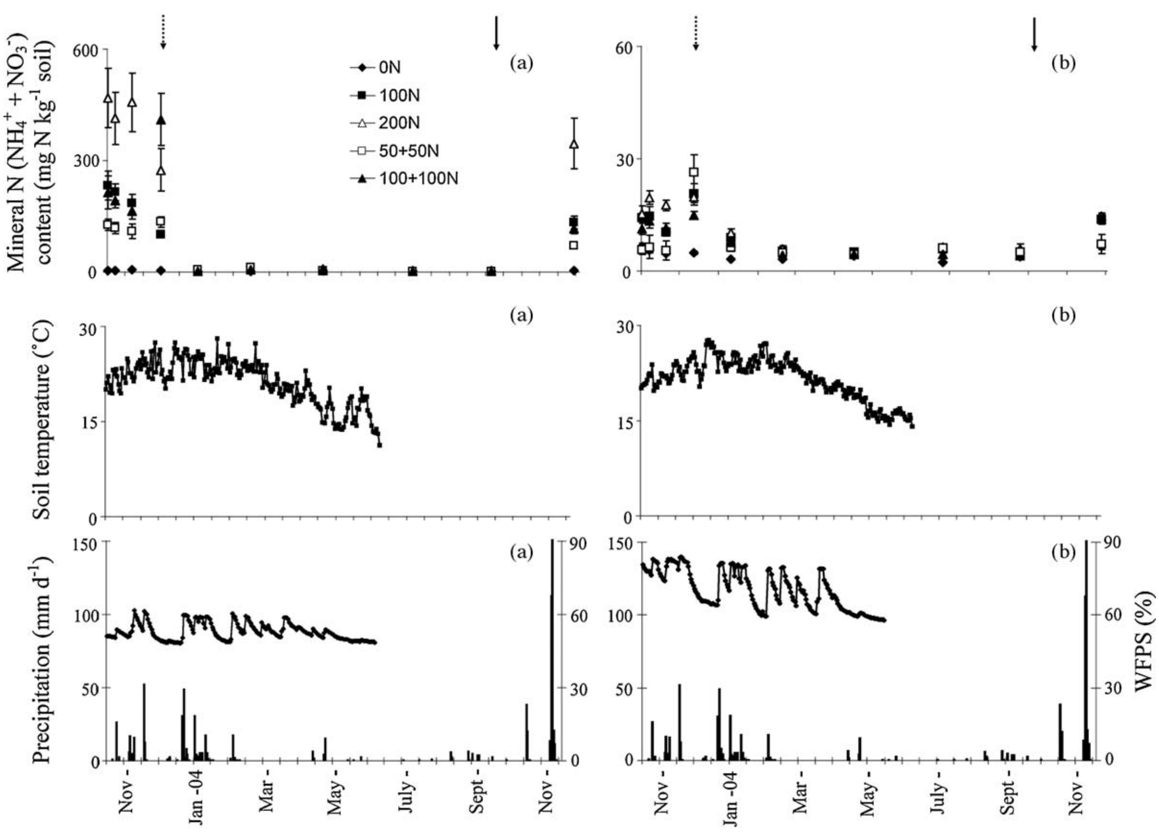

Fig. 1. Soil and climate parameters for split N fertilizer experiment measured between November 2003 and 2004 in (a) cane-row and (b) between-row positions in 3rd and 4th ratoon sugarcane crop, subtropical Queensland, Australia. Mineral N (NH_4^+ and NO_3^-) content (mg N kg^{-1} soil) is shown in the top panel (note different units in *Y*-axis between panels a and b) and soil temperature (°C) in middle panels. Water-filled pore space (WFPS), measured in the top 10 cm soil layer, is shown on 2nd *Y*-axis above daily precipitation bars (mm) in the bottom panels. Soil and climate parameters were monitored from November 2003 to June 2004; seasons are denoted as summer (Su), autumn (Au), winter (Wi), and spring (Sp). Arrows represent dates of N fertilizer application as liquid urea (solid arrow) and as broadcast fertilizer (dotted arrow) for split N fertilizer sub-plots.

2.5. Data analysis

Statistical analyses were carried out using Statistica Software (Carver, Brooks/Cole, Canada). Normality of distribution of dependent and independent variables was tested using the Kolmogorov–Smirnov test at $P < 0.05$ level of significance. N_2O flux was tested for normality of distribution using Shapiro–Wilk *W* test and log-normally (ln) transformed before statistical analysis. Statistical significance of differences at $P < 0.05$ level between means were calculated using GLM-ANOVA, with differences between treatments determined using LSD all-pairwise comparisons test. Correlations between log-transformed N_2O emissions and independent variables were calculated using stepwise multiple regression analysis (casewise elimination). N_2O fluxes are displayed as raw (untransformed) data in figures and tables (except Table 3 which is log-transformed). Results of ln-transformed N_2O fluxes at $P < 0.05$ and $P < 0.01$ levels of significance are indicated by symbols, or are noted within the text.

3. Results

3.1. Environmental variables

Distinct seasonal differences in temperature, rainfall, and soil mineral N concentration were observed. Monthly mean air temperature during *in situ* sampling of N_2O flux (November 2003–2004) ranged between 4.7 and 30.2 °C (data not shown); precipitation during this period totalled 800 mm, 78% of which was received during the summer period (November–January). Total precipitation during N_2O measurement campaigns was similar to amounts recorded during 1st and 2nd ratoon cropping years (830 and 876 mm, respectively), although minimum temperature and annual rainfall were lower than nearby (~20 km) long-term recorded averages (14.8 °C and 1015 mm, respectively). Climate variability was reflected in soil properties including water-filled pore space (WFPS) and mineral N; WFPS was highest during summer rainfall events, and decreased rapidly during drying events, particularly during warmer months (Fig. 1). Water-filled pore space (mean ± S.E.) was significantly higher in between-row (70.3 ± 0.6) than cane-row (52.9 ± 0.2) positions (two-tailed *t*-test, $T = 28.61$, df = 411, $P < 0.01$). Soil temperature at 10 cm depth ranged between 11.2 and 27.7 °C (Fig. 1) and was significantly higher (mean ± S.E) in between-row (21.46 ± 0.16) than cane-row (20.90 ± 0.17) positions (two-tailed *t*-test, $T = 2.38$, df = 866, $P < 0.05$).

Concentrations of soil mineral N (NH_4^+-N and NO_3^--N) in the top 10 cm soil layer in 0N treatments were <2 mg NH_4^+-N kg^{-1} and < 8 mg NO_3^--N kg^{-1} (data not shown), with little seasonal variation (Fig. 1). Compared with 0N application, NH_4^+-N and NO_3^--N concentrations were significantly ($P < 0.05$) higher in the 100N and 200N treatments in cane-row and between-row positions, and peaked during summer months immediately after N fertilizer application. Soil mineral N contents in the NH_4^+ form in these treatments ranged between 0.08–0.3% (100N) and 0.10–

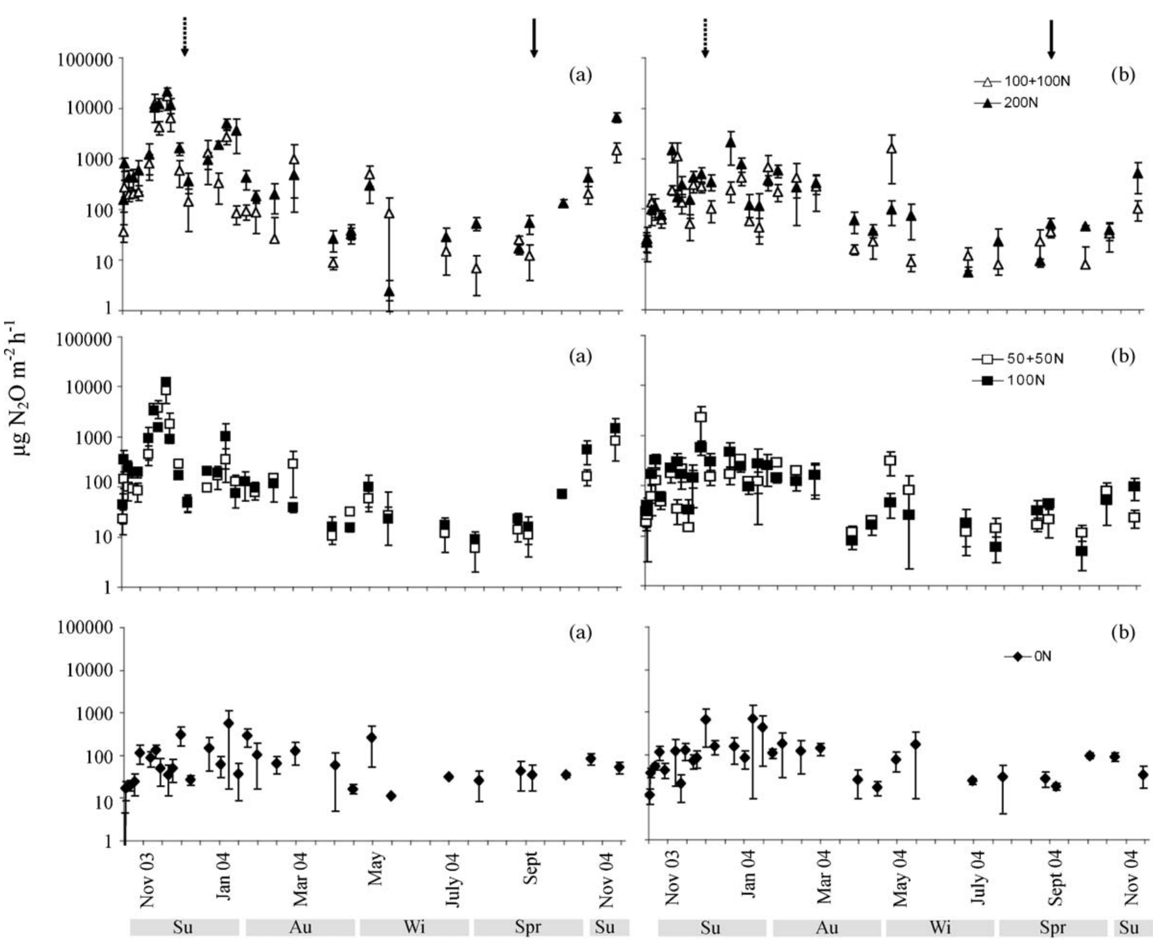

Fig. 2. Seasonal patterns of soil N_2O flux from November 2003–2004 in 3rd and 4th ratoon sugarcane crop, subtropical Queensland, Australia. N_2O flux measured in (a) cane-row and (b) between-row positions represent mean and standard deviations of five chambers at each position. Top and centre panels show N_2O flux from application of 200 and 100 kg N ha^{-1} $year^{-1}$, applied as single or split applications. Bottom panel shows N_2O flux from cane-row and between-row positions without additional N application (0N treatment). Arrows represent dates of N fertilizer application as liquid urea (solid arrow) and as broadcast fertilizer (dotted arrow) for split N fertilizer sub-plots.

Table 4
Cumulative annual N_2O-N emission and emission factor (mean ± S.E.) estimated for November 2003–2004 period in 3rd and 4th ratoon sugarcane crop, subtropical Queensland, Australia.

	0N	50 + 50N	100N	100 + 100N	200N
Cumulative annual N_2O-N emission (kg N_2O-N ha^{-1} $year^{-1}$)	2.86 ± 0.34	3.86 ± 0.65	3.93 ± 0.23	5.81 ± 1.88	9.56 ± 1.33
Emission factor		1.00 ± 0.64	1.07 ± 0.25	2.95 ± 0.17	6.70 ± 0.63

0.29% (200N). The concentrations of soil mineral N within the cane-row decreased across all treatments within the first 2 months after N fertilizer application (Fig. 1).

Application of irrigation water to the 3rd ratoon crop 106 and 107 days after harvest resulted in increased soil moisture contents for 19 days after simulated flooding (Fig. 3). During this period, average water-filled pore space in waterlogged sub-plots (59.76 ± 0.25 cane-row; 82.57 ± 0.28 between-row) was significantly higher than non-waterlogged sub-plots (50.94 ± 0.25 cane-row; 79.63 ± 0.84 between-row) (Student's two-tailed *t*-test, $P < 0.05$, $n = 18$).

3.2. N_2O fluxes

N_2O fluxes were non-normally distributed (Shapiro–Wilk *W* test, $W = 0.27$, $P < 0.01$) and showed large seasonal variations (Fig. 2). Mean N_2O emissions measured during spring and summer months ranged between 89 and 3653 μg N_2O m^{-2} h^{-1} and were significantly higher than mean N_2O emissions measured during autumn and winter months, which ranged between 9 and 215 μg N_2O m^{-2} h^{-1} (Mann–Whitney test, $Z = 2.83$, $P < 0.01$). Significant reduction in N_2O emissions during autumn and winter months coincided with lower temperature, rainfall and mineral N availability, indicating that temperature, rainfall and available soil mineral N, were of common influence on N_2O emissions across all treatments.

Maximum and minimum N_2O emissions were observed in 200N cane-row (21.2 mg N_2O m^{-2} h^{-1}; Fig. 2a) and 0N between-row positions (0.01 mg N_2O m^{-2} h^{-1}; Fig. 2b), respectively. During spring and summer months, mean N_2O emissions followed N application rates ($0 < 100 < 200$ kg N ha^{-1}), with statistical differences between treatments observed in cane-row and between-row positions (Table 3). Mean N_2O emissions during spring and summer months were significantly lower in split application of N for 200N treatments only (Table 3).

Contributions of fertilizer application to N_2O emission followed N application rate, with lowest estimated cumulative N_2O-N emissions in 0N and 50N + 50N plots and highest emissions in 200N plots (Table 4). Splitting N application into 2 applications decreased N_2O emissions only at the highest N rate (200 kg N ha^{-1}), reducing the estimated emission factor from 6.7% to 2.95% (Table 4).

Increased N_2O emissions were observed in the waterlogged treatments in cane-row positions only (Fig. 3). Mean log-transformed (ln) N_2O emissions for waterlogged plots (μg ln N_2O m^{-2} h^{-1}) during the waterlogging experiment ranged from 5.6 ± 1.8 (0N), 7.8 ± 1.3 (100N) and 8.4 ± 1.8 (200N). Waterlogged plots had significantly ($P < 0.01$) higher N_2O emissions than

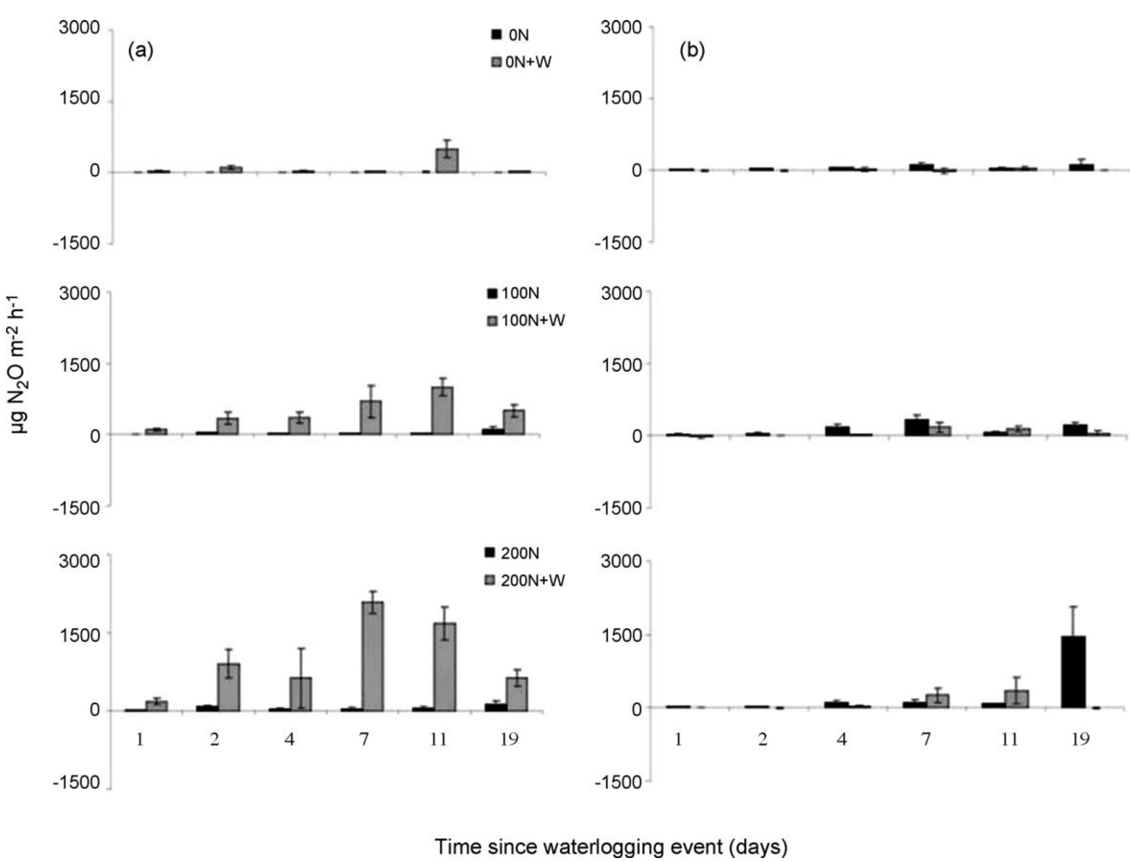

Fig. 3. Soil N_2O emissions after application of experimental waterlogging in control and waterlogged (+W) plots in 3rd ratoon sugarcane crop, subtropical Queensland, Australia. N_2O flux measured in (a) cane-row and (b) between-row positions represent mean and standard deviations of five chambers at each position.

Table 5
Standardized regression coefficients (β value) of log-normally transformed N_2O emission rate and soil physical parameters in cane-row and between-row positions, 3rd ratoon sugar cane soil, subtropical Queensland, Australia.

Soil parameter	β value[a]	
	Cane-row	Between-row
Soil temperature (°C)	0.484*	0.532*
WFPS (%)	0.296*	0.168*
NH_4^+-N (mg kg^{-1})	0.438*	0.095
NO_3^--N (mg kg^{-1})	0.026	0.317*

[a] Significant β values are highlighted with * at the $P < 0.05$ level of significance.

non-waterlogged plots for all N treatments, with mean ln N_2O emissions of 3.3 ± 1.7 (0N), 4.9 ± 1.9 (100N) and 5.7 ± 1.3 (200N) (*t*-test assuming unequal variance, df = 51). Similar trends in N_2O emissions between treatments were detected 19 days after waterlogging.

3.3. Relationship between soil properties and N_2O flux

The relationships between soil temperature, WFPS, NH_4^+-N and NO_3^--N at 0–10 cm soil depth and N_2O emissions were examined in cane-row and between-row positions (Table 5). Soil N_2O emissions were significantly correlated with soil temperature, NH_4^+-N and WFPS in cane-row positions (n = 130, R^2 = 0.48, $P < 0.05$) (Table 5). In between-row positions, soil temperature, NO_3^--N and WFPS were significantly correlated with N_2O emissions (n = 130, R^2 = 0.48, $P < 0.05$; Table 5).

4. Discussion

Our study contributes to the growing body of knowledge that N_2O emissions from commercial sugarcane farms in Australia are higher than current estimates in IPCC Tier 1 reporting (IPCC, 2006) (1%) and in the National Greenhouse Gas Inventory (AGO, 2007) which assumes an emission factor of 1.25% of applied fertilizer N as N_2O. Our results are within the range reported in recent years for Australian sugarcane systems, which note cumulative N_2O emissions up to 72 kg N_2O ha^{-1} and emission factors between 1.31% and 21% (Weier, 1999; Denmead et al., 2007, 2008, 2009; Wang et al., 2008; Macdonald et al., 2009).

Large variability in amplitude and temporal dynamics in N_2O emissions in response to N fertilization have been reported, and appear to depend on fertilizer type, N application method, soil type, and frequency of rainfall and irrigation (Granli and Bøckman, 1995; Dalal et al., 2003). In humid subtropical and tropical systems, N efficiency tends to be lower than in temperate systems (Granli and Bøckman, 1995), which may reflect differences in climate (higher temperatures and rainfall) and soil (highly weathered, permeable and acidic soils), as well as less knowledge of optimum fertilizer management than in temperate cropping systems (Baligar and Bennett, 1986; Granli and Bøckman, 1995).

Effects of fertilizer addition and waterlogging events on soil N_2O flux have been studied in subtropical agricultural soils, including sugarcane (Matson et al., 1996; Weier et al., 1998; Weier, 1998, 1999; McSwiney and Robertson, 2005; Pattey et al., 2007; Denmead et al., 2009). However, information relating to spatial and temporal variability of N_2O fluxes, with the exception of paddy rice cropping, is scarce (Granli and Bøckman, 1995; Khalil et al., 2007). We found strong seasonal variation in N_2O fluxes across all treatments, with highest N_2O emissions recorded in the first 2 months after N fertilizer application. Similarly, Weitz et al. (2001) note that across diverse climate zones and land uses, N_2O emissions are commonly elevated during the first weeks following N fertilization and are followed by declining N_2O emissions to approach background flux rates of a soil.

Although a wide range of fertilizer management (type, quantity, method of application) is used in the Australian sugarcane industry, few studies have examined N_2O emissions in the context of management effects. Currently it is not clear how different N fertilizer application methods affect N_2O emissions from sugarcane fields. N_2O emissions from sub-surface N fertilized plots in this study (average 1–4 mg N_2O-N m^{-2} h^{-1}) are similar to Weier (1999) who reported <1 mg N_2O-N m^{-2} h^{-1} in sugarcane cropping soils receiving 160 kg N ha^{-1} of surface broadcast urea. Emissions from both studies are higher than the values reported by Matson et al. (1996) (<1 μg N_2O-N m^{-2} h^{-1}), who compared N_2O flux from sugarcane soils receiving urea fertilizer, applied as broadcast or sub-surface irrigation lines. A similar magnitude of N_2O emission rates between broadcast and sub-surface treatments was observed; however, the emissions 'peak' remained elevated for much longer periods after broadcast fertilizer application (Matson et al., 1996) than in our study. There is no doubt that the different N_2O emissions observed in fields receiving different fertilizer types and application methods are caused not only by fertilizer characteristics but also impacted by climate, precipitation and soil type, and this makes unequivocal conclusions difficult. The soil in our study had a comparatively high organic carbon content of 3% yet the lower range of N_2O fluxes reported by Matson et al. (1996) occurred at sites with soil carbon values ranging between 1.3% and 8.1%. It is possible that the lower soil pH in our study (4.7–5.3) compared to Matson et al. (1996) (6.1 ± 0.3) may have contributed to higher N_2O emissions, since the reduction of N_2O to N_2 is inhibited more than the reduction of NO_3^- by acidic conditions (Dalal et al., 2003).

We saw that split application of fertilizer had no measurable effect on N_2O emissions at 100 kg N ha^{-1} rate, possibly because the low N uptake rate by sugarcane kept mineral N levels at similar concentrations in both methods of application. However, at higher N rate significantly lower (>50%) cumulative annual N_2O emissions were observed at the 200 kg N ha^{-1} split rate compared to the single application of 200 kg N ha^{-1} treatment. A mixed response to split fertilizer effects on N_2O emissions has been reported in the literature, including no effect (Ciarlo et al., 2008), reduced N_2O emissions (Burton et al., 2008) and higher N_2O emissions (Weier, 1999). Similar to the inconsistent N_2O emissions associated with different fertilizer types and application methods discussed above, Bouwman and Boumans (2002) suggested that confounding effects on N_2O emissions of split N fertilizer application are due to unclear separation of contributing factors including local climate, fertilization rate, fertilization mode and measurement period. Inter-annual variability in split fertilizer effects has been associated with timing of application during growing season, in combination with rainfall events (Yan et al., 2001; Burton et al., 2008). Weier (1999) showed that split application of urea applied at 160 kg N ha^{-1} to a sugarcane crop initially resulted in lower N_2O emissions but resulted in greater N_2O emissions later when soil moisture was higher. These previous studies and our own study suggest that timing and rate of fertilizer application is important and that high soil moisture conditions at the time of application or soon after and much higher N rates should be avoided (Saggar et al., 2007). These findings also indicate that the potentially beneficial effects of split fertilizer application can be overridden by other factors such as soil moisture and rainfall events.

In our study, increased soil moisture from natural (heavy rainfall) and simulated (irrigation) events, resulted in short-term increase in N_2O emissions in this study and lower crop N acquisition and N fertilizer use efficiency (Kingston et al., 2008). For our study site, Kingston et al. (2008) estimated that ~80 kg N ha^{-1} is acquired by the crop from mineralisation of soil organic N; thus, in addition to N fertilizer, a proportion of organic N mineralised would have been available for conversion to N_2O. The contribution of soil N to N_2O emissions was confirmed in treatments receiving no added N fertilizer during the study period (2.86 kg N_2O-N ha^{-1} $year^{-1}$), this annual cumulative N_2O emission was nearly 74% and 30% of plots receiving N fertilizer at 100 kg N ha^{-1}, and 200 kg N ha^{-1}, respectively.

Taken together, our results indicate that in sugarcane soils with higher organic carbon content, such as in the soil studied here, and conditions where waterlogging occurs early in the growing season due to extreme rainfall or scheduled irrigation events, high temperatures and high mineral N concentrations (Table 5) resulting from N fertilizer application, N loss through N_2O emission from soil is likely to be high.

5. Conclusions

We observed significant N_2O emissions and spatial and temporal variation of these emissions from soils under a 3rd ratoon sugarcane crop in subtropical Australia. We provide further evidence that the currently used Australian emission factor of 1.25% of applied fertilizer N underestimates N_2O emissions and highlights that the low nitrogen use efficiency of sugarcane crop systems may partly be due to N_2O emissions from soil. For several decades, high N fertilizer rates have characterized Australian sugarcane cropping, but in recent years recommended rates have been reduced to 120–160 kg N ha^{-1} or less and further decreases are imminent as environmental consequences of N loss are acknowledged. Sub-surface application of urea in our study appeared to result in N_2O emissions of similar magnitude to that previously reported in Australian tropical sugarcane cropping soils which received urea as broadcast fertilizer, indicating that in some instances, fertilizer type and N application regime may be less effective as means to reduce N_2O emissions than lowering N fertilizer application rates or controlled timing of fertilizer application. A general trend of increasing N_2O emissions with fertilizer N application was observed, although effects of timing of fertilizer application to N_2O emissions were variable. Waterlogging of soils due to heavy rainfall or flood increased the magnitude of N_2O emissions and indicates that N_2O emissions can be reduced by timing N fertilizer application so that high soil moisture is avoided, including careful consideration of flood irrigation practices. Given the extensive variation in soil type, climate and management in Australian sugarcane farming systems, integrated field and model-based approaches are required to assist national reporting and to identify best management practices for mitigating N_2O emissions at the farm-level. To devise effective N management strategies for minimising greenhouse gas emissions, including N_2O, CH_4 and CO_2, process-based modelling (e.g. Kiese et al., 2005; Thorburn et al., 2010) and whole-farm accounting (e.g. Janzen et al., 2006) should complement field-based studies to establish generalities and inform future sustainable sugarcane farming.

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