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ORIGINAL ARTICLE

Can nitrogen fertiliser and nitrification inhibitor management influence N_2O losses from high rainfall cropping systems in South Eastern Australia?

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Abstract Nitrous oxide (N_2O) is a potent greenhouse gas released from high rainfall cropping soils, but the role of management in its abatement remains unclear in these environments. To quantify the relative influence of management, nitrogen (N) fertiliser and soil nitrification inhibitor was applied to separate but paired raised bed and conventionally flat field experiments in south west Victoria, to measure emissions and income from wheat and canola planted 2 and 3 years after conversion from a long-term pasture. Management included four different rates of N fertiliser, top-dressed with and without the nitrification inhibitor Dicyandiamide (DCD), which was applied in solution to the soil in the second year of experimentation. Crop biomass, grain yield, soil mineral N, soil temperature and soil water and N_2O flux were measured. Static chamber methodology was used to identify relative differences in N_2O loss between management. In the second crop (wheat) following conversion, N_2O losses were up to 72 % lower ($P < 0.05$) in the furrows, receiving the lower rate of N fertiliser compared with the highest rate, with less frequent reductions observed in the third crop (canola); losses of N_2O from the beds was unaffected by N rate, perhaps from nitrate leakage into the adjacent furrow of the raised bed experiment. On the nearby flat experiment, nitrate leaching may have diminished the effects of N rate and DCD on N_2O flux. Furthermore the extra N did not significantly increase grain yield in either the wheat or canola crops on both experiments. The application of DCD in the canola crop temporarily reduced ($P < 0.05$) N_2O production by up to 84 % from the beds, 83 % in the adjacent furrows and 75 % on the flat experiment. Grain yield was not significantly ($P < 0.001$) affected however, canola income was reduced by $1407/ha and $1252/ha, compared with no addition of inhibitor on the respective bed and flat experiments. Although N_2O fluxes are driven by environmental episodic events, management will play a role in N_2O abatement. However, DCD currently appears economically unfeasible and matching N fertiliser supply to meet crop demand appears a better option for minimising N_2O losses from high rainfall cropping systems.

Keywords Wheat (*Triticum aestivum* L.) · Canola (*Brassica napus* L.) · Nitrogen · Nitrous oxide · Soil mineral nitrogen · Water filled pore space · Raised bed · Static chamber

Sally J. Officer: deceased.

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Introduction

Although nitrous oxide (N_2O) accounts for only a small percentage of total annual global greenhouse gas emissions, it absorbs approximately 300 times as much infra-red radiation per kilogram of carbon dioxide (CO_2) (Crutzen 1981) and can play a significant role in elevating global temperatures (Lashof and Ahuja 1990). Approximately 60 % of annual global N_2O emissions occur from soil microbial activity (Mosier et al. 1998), a result of at least four soil microbial driven processes; (1) nitrification, where soil bacteria convert ammonium (NH_4^+) into nitrate (NO_3^-) (2) denitrification, where soil microbes consume oxygen from NO_3^- compounds under anaerobic conditions (3) assimilatory NO_3^- reduction, where NO_3^- is converted back into nitrite (Dalal et al. 2003) and (4) dissimilatory NO_3^- reduction, where NO_3^- is converted back into NH_4^+. However, denitrification is widely considered the main process leading to N_2O production from soil (Tiedje 1994; Rochester 2003; Soussana et al. 2010).

Denitrification takes place in soils when demand for oxygen exceeds supply, which is likely under waterlogged conditions. The physical properties of the soil influence pore space, and as pores fill with water, oxygen diffusion is restricted, resulting in greater N_2O emissions (Burford and Stefanson 1973; Stefanson 1973). Therefore the proportion of water-filled pore space (WFPS) can influence the rate of N_2O production (Dalal et al. 2003). Normally when WFPS is below 40 %, N_2O production is low, but increases rapidly as WFPS approaches 80 % (Ciarlo et al. 2007) but thereafter generally declines as N_2 becomes the major form of gas loss (Davidson 1992; Bouwman 1998). Other variables can also influence the rates of denitrification, including soil temperature, soil organic carbon (C), soil nitrogen (N) supply (fertiliser and organic) and soil pH (Castaldi 2000; Rochester 2003; Stehfest and Bouwman 2006 and Peoples et al. 2009).

Farming systems with high soil C and N stores that are prone to prolonged periods of saturated conditions are likely to produce significant quantities of N_2O. In the high rainfall (>650 mm) zone of south west Victoria, paddocks are sometimes converted from long-term (>10 years) legume and grass pasture to wheat, have high organic soil C (>3.5 %) and often experience waterlogging from excess winter rainfall. Zhang et al. (2004) estimated up to 300 kg N/ha mineralising after the transition from a long-term legume based pasture to cropping in south west Victoria. Recent investigations using continuous automated gas sampling of a paddock converted to cropping in south west Victoria measured large N_2O emissions, up to 35 kg N_2O–N/ha/year (Officer et al. 2012).

The potentially very high rates of N_2O associated with cropping in this environment have generated significant interest in mitigation strategies that could reduce these nationally significant rates of greenhouse gas emissions. Recently there have been some Australian studies quantifying N_2O losses from winter cropping soil (Barker-Reid et al. 2005; Barton et al. 2008; Officer et al. 2008; Barton et al. 2010; Barton et al. 2011), but often conducted in much lower rainfall environments, with low soil organic C (<1.5 %), reporting low N_2O fluxes and limited assessment of anthropogenic management effects on emissions. Research elsewhere has shown that the nitrification inhibitor Dicyandiamide (DCD) can reduce the release of N_2O by up to 26 % in European cropping systems (Weiske et al. 2001) and 70 % from urine patches in New Zealand dairy pastures (Di et al. 2007). The IPCC (2006) estimates approximately 1 % of N fertiliser application is likely to be emitted as N_2O, raising the possibility of efficient fertiliser delivery reducing emissions.

This paper evaluates the role of management in the abatement of N_2O on a high rainfall commercial cropping paddock in south west Victoria. The strategies include different rates of N fertiliser applied with and without DCD, to two separate field experiments established on raised beds and conventionally flat cropping systems; to test the hypothesis that N fertiliser rate and nitrification inhibitor management can influence relative N_2O emissions from high rainfall cropping systems.

Materials and methods

Experimental sites

Two separate but adjacent, field experiments were conducted from 2010 to 2011 within one paddock located on a commercial cropping farm near Strathkellar (142°7′E, 37°37′S) in south west Victoria. A raised bed experiment (bed experiment) was located on a Mottled, Meso-Natric Grey Sodosol soil, while

another experiment was located on level terrain (flat experiment); on a Ferric-Sodic Red Chromosol soil (Isbell 2003). Topsoil (0–20 cm) clay content was 15–20 %, gradually increasing to 45–50 % by 70 cm depth on both soils.

Paddock history

Prior to the establishment of the two experiments, the paddock consisted of a long-term (10 years) mixed sward of subterranean clover (*Trifolium subterraneum* L.) and perennial grass pasture, until 2009 when wheat (*Triticum aestivum* L.) cv. Bolac was planted. In the following year glyphosate (658 g of a.i./ha) was sprayed to control summer weeds and the wheat stubble burnt and scarified, before a bed former constructed raised beds on 2 April 2010. Beds were 2 m wide and furrows 20 cm deep by 35 cm wide. Raised beds were formed on approximately 80 % of the paddock, with the remaining proportion left conventionally flat.

Experimental design

Two separate field experiments, consisting of eight main treatments and replicated three times in a two factor, factorial design were established on the raised bed and flat experimental sites. Plots on both experiments were 6 m wide, or three raised beds wide on the bed experiment, by 15 m long. Four different rates of N fertiliser (first factor) were applied in the presence and absence of the soil nitrification inhibitor (second factor) DCD. The four rates included a low (LN), medium (MN), high (HN) and very high (VN) N fertiliser input. In 2010, both experiments received identical quantities of N fertiliser for each respective N treatment, but in 2011, experiments received different levels of N fertiliser for each respective N treatment (Table 1). The N fertiliser rates were within the range commonly applied by commercial farmers to wheat and canola (*Brassica napus* L.) in the high rainfall zone of south west Victoria.

Baseline soil chemical and physical properties

Before experimentation, soil organic C, total soil N, soil P and exchangeable aluminium levels generally declined with depth, and conversely soil pH, exchangeable sodium and bulk density increased with depth under both experimental sites (Table 2). Electrical conductivity, S and K initially decreased with depth and then increased in the deeper layers, under both experimental sites. In the topsoil layer (0–10 cm) of the furrows, on the bed experimental site, all soil parameters were lower in comparison to the adjacent beds, with the exception of soil K and bulk density.

Table 1 The quantity of N fertiliser applied for each N treatment, on the bed and flat experiments in 2010 and 2011, at Strathkellar in south west Victoria

Treatment[a]	N fertiliser input (kg N/ha)[b]	
	2010	2011
Bed experiment		
LN	60	38
MN	85	63
HN	110	88
VN	160	138
Flat experiment		
LN	60	17
MN	85	42
HN	110	67
VN	160	117

[a] Applies to treatments both in presence and absence of DCD

[b] Includes basal and top-dressed N applications

Climatic and soil temperature measurements

An automated tipping bucket rain gauge (Hastings Dataloggers, Port Macquarie, Australia, www.hdl.com.au) installed in close proximity to the experimental site measured hourly rainfall. Hourly topsoil water was monitored by theta probes (Theta-Probe MK2x, Delta-T Devices Ltd, Burwell England) and installed to a depth of 6 cm in all MN treatments of each replicate of both experiments. A FT100 temperature probe (Hastings Dataloggers, Port Macquarie, Australia, www.hdl.com.au) measured hourly topsoil (0–10 cm) temperature. One soil temperature probe was installed in the MN treatment within the second replicate of the bed and flat experiments in 2010. The following year, additional soil temperature probes were installed in all MN plots of both experiments. On the bed experiment, probes (theta and soil temperature) were placed on top of the raised bed and in the middle of the adjacent furrow.

Table 2 Soil chemical and physical properties of the bed and flat experiments at Strathkellar in south west Victoria

Soil depth (cm)	Organic carbon (%)[a]	Total nitrogen (%)[b]	Soil pH($CaCl_2$)[c]	Electrical conductivity (dS/m)[d]	Exchangeable aluminium (%)[e]	Exchangeable sodium (%)[e]	Sulphur (mg/kg)[f]	Phosphorus colwell (mg/kg)[g]	Potassium colwell (mg/kg)[g]	Bulk density (g/cm^3)[h]
Bed experiment (bed top)										
0–10	3.61 (±0.25)	0.32 (±0.01)	4.69 (±0.28)	0.21 (±0.03)	3.37 (±0.28)	3.17 (±0.03)	42.80 (±8.36)	60.00 (±3.79)	135.33 (±5.93)	1.20
10–20	2.03 (±0.40)	0.25 (±0.01)	4.53 (±0.08)	0.12 (±0.03)	3.94 (±0.28)	4.76 (±0.04)	25.58 (±9.06)	20.00 (±4.04)	62.33 (±3.53)	1.25
20–30	0.92 (±0.05)	0.12 (±0.00)	4.98 (±0.12)	0.06 (±0.01)	1.14 (±0.28)	7.79 (±0.03)	15.90 (±1.16)	6.67 (±0.88)	52.33 (±2.67)	1.36
30–40	0.75 (±0.02)	0.09 (±0.01)	5.35 (±0.09)	0.07 (±0.01)	0.61 (±0.28)	11.35 (±0.09)	11.71 (±0.65)	5.00 (±1.00)	76.00 (±4.36)	1.51
40–60	0.66 (±0.07)	0.08 (±0.00)	6.06 (±0.04)	0.09 (±0.01)	0.42 (±0.28)	15.63 (±0.11)	13.22 (±0.65)	2.00 (±0.00)	106.33 (±8.21)	1.64
60–80	0.57 (±0.02)	0.08 (±0.00)	6.57 (±0.02)	0.16 (±0.01)	0.29 (±0.28)	19.60 (±0.08)	23.79 (±2.30)	2.00 (±0.00)	109.67 (±3.28)	1.40
80–100	0.65 (±0.08)	0.05 (±0.01)	6.90 (±0.06)	0.25 (±0.00)	0.23 (±0.28)	22.34 (±0.17)	37.29 (±0.76)	4.67 (±1.20)	103.33 (±1.45)	1.40
Bed experiment (furrow)[i]										
0–10	2.31 (±0.15)	0.22 (±0.01)	4.46 (±0.04)	0.08 (±0.01)	4.99 (±0.57)	2.33 (±0.34)	13.44 (±0.91)	55.67 (±9.09)	167.60 (±19.98)	1.40
Flat experiment										
0–10	3.92 (±0.07)	0.40 (±0.01)	4.62 (±0.12)	0.25 (±0.01)	2.47 (±0.28)	2.89 (±0.04)	29.42 (±0.59)	133.67 (±7.79)	260.00 (±34.04)	1.20
10-20	1.71 (±0.14)	0.25 (±0.01)	4.64 (±0.08)	0.13 (±0.02)	2.33 (±0.28)	4.96 (±0.05)	25.69 (±2.70)	36.33 (±8.19)	123.33 (±12.39)	1.29
20–30	1.06 (±0.31)	0.12 (±0.01)	5.68 (±0.34)	0.11 (±0.01)	1.04 (±0.28)	8.77 (±0.03)	25.13 (±2.41)	17.33 (±2.03)	98.00 (±7.57)	1.32
30–40	0.81 (±0.10)	0.10 (±0.01)	5.65 (±0.27)	0.12 (±0.01)	0.56 (±0.28)	13.18 (±0.14)	22.12 (±2.18)	9.33 (±1.45)	113.67 (±6.33)	1.37
40–60	0.68 (±0.02)	0.08 (±0.01)	5.85 (±0.29)	0.16 (±0.00)	0.38 (±0.28)	18.72 (±0.20)	21.32 (±2.49)	3.50 (±0.41)	117.50 (±4.49)	1.28
60–80	0.55 (±0.02)	0.06 (±0.01)	6.30 (±0.05)	0.26 (±0.01)	0.26 (±0.28)	24.17 (±0.15)	29.83 (±7.34)	11.00 (±7.35)	111.50 (±6.94)	1.29
80–100	0.77 (±0.13)	0.06 (±0.00)	6.30 (±0.27)	0.47 (±0.02)	0.27 (±0.28)	27.55 (±0.25)	51.09 (±12.28)	14.00 (±0.00)	98.50 (±1.22)	1.32

Values represent the mean of the three replicates for each experiment, numbers in brackets ± SE

[a] Measured by Walkley and Black (1934) method

[b] Measured by combustion of air dry soils using LECO combustion analyser

[c] Measured in 0.01 M $CaCl_2$ solution at a 1:5 soil to extract ratio using a glass electrode

[d] Measured in water using a probe and a1:5 soil to extract ratio

[e] Measured in 0.1 M NH_4Cl/0.1 M $BaCl_2$ at a 1:10 soil to extract ratio for two hours, before concentrations determined by Inductively Coupled Plasma

[f] Measured by Colwell (1965) and Rayment and Higginson (1992) methods

[g] Measured by Blair et al. (1991) method

[h] specified elsewhere in the Materials and Methods

[i] Separate 0–10 cm samples were collected from the bed top and adjacent furrow

Crop and fallow management

Both experiments were sprayed on 3 May 2010 with a tank mix of glyphosate (752 g of a.i./ha) and 2,4-D (480 g of a.i./ha) to eradicate weeds. Trifluralin (960 g of a.i./ha) was sprayed shortly before sowing wheat cv. Pugsley at 85 kg/ha on 21 May 2010. A basal application of N and phosphorus (P) was applied as DAP (Di-Ammonium Phosphate, 14 kg/ha of N and 16 kg/ha of P) with the seed, and treated with flutriafol (125 g of a.i./ha) to combat future threats of stripe rust (*Puccinia striiformis*). On 24 May 2010, a tank mix of s-metolachlor (240 g of a.i./ha) and alpha-cypermethrin (10 g of a.i./ha) was applied to control toad rush (*Juncus bufonius*) and red legged earthmite (RLEM) (*Halotydeus destructor*). A follow up fungicide application of prothioconazole (42 g of a.i./ha) and tebuconazole (42 g of a.i./ha) was applied on 30 September 2010 to prevent outbreaks of stripe rust and stem rust (*Puccinia gramius tritici*).

Stubbles on both experiments were intensively grazed with merino ewes at approximately 50 Dry Sheep Equivalents/ha followed by burning on 18 March 2011. All treatments were sprayed on 25 April 2011 with glyphosate (752 g of a.i./ha) to eradicate weeds. Trifluralin (960 g of a.i./ha) was sprayed shortly before sowing canola cv. Garnet at 3 kg/ha on 3 May 2011. A basal application of N and P was applied as DAP (17 kg/ha of N and 19 kg/ha of P) with the seed. On 5 May 2011, s-metolachlor (240 g of a.i./ha) was applied to control toad rush. Severe waterlogging over the 2011 winter meant both experiments became untrafficable, and in-crop weed control was not possible. Both experiments in both years were sown, with a conventional air-seeder equipped with a parallelogram guided by 2 cm GPS auto steer, with knife points and press wheels spaced 30 cm apart.

N fertiliser and soil nitrification inhibitor management

On both experiments, urea was top-dressed by hand at 25, 50 and 100 kg N/ha to the MN, HN and VN treatments respectively, on 23 August in both years. Top-dressing N coincided with the first node stage (GS 31) of wheat growth (Zadoks et al. 1974), and the internodal growth stage (GS 2.04–2.06) of canola (Slyvester-Bradley and Makepeace 1984). An additional 46 kg N/ha as urea fertiliser, was top-dressed by aeroplane across both experiments on 13 September 2010. On 22 August 2011, 21 kg N/ha and 24 kg S/ha was applied as sulphate of ammonia, by aeroplane across all treatments on the bed experiment. Both aerial applications of N were applied to the broader paddock by the collaborating farmer, who chose not to spread sulphate of ammonia on the flat proportion of the paddock in 2011, due to the low yield potential of the waterlogged canola. DCD was applied at 10 kg of a.i./ha on 3 June and 24 August 2011, using a motorised backpack spray unit fitted with a 2 m boom.

Soil sample collection for chemical analysis and bulk density

On both experiments ten deep soil cores (internal diameter 42 mm) were randomly collected from each replicate on 2 June 2010 and four cores were randomly collected from the LN and VN plots on 18 April and 23 November 2011. On each occasion the cores were divided into 10 cm increments to 40 cm depth, and thereafter in 20 cm increments to 100 cm depth. On the bed experiment soil samples were only taken from the beds. Five of the ten cores collected in June 2010 and three of the four cores collected in April and November 2011, were combined for each layer within each replicate or plot. Samples were then oven dried at 40 °C for 48 h and passed through a 2 mm sieve in preparation for chemical analysis. The remaining five cores collected in June 2010 and the remaining core collected on each occasion in April and November 2011 were then weighed and oven dried at 105 °C for 48 h and weighed again to determine gravimetric water, bulk density and or volumetric water.

Surface soil mineral N (NH_4^+ and NO_3^-) was measured monthly throughout each growing season. On each occasion between 12 and 15 soil cores (internal diameter 20 mm) were randomly collected to a depth of 10 cm, from all the LN, VN and VN + DCD treatments on both experiments. Within each plot of the bed experiment, separate soil samples were taken from the top of the beds and from the adjacent furrows. Samples were oven dried at 40 °C for 48 h, and passed through a 2 mm sieve in preparation for soil mineral N analysis.

Additional topsoil samples were taken by hand to measure bulk density, using stainless steel rings (internal diameter 50 mm) to 10 cm depth from the LN, VN and VN + DCD treatments of both

experiments in August and September 2011. In each plot three random samples were collected and on the bed experiment, separate samples were taken from the beds and the adjacent furrows. Samples were then weighed, and then oven dried at 105 °C for 48 h, before reweighing.

Crop biomass, grain yield and grain protein

Wheat biomass was measured at crop maturity on 4 January 2011, by cutting three random locations of 1 m row of crop, while canola biomass was taken prior to windrowing on the 8 November 2011, by cutting two random locations, of 3 rows of crop by 1 m. On both occasions crop was cut at ground level and bulked within each plot, subsamples were retained and oven dried at 65 °C until constant weight was reached.

Wheat grain yield was measured by mechanically harvesting each plot. A sub-sample of grain was retained to assess grain quality. Wheat grain protein was calculated by multiplying grain N concentration by 5.7 (Halvorson et al. 2004). Mechanical harvesting of canola was not possible, bulk biomass samples collected before windrowing were dried at 40 °C and combined with oven dried subsamples from each plot and threshed to separate seed from biomass. On the bed experiment crop productivity was only measured from the beds.

Partial Budget

Variable costs of $350 and $450/ha were assumed for respective wheat and canola crops; urea and sulphate of ammonia fertiliser were $500 and $575/t, respectively, and each application of DCD cost $666/ha. Returns for Australian Premium White wheat with 10.5 % grain protein and canola with 42 % oil content, were those that applied in February 2011. Partial budgets were calculated by multiplying grain yield by price less variable cost, additional top-dressed fertiliser and DCD application costs.

N_2O gas sample collection

N_2O gas concentrations were measured from 14 September 2010 to 4 November 2011, with most measurements taken during the growing season, except 14 December 2010 and 6 January 2011. Over the growing season, N_2O fluxes were measured on a weekly to fortnightly frequency from both experiments.

Static chambers were constructed using modified 25 L plastic drums (internal diameter at the base of 300 mm) with the bases cut off. Chambers remained in the field, but periodically repositioned to minimise micro-climatic artefacts. However, the shoulders of the drums would have interfered with rainfall interception and so a funnel, 300 mm diameter at the top and 210 mm diameter opening at the bottom was constructed by cutting the top out of a second drum and lid, inverted and glued, and fitted to the base to capture rainfall over the same diameter. When gas sampling, the funnel was replaced with a modified lid, fitted with an 'S' valve and rubber septum, and a 9 volt battery powered computer fan mounted on the bottom of the lid provided continuous gas circulation. The 'S' valve released any pressure build up that occurred when sampling during warm periods. The static chamber design was validated against conventional automated chambers, giving the same magnitudes of N_2O flux.

Two chambers installed within 2 m proximity of each other in each plot were inserted into the soil to a depth of 5 cm, between crop rows, in all the LN, VN and VN + DCD treatments of both experiments. The close installation of chambers was necessary to place raised platforms between chambers to minimise soil compaction and plot damage from frequent samplings. In each plot of the bed experiment, two chambers were installed on top of the bed and two in the adjacent furrow. Chang et al. (1998) reported that N_2O could be emitted by plants, and so crop and weeds were frequently eradicated from all chambers by spraying glyphosate. However, the close proximity of crop adjacent to the chambers ensured rhizosphere effect on soil derived emissions. On all occasions, fluxes were measured from both experiments between 10 am and 2 pm. After pouring water into the 'S' valve and fitting the gas sampling lid, samples were collected by syringe at 0, 20, 40 and 60 min after lid emplacement. Twenty mL air samples were injected into 12 ml evacuated exetainers (Labco Limited, High Wycombe, UK) and posted to the University of Melbourne, Parkville Campus for analysis by gas chromatograph. Tinytag plus 2 temperature data loggers (Hastings Dataloggers, Port Macquarie, Australia, www.hdl.com.au) were placed inside one chamber in each replicate of both experiments to

monitor changes in air temperature during gas sampling.

Calibration of the Theta probe and conversion to water filled pore space (WFPS)

When topsoil samples were collected from both experiments for soil mineral N analysis in 2011, a subsample was retained, weighed and oven dried at 105 °C for 48 h and weighed again to determine gravimetric water. A regression analysis determined an equation, used to convert theta probe data to volumetric water. Calibration equations for each experiment included:

Beds on the bed experiment and the flat experiment:

$$\text{Volumetric soil water} = (0.0042 \times \text{water content}) + 0.1961 \left(R^2 = 0.80\right)$$

Furrows:

$$\text{Volumetric soil water} = (0.0046 \times \text{water content}) + 0.2233 \left(R^2 = 0.85\right)$$

Water filled pore space was then determined by dividing volumetric water content by total porosity (Linn and Doran 1984).

Chemical and data analysis

Soil NO_3^- and NH_4^+ analysis involved soils extracted with 1 M of KCl solution for 1 h at 25 °C; the resulting solution was then measured on a Lachat Flow Injection Analyzer (Searle 1984). Gas samples were analysed by a fully automated Gas Chromatograph (Agilent 7890A, Agilent Technologies Inc. Wilmington, USA) equipped with a micro electron capture detector to quantify N_2O ($N_2O_{(g)}$) concentration and then converted to gas density ($N_{(g)}$) by:

$$N_{(g)} = N_2O_{(g)} \times (P \times 2Mw)/(R \times T)$$

where P is atmospheric standard air pressure of 101.31 kPa, Mw is the molecular weight of N, R is the universal gas constant (8.314 j K^{-1} mol^{-1}), and T is chamber air temperature (Kelvin). Gas density was then adjusted for chamber volume. Fluxes were calculated from the linear increase in gas density in the chamber headspace with time; flux rates with a regression coefficient (r^2) of <0.80 were discarded (Barton et al. 2008).

Statistical analysis

Separate statistical analyses were preformed to determine the impact of N rate and DCD application on crop productivity, N_2O fluxes and topsoil mineral N for each experiment; N_2O flux and topsoil mineral N collected from the beds and furrows of the bed experiment were also analysed separately. Treatment differences in crop biomass, grain yield, grain quality and topsoil mineral N were tested using analysis of variance (ANOVA) appropriate for completely randomised block design. Logarithmic (base 10) transformations were used to normalise the N_2O flux data before Residual Maximum Likelihood (REML) analyses was used to determine treatment differences. All analysis was undertaken using Genstat 13 Edition (Lawes Agricultural Trust, Hampenden, UK).

Results

Rainfall

In 2010 annual rainfall was 60 mm above the long-term (1889–2009) mean of 677 mm, but growing season rainfall (April–November) was 24 mm below the long-term mean of 530 mm. The rainfall pattern in 2011 was similar to the previous year, with annual rainfall 38 mm above the long-term mean, and growing season rainfall 86 mm below the long-term mean. In both years above average summer rainfall, was largely responsible for the higher than average annual rainfall, with 126 mm recorded in December 2010 followed by 125 mm in January 2011.

Temporal changes in daily soil temperature and water filled pore space

Soil temperatures generally increased on both field experiments from 7 to 20 °C, between 25 August 2010 and 7 January 2011 (Figs. 1a, 2a, 3a). From the 7 April to 16 July 2011, temperatures on both experiments generally declined from 17 to 7 °C, before increasing to around 18 °C by 9 November (Figs. 1b, 2b, 3b).

Topsoil WFPS on both experiments responded to periods of high rainfall (>20 mm), associated runoff, surface pondage and evapotranspiration. On the beds

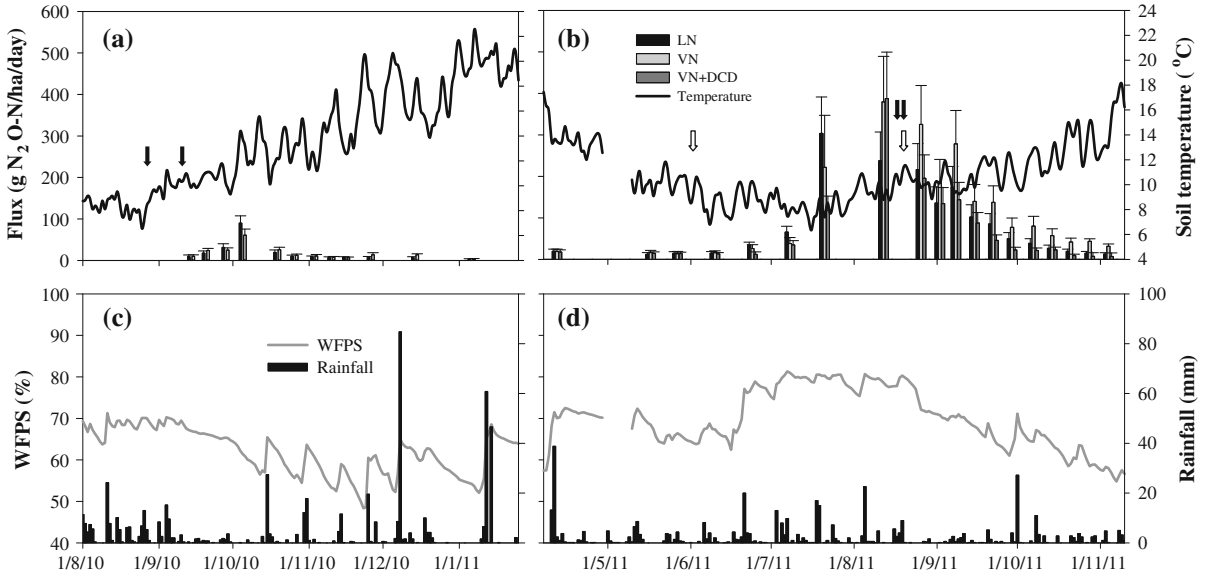

Fig. 1 Mean temporal changes in N_2O fluxes and soil temperature (**a** and **b**), daily rainfall and WFPS (**c** and **d**) on the bed top of the bed experiment from 1 August 2010 to 25 January 2011 (**a** and **c**) and 7 April to 10 November 2011 (**b** and **d**) for the LN, VN and VN + DCD treatments (mean of three replicates), at Strathkellar in south west Victoria. *Closed arrows* indicate N fertiliser application, *open arrows* indicate DCD application. *Bars* ± SE (n = 3)

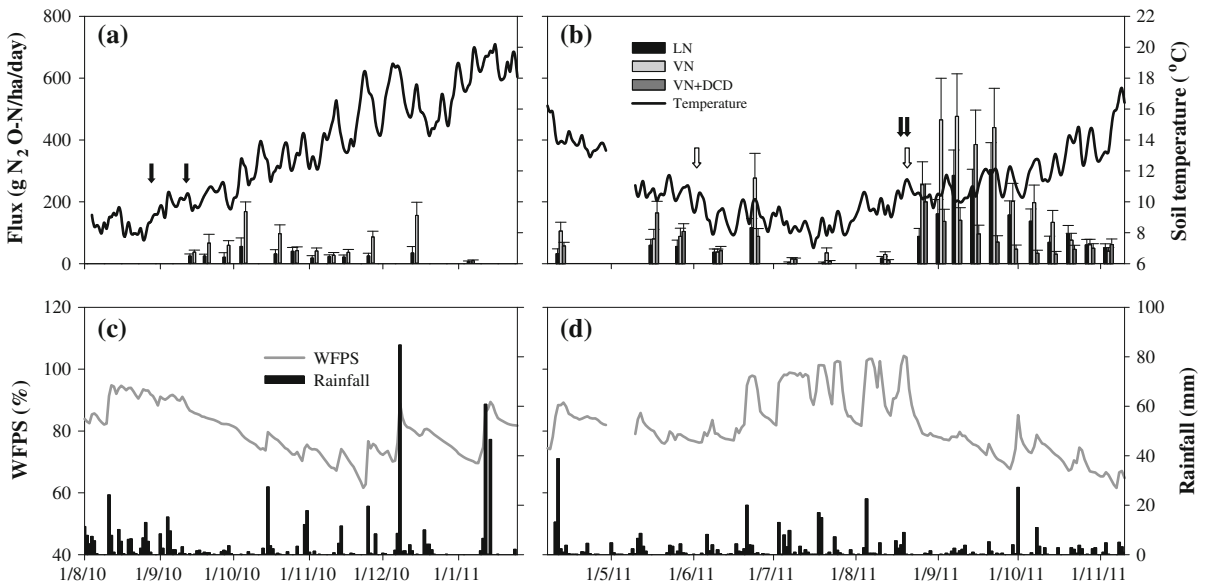

Fig. 2 Mean temporal changes in N_2O flux and soil temperature (**a** and **b**), daily rainfall and WFPS (**c** and **d**) in the furrows of the bed experiment from 1 August 2010 to 25 January 2011 (**a** and **c**) and 7 April to 10 November 2011 (**b** and **d**) for the LN, VN and VN + DCD treatments (mean of three replicates), at Strathkellar in south west Victoria. *Closed arrows* indicate N fertiliser application, *open arrows* indicate DCD application. *Bars* ± SE (n = 3)

of the bed experiment, WFPS was in the range of 48–81 % (Fig. 1c, d) and the only notable period of high WFPS (>70 %), occurred between 21 June and 3 September 2011 (Fig. 1d). In the adjacent furrows, WFPS ranged between 62 and 104 % (Fig. 2c, d); but remained >70 % for the majority of the study.

On the flat experiment, WFPS ranged from 53 to 104 % (Fig. 3c, d) over the study period; with three

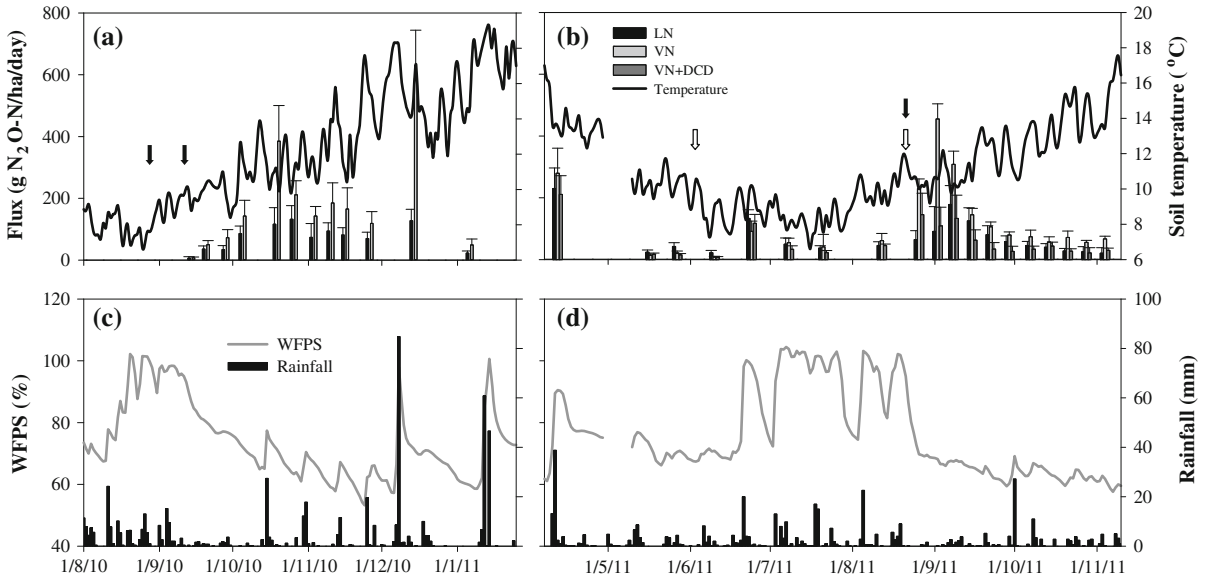

Fig. 3 Mean temporal changes in N_2O flux and soil temperature (**a** and **b**), daily rainfall and WFPS (**c** and **d**) on the flat experiment from 1 August 2010 to 25 January 2011 (**a**, and **c**) and 7 April to 10 November 2011 (**b** and **d**) for the LN, VN and VN + DCD treatments (mean of three replicates), at Strathkellar in south west Victoria. *Closed arrows* indicate N fertiliser application, *open arrows* indicate DCD application. *Bars* ± SE (n = 3)

prolonged periods of high WFPS (>70 %) observed between 15 August to 2 October 2010, 10 April to 18 May 2011 and 17 June to 25 August 2011.

Profile soil mineral N and soil water

Before imposing treatments on the bed experiment in June 2010, 259 (± 27) kg/ha of mineral N (NH_4^+ and NO_3^-) was stored in the top 1 m of the soil profile of which 92 % was NO_3^-; with slight bulges of N observed at 50 and 90 cm depths (Fig. 4a). At the same time, on the adjacent flat experiment, 343 (±12) kg/ha of mineral N was distributed throughout the top 1 m of the soil profile of which 88 % comprised of NO_3^-; with a bulge in N observed at 50 cm depth (Fig. 4b).

In April 2011 7 months after imposing treatments on the bed experiment, the LN and VN treatments had 226 (±34) and 252 (±51) kg/ha of mineral N stored in the top 1 m of the soil profile under respective LN and VN treatments, of which 70 % was NO_3^-. On the bed experiment, a small bulge of N was observed at 50 cm depth under the LN treatment (Fig. 4c), and a larger bulge at the same depth under the VN treatment (Fig. 4d). By November 2011 on the bed experiment, mineral N had declined under both the LN and VN treatments to a depth of 50 cm, with no notable change below this depth under the LN treatment, while N increased at and below 70 cm under the VN treatment (Fig. 4d).

On the flat experiment in April 2011, 224 (±39) and 276 (±30) kg/ha of mineral N had accumulated in the top 1 m of the soil profile under the LN and VN treatments respectively, of which NO_3^- comprised 76 % under both treatments. Mineral N was more evenly distributed throughout the soil profile in April under the LN treatment on the flat experiment (Fig. 4e), in contrast more than half the N was stored in the lower profile (≥50 cm) of the VN treatment (Fig. 4f). By November 2011, there was a marginal decline in mineral N in the top 30 cm of the profile under both LN and VN treatments on the flat experiment, but no notable change below this depth under the LN treatment, while N increased at and below 70 cm, under the VN treatment (Fig. 4f).

On the bed experiment in April 2011, there was 334 (±23) mm of stored soil water (mean of LN and VN treatments) in the top 1 m of the soil profile, by the following November levels had decreased to 272 (±20) mm, with most of the change observed in the top 40 cm (Fig. 5a). On the nearby flat experiment in April 2011, there was 385 (±3) mm of soil water

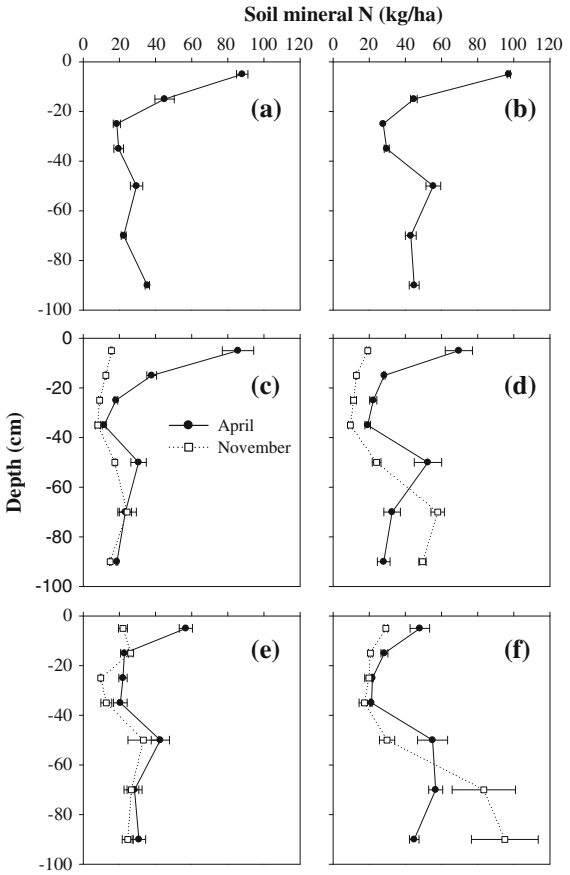

Fig. 4 Distribution of mineral N (NO_3^- and NH_4^+) through the soil profile, under the bed (**a**) and flat (**b**) experiments in June 2010 (mean of three replicates); and under the LN (**c** and **e**) and VN (**d** and **f**) treatments on the bed (**c** and **d**) and flat (**e** and **f**) experiments in April and November 2011, at Strathkellar in south west Victoria (mean of three replicates). *Bars* ± SE

(mean of LN and VN treatments) stored in the top 1 m of the profile, by the following November levels had decreased to 342 (±27) mm, with most of the change observed in the top 40 cm (Fig. 5b).

Temporal changes in topsoil (0-10 cm) mineral N (NO_3^- and NH_4^+)

Soil NO_3^- on the beds of the bed experiment was not significantly altered by treatment throughout the experiment, but did change significantly ($P < 0.001$) with time. There was a trend ($P = 0.073$) for higher soil NH_4^+ levels under the VN + DCD treatment compared with the VN treatment in 2011. On the beds, mean treatment topsoil NO_3^- ranged between 5 (±1) and 89 (±9) kg/ha, with the highest levels measured

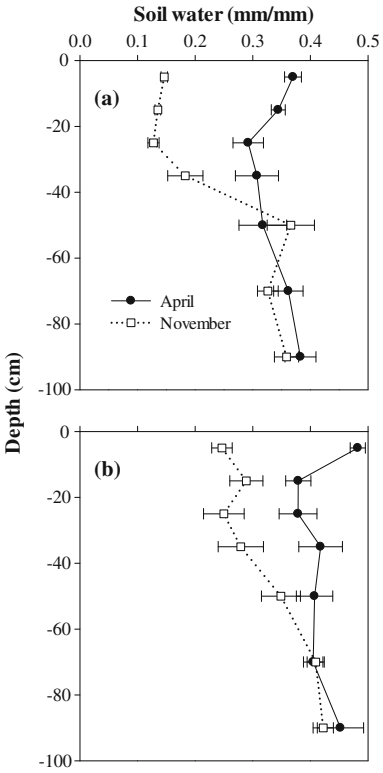

Fig. 5 Distribution of volumetric soil water through the soil profile under the bed (**a**) and flat (**b**) experiments in April and November 2011. Mean of three replicates of the LN and VN treatments for both experiments, at Strathkellar in south west Victoria. *Bars* ± SE

around planting; but NO_3^- did not change significantly following N fertiliser application (Table 3). Topsoil NH_4^+ ranged from 7 (±1) to 66 (±6) kg/ha for all sampling dates between August 2010 to November 2011 (Table 3).

In the adjacent furrows of the bed experiment, no significant treatment differences in soil NO_3^- and NH_4^+ were observed throughout the experiment, but there was a significant ($P = 0.002$) effect of time. There was a trend ($P = 0.076$) for elevated soil NO_3^- levels in the furrows of the VN treatment compared with the furrows of the VN + DCD and LN treatments; and a trend ($P = 0.072$) towards a significant treatment by time interaction, with higher soil NH_4 in the furrows of the VN + DCD treatment compared with the VN treatment in 2011. In the furrows, mean treatment topsoil NO_3^- ranged between 6 (±1) and 39 (±7) kg/ha, and topsoil NH_4 ranged from 10 (±2) to 109 (±15) kg/ha for all sampling dates between August 2010 to November 2011 (Table 3).

Table 3 Mean temporal changes in topsoil (0–10 cm) NO_3^- and NH_4^+ (kg/ha) on the bed top and furrow of the bed experiment and the flat experiment, at Strathkellar in south west Victoria

Date	NO3$^-$				NH4$^+$			
	LN	VN	VN + DCD	Mean of all treatments	LN	VN	VN + DCD	Mean of all treatments
Bed experiment (bed top)								
10/08/2010	18 (±3)	21 (±5)		20 (±3)	8 (±1)	8 (±1)		8 (±0.4)
24/09/2010	9 (±1)	20 (±3)		15 (±3)	60 (±9)	72 (±1)		66 (±6)
20/10/2010	22 (±4)	30 (±3)		26 (±3)	14 (±4)	15 (±3)		15 (±2)
26/11/2010	9 (±4)	17 (±2)		13 (±3)	6 (±0.1)	6 (±0.4)		6 (±0.2)
20/01/2011	26 (±2)	35 (±3)		30 (±2)	6 (±0.4)	8 (±2)		7 (±1)
18/04/2011	79 (±18)	58 (±11)	48 (±8)	62 (±8)	10 (±1)	12 (±4)	11 (±1)	11 (±1)
1/06/2011	99 (±6)	87 (±17)	81 (±24)	89 (±9)	26 (±9)	22 (±6)	17 (±3)	22 (±3)
15/06/2011	40 (±4)	85 (±21)	89 (±18)	71 (±11)	8 (±0.4)	12 (±4)	14 (±1)	11 (±2)
27/07/2011	14 (±2)	16 (±2)	11 (±6)	13 (±2)	34 (±5)	27 (±4)	30 (±5)	30 (±3)
23/08/2011	7 (±1)	8 (±2)	8 (±1)	8 (±1)	34 (±4)	13 (±1)	44 (±4)	30 (±5)
28/09/2011	4 (±1)	9 (±3)	6 (±0.4)	6 (±1)	16 (±3)	18 (±3)	26 (±1)	20 (±2)
25/10/2011	4 (±1)	8 (±1)	4 (±0.4)	5 (±1)	16 (±3)	18 (±0.4)	18 (±2)	17 (±1)
Bed experiment (furrow)								
10/08/2010	8 (±1)	8 (±1)		8 (±1)	11 (±1)	8 (±1)		10 (±1)
24/09/2010	11 (±5)	9 (±3)		10 (±3)	90 (±22)	128 (±18)		109 (±15)
20/10/2010	33 (±10)	44 (±12)		39 (±7)	50 (±10)	76 (±17)		36 (±10)
26/11/2010	24 (±9)	43 (±10)		34 (±7)	9 (±1)	18 (±3)		14 (±3)
20/01/2011	18 (±7)	35 (±6)		26 (±6)	8 (±1)	11 (±3)		10 (±2)
18/04/2011	16 (±2)	26 (±6)	19 (±4)	20 (±3)	11 (±3)	18 (±5)	9 (±1)	13 (±2)
1/06/2011	17 (±3)	30 (±3)	31 (±4)	26 (±3)	16 (±2)	23 (±3)	15 (±2)	18 (±2)
15/06/2011	12 (±3)	21 (±6)	19 (±3)	17 (±2)	9 (±2)	12 (±0.5)	10 (±1)	10 (±1)
27/07/2011	4 (±2)	6 (±1)	9 (±2)	6 (±1)	28 (±3)	31 (±0.5)	30 (±4)	30 (±1)
23/08/2011	8 (±2)	10 (±3)	6 (±2)	8 (±1)	78 (±9)	50 (±3)	52 (±11)	60 (±6)
28/09/2011	15 (±2)	52 (±9)	11 (±1)	26 (±7)	24 (±4)	44 (±9)	93 (±18)	54 (±12)
25/10/2011	4 (±0.4)	20 (±7)	8 (±0.4)	11 (±3)	37 (±15)	37 (±6)	46 (±5)	40 (±5)
Flat experiment								
10/08/2010	27 (±12)	16 (±3)		21 (±6)	16 (±4)	13 (±0.4)		15 (±2)
24/09/2010	8 (±0.4)	9 (±2)		8 (±1)	63 (±7)	87 (±18)		75 (±10)
20/10/2010	34 (±5)	55 (±5)		44 (±6)	19 (±4)	18 (±1)		19 (±2)
26/11/2010	17 (±3)	30 (±6)		23 (±4)	9 (±0.4)	11 (±1)		10 (±1)
20/01/2011	23 (±2)	22 (±3)		23 (±2)	14 (±5)	8 (±0.1)		11 (±3)
18/04/2011	47 (±7)	32 (±8)	47 (±15)	42 (±6)	10 (±0.4)	11 (±0.1)	10 (±1)	10 (±0.3)
1/06/2011	73 (±12)	51 (±14)	44 (±19)	56 (±9)	17 (±3)	11 (±3)	14 (±3)	16 (±2)
15/06/2011	27 (±3)	26 (±2)	27 (±5)	27 (±2)	7 (±1)	9 (±2)	8 (±1)	8 (±1)
27/07/2011	4 (±0.1)	4 (±0.4)	4 (±0.4)	4 (±0.2)	36 (±5)	39 (±2)	40 (±8)	39 (±3)
23/08/2011	9 (±2)	8 (±1)	10 (±0.4)	9 (±1)	12 (±0.1)	12 (±1)	16 (±1)	14 (±1)
28/09/2011	10 (±0.4)	32 (±7)	19 (±3)	20 (±4)	16 (±1)	17 (±2)	31 (±3)	21 (±3)
25/10/2011	6 (±0.4)	8 (±1)	12 (±4)	9 (±2)	18 (±1)	19 (±3)	24 (±4)	20 (±2)

Values represent the mean of the three replicates for each experiment, numbers in brackets ± SE

On the flat experiment, soil NO_3^- and NH_4^+ were not significantly affected by treatment, but did change with time ($P < 0.001$). On the flat experiment, mean treatment topsoil NO_3^- ranged between 4 (±0.2) and 56 (±9) kg/ha, with the highest levels measured in the 2011 autumn (Table 3). Topsoil NH_4^+ ranged from 8 (±1) to 75 (±10) kg/ha across all sampling dates between August 2010 to November 2011 (Table 3).

Crop productivity

In both the wheat and canola crops, no significant differences from N rate (LN, MN, HN and VN) were observed in maturity biomass, grain yield and wheat grain protein on the bed and flat experiments (data not shown). In the canola crop, no significant effect of DCD or an interaction between N rate and DCD was observed in maturity biomass and grain yield on the bed and flat experiments (data not shown).

On the bed experiment, wheat yielded 18,529 (±982) kg DM/ha, 6,761 (±464) kg/ha of grain and 14.2 (±0.5) % of protein at maturity, and in the following season canola yielded 13,377 (±1449) kg DM/ha and 3,684 (±369) kg/ha of grain at maturity, across all treatments. On the flat experiment, wheat yielded 14,449 (±1021) kg DM/ha, 4,909 (±329) kg/ha of grain and 15.3 (±0.5) % of protein at maturity, and the canola in the following season yielded 7,871 (±743) kg DM/ha and 1,046 (±302) kg/ha of grain at maturity, across all treatments.

Separate analysis of each experiment showed no significant difference in wheat and canola net income ($/ha) from N rate; or a significant interaction between N rate and DCD in the canola crop. However, a significant ($P < 0.001$) income reduction from the application of DCD to canola was found. On the bed experiment the mean net income from the VN + DCD treatment was -$204/ha, compared with $1203/ha from no addition of DCD (mean of LN and VN treatments). The mean net income from the VN + DCD treatment was -$1357/ha, compared with -$105/ha from no addition of DCD (mean of LN and VN treatments), on the flat experiment.

N_2O fluxes

From September 2010 to November 2011, mean treatment emissions from the beds were generally <100 g N_2O–N/ha/day, except for the period from 21 July to 9 September 2011 when emissions averaged 215 g N_2O–N/ha/day (Fig. 1a, b). From 14 September 2010 to 15 September 2011, no significant treatment differences in N_2O emissions were observed on the beds, of the bed experiment. However, on 22 September, 7, 14 and 28 October, fluxes were up to 84 % lower ($P < 0.05$) from the beds of the VN + DCD treatment compared with the VN treatment. Generally there were no differences in emissions between the LN and VN treatments, except on the 14 October 2011, when emissions were 53 % lower from the beds of the LN treatment.

Mean treatment N_2O losses fluctuated between 9 and 301 g N_2O–N/ha/day in the furrows of the bed experiment from September 2010 to November 2011(Fig. 2a, b), with the only prolonged period of high emissions (>100 g N_2O–N/ha/day) observed between 26 August 2011 and 7 October 2011 (Fig. 2b). Between 28 September to 19 October, and again on 3 November 2010, fluxes were up to 72 % lower ($P < 0.05$) from the furrows of the LN treatment compared with the furrows of the VN treatment. In the following season, significantly ($P < 0.05$) lower emissions from the furrows of the LN treatment were only observed on 29 September and 14 October 2011, when emissions were up to 48 % lower than the VN treatment. On all sampling dates between 8 September to 14 October 2011, emissions from the furrows were <83 % lower ($P < 0.05$) from the VN + DCD treatment compared with the VN treatment. Unexpectedly on 17 May 2011, prior to the imposition of management strategies, fluxes were 64 % lower ($P < 0.05$) from the LN compared with the VN + DCD treatment.

There were two prolonged periods where mean treatment emissions exceeded 100 g N_2O-N/ha/day from the flat experiment; from 5 October to 16 November 2010 and 26 August to 15 September 2011 when fluxes averaged 151 and 157 g N_2O–N/ha/day for respective periods (Fig. 3a, b). Significant treatment differences in fluxes were only observed from the flat experiment on 2 September 2011, when emissions were 80 and 76 %, lower ($P < 0.05$) from the LN and VN + DCD treatments respectively, compared with the VN treatment.

Discussion

Influence of management on N_2O emissions

Management of the VN treatments appeared to over supply N fertiliser to both wheat and canola, but this

did not necessarily translate into frequently higher ($P < 0.05$) N_2O fluxes, compared with the LN treatment on both experiments. While topsoil mineral N data showed a trend ($P = 0.076$) towards higher NO_3^- concentrations in the furrows from higher N application no apparent trend ($P = 0.480$) in NO_3^- concentrations were observed on the beds. Bakker et al. (2005) showed significantly higher runoff from raised beds than conventional no-till seed beds, and nitrate is highly mobile and prone to escape (Di and Cameron 2005). Another possible pathway for NO_3^- escape was subsurface lateral flow, where water perches on the heavy clay 'b' horizon of the soil profile, and subsequent rainfall causes subterraneous lateral drainage (Ridley et al. 2003). We suspect that NO_3^- leakage from the beds of the VN treatment into the adjacent furrows where WFPS was likely to cause denitrification, may have contributed to the significantly higher ($P < 0.05$) N_2O flux, than that of the LN treatment, during the 2010 season. Furthermore, severely waterlogged conditions in the furrows would have restricted plant N uptake. The theory of NO_3^- leakage would also explain why N_2O fluxes from the beds appeared largely unaffected by N rate; and why N_2O flux differences between N rates in the furrows of the canola crop, were only observed after sudden elevations in WFPS from rainfall and associated runoff (Fig. 2b). However, we also acknowledge that the placement of static chambers in the furrows could have reduced NO_3^- accumulation from surface runoff, and possibly an underestimation of N_2O flux.

DCD had some effect on NH_4^+concentrations in the topsoil ($P = 0.073$) on both the beds and furrows, but no effect on the flat experiment. Soil nitrification inhibitor was not applied in the 2010 season and explains the potential interaction with time. DCD directly inhibits nitrification by reducing the microbial conversion of NH_4^+ to NO_2^-, of which N_2O is a by product (Malla et al. 2005). However, there is conjecture about the role of inhibitors for indirectly reducing denitrification rates through the reduction in NO_3^- supply (Vallejo et al. 2001). Vallejo et al. (2001) found that although DCD inhibited the oxidation of NH_4^+ to NO_3^-, there was no subsequent reduction in the rate of denitrification. Barton et al. (1999) concluded that in most agricultural soils, fertiliser additions increase soil NO_3^- concentrations such that denitrification is not limited by NO_3^- availability. This may partly explain why the effect of DCD was more pronounced after the second application on both experiments, when WFPS were at levels where N_2O originating from denitrification was less likely (Dalal et al. 2003).

There are several alternative pathways where excess N can escape plant uptake (Di and Cameron 2005). In our study there was evidence of N leaching deeper into the soil profile, especially under the VN treatment on the flat experiment (Fig. 4f). Leaching of N and a long delay between the first fertiliser application (23 August 2010) and flux measurement may partly explain why N rate appeared to have little effect ($P = 0.064$ on 28 September) on emissions on the flat experiment in 2010; N application was followed by three rainfall events exceeding 10 mm before the first N_2O measurement (Fig. 3a, b). By comparison, in the following canola crop on 2 September 2011, the only time a significant effect of N rate was found on the flat experiment, N_2O measurements closely followed N application, during a period accompanied by low rainfall.

Temporal patterns of N_2O emissions

N_2O production appeared largely driven by WFPS and soil temperature. On the beds and adjacent furrows, and on the flat experiment, high emissions generally coincided with WFPS levels of between 70 and 80 %. However, when WFPS exceeds 75 %, the ratio of N_2 to N_2O production increases (Davidson 1992; Weir et al. 1993), resulting in a decline in N_2O as WFPS approaches 100 %. This may explain the low N_2O fluxes in the furrows of the bed experiment and the nearby flat experiment, between the 8 July and 12 August 2011, when WFPS exceeded 90 % for much of this period. Differences in WFPS from the beds, may also explain the low N_2O fluxes between 14 September 2010 and 6 January 2011 (Fig. 1a, c) compared with the period from 21 July to 22 September 2011 (Fig. 1b, d), when fluxes were two to three fold higher.

Changes in soil temperature also appeared to partly explain the temporal patterns of N_2O loss. There were periods when WFPS reached levels on the beds conducive to high N_2O fluxes, yet the magnitude of emissions was low such as the 24 June and 8 July 2011 (Fig. 1b, d); a period associated with a downward trend in soil temperature (Fig. 1b).

Large variability in N_2O fluxes made it difficult to separate the effects of management from temporal

emissions in response to changes in climatic conditions, especially on the flat experiment. Parkin (1987) found that available C is irregularly distributed and can result in 'hot spots' of denitrifying activity. Uneven distribution of surface moisture after intense rainfall resulting in some re-distribution of surface water, causing uneven water filled pore contents across the entire site may have also contributed to N_2O flux variance. Significant differences in N_2O fluxes on the flat experiment were recorded only after periods of low rainfall (2 September 2011). In contrast, on 5 October and 14 December 2010, despite large differences in treatment means, fluxes were statistically the same when samples were collected after large intense rainfall events (Fig. 3b). In contrast, on the adjacent bed experiment, there was less variation in N_2O fluxes from the beds and furrows, perhaps a result of man made surface drainage regulating water movement and reducing variation in soil water contents on the beds and furrows.

Influence of management on crop performance

Extra N fertiliser applied above the base rate to wheat and canola, and the application of DCD to canola, did not improve crop yield. Based on potential grain yield models (French and Schultz 1984), and assuming a water use efficiency of 10 kg per mm of plant available water for canola (Robertson and Kirkegaard 2005), we estimated potential grain yields of 6.5 and 3.8 t/ha for respective wheat and canola crops sown at Strathkellar. Applying N fertiliser clearly did not enhance the ability of either wheat or canola achieving water limited potential yield on the flat experiment. Whilst acknowledging the limitations of such models, the large difference between potential and measured yield, implies some other factor(s) prevented a grain yield response to N fertiliser application.

Transient waterlogging in both years on the flat experiment would have restricted crops from achieving water limited potential yield. Waterlogging results in low soil oxygen concentrations that limit root function and survival (Trought and Drew 1980; Huang et al. 1994) causing significant yield loss, depending on the timing of waterlogging with respect to crop growth stage, and the duration of waterlogging (Watson et al. 1976; Cannell and Belford 1980; Belford et al. 1985). Belford et al. (1985) showed that waterlogging over a 21 day period during wheat stem elongation, significantly reduced grain production by up to 32 %, compared with wheat growing in freely draining soil. Significant reductions in canola yield over a 10 day period from waterlogging have also been reported (Cannell and Belford 1980). High WFPS (>65 %) measured in our study would have reduced soil oxygen diffusion (Bollmann and Conrad 1998) during wheat stem elongation from 15 August to 22 September 2010 (Fig. 3c), and during canola rosette to stem extension growth, between 21 June and 23 August 2011 (Fig. 3d), consequently reducing yield. Presumably waterlogging was less of a constraint to crop yield on the beds, as raised beds are designed to drain excess rainfall into the adjacent furrow (Bakker et al. 2005).

Another possible explanation for crops not reaching their water limited potential yield were soil chemical constraints. Low soil pH can restrict crop yield by inhibiting root growth, especially when associated with high exchangeable aluminium (Fageria et al. 1988), but levels were unlikely to cause significant yield losses on both experiments (Table 2). Deeper in the profile (60–100 cm), exchangeable Na percentages were at levels (>19.6 %) capable of causing soil structural degradation (Naidu and Rengasamy 1993) and reduced canola root growth and subsoil water extraction (Passioura 1991), on both experiments in 2011 (Table 2; Fig. 4a, b). Unfortunately post harvest profile measurements of mineral N and soil water under the previous wheat crops were abandoned and probably meaningless, after high rainfall events in December 2010 and January 2011. However, Nuttall et al. (2003) suggested a critical exchangeable Na percentage of 19 %, before subsoil water use by wheat growing in Calcarosol soils was significantly affected.

Consecutive wheat crops planted in 2009 and 2010, in combination with cool moist conditions contributed to the development of the wheat fungal disease eyespot (*Pseudocercosporella herpotrichoides*) on both experiments in 2010. In 2011, populations of grey field slugs (*Deroceras reticulatum*) and associated feeding on canola was observed on both experiments, despite pre and post sowing baiting. Both disease and pest stresses could have also limited yields of wheat and canola. In both crops, herbicide management was sufficient to keep weed populations low, and significant competition for resources was unlikely.

Despite evidence that soil water and soil N extraction was limited in deeper soil layers (Figs. 4, 5), there

appeared sufficient N in the LN treatment of both experiments to meet either the constrained or potential yield. Leaching of N to depth under the VN treatment in both experiments (Fig. 4d, f), high wheat grain protein (>13.7 %), and no crop response to extra N under waterlogged conditions (Belford et al. 1985) would suggest a non N limited environment. In addition to the mineral N present in the top 0.5 m of soil profiles under both experiments at sowing, there was the potential for significant amounts of in-crop N mineralisation (Angus et al. 1998). Although mineralisation was not measured in our study, a simple model proposed by Baldock (2003) accounting for soil organic carbon, soil carbon to nitrogen ratio and bulk density can be used to estimate the potential supply of N from the decomposition of organic matter during crop growth. Applying this model to the Strathkellar soils, where organic C on the beds (3.61 %) and the nearby flat experiment (3.92 %) are high, upwards of 120 kg N/ha may have mineralised during the growing season, in both years.

While DCD can inhibit the conversion of NH_4^+ into NO_3^- and thereby temporarily keeping N in a less mobile, but plant available form (McTaggart et al. 1997), we observed no benefits to crop yield in our study. Other studies have also found no effect of DCD on crop yield (Francis 1995; Gioacchini et al. 2002). Gioacchini et al. (2002) found that DCD held more of the fertiliser-derived N in an NH_4^+ form, but this was accompanied by greater immobilisation of NH_4^+ by soil microbes. In our study it is possible that the high N mineralisation potential of the Strathkellar soils might also explain the non response in canola yield to applied DCD; the retention of plant available N maybe more beneficial to crop yield under low soil N supply. Furthermore, our economic analysis showed that DCD represents a significant input cost, and is currently economically unfeasible.

Conclusion

This study has demonstrated that current management strategies may have limited ability to reduce potentially large rates of N_2O emissions in this environment. The study also highlighted the importance of understanding constraints to crop productivity, and the need to consider these constraints in formulating target crop yield to estimate N fertiliser requirement and avoiding unnecessary N losses (atmospheric and leaching). Our research has also demonstrated a high degree of difficulty in separating environmentally driven episodic N_2O flux events in response to rainfall and temperature, and inherent field variability from genuine anthropogenic influences. We have produced some evidence that N fertiliser management and the application of DCD will directly affect N_2O emissions and income from grain production, in high rainfall cropping environments. Although DCD application assisted to reduce N_2O, its use currently remains economically unviable in these cropping systems. Better matching of N input with plant demand to avoid excessive N availability appears a more financially feasible option.

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References

Angus JF, van Herwaarden AF, Fischer RA, Howe GN, Heenan DP (1998) The source of mineral nitrogen for cereals in south-eastern Australia. Aust J Agric Res 49:511–522

Bakker DM, Hamilton GJ, Houlbrooke DJ, Spann C (2005) The effect of raised beds on soil structure, waterlogging, and productivity on duplex soils in Western Australia. Aust J Agric Res 43:575–585

Baldock J (2003) Match fertiliser rates with available water. Farming Ahead 140:40–43

Barker-Reid F, Gates WP, Wilson K, Baigent R, Galbally IE, Meyer CP, Weeks IA, Eckard RJ (2005) Soil nitrous oxide emissions from rainfed wheat in SE Australia. In: van Amstel A (ed) Fourth international symposium on non-CO_2 greenhouse gases (NCGG-4) science, control, policy and implementation. Mill Press, Utrecht, pp 25–32

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

Barton L, Kiese R, Gatter D, Butterbach-Bahl K, Buck R, Hinz C, Murphy DV (2008) Nitrous oxide emissions from a cropped soil in a semi-arid climate. Global Change Biol 14:177–192

Barton L, Murphy DV, Kiese R, Butterbach-Bahl K (2010) Soil nitrous oxide and methane fluxes are low from a bioenergy crop (canola) grown in a semi-arid climate. Global Change Biol Bioenerg 2:1–15

Barton L, Butterbach-Bahl K, Kiese R, Murphy DV (2011) Nitrous oxide fluxes from a grain–legume crop (narrow-

leafed lupin) grown in a semiarid climate. Global Change Biol 17:1153–1166
Belford RK, Cannell RQ, Thomson RJ (1985) Effects of single and multiple waterloggings on the growth and yield of winter wheat on a clay soil. J Sci Food Agric 36:142–156
Blair GJ, Chinoim N, Lefroy RDB, Anderson GC, Crocker GJ (1991) A soil sulfur test for pastures and crops. Aust J Soil Res 29:619–626
Bollmann A, Conrad R (1998) Influence of O_2 availability of NO and N_2O release by nitrification and denitrification in soils. Global Change Biol 4:387–396
Bouwman AF (1998) Nitrogen oxides and tropical agriculture. Nature 392:866–867
Burford JR, Stefanson RC (1973) Measurement of gaseous losses of nitrogen from soils. Soil Biol Biochem 5:33–141
Cannell RQ, Belford RK (1980) Effects of waterlogging at different stages of development on the growth and yield of winter oilseed rape (*Brassica napus* L.). J Sci Food Agric 31:963–965
Castaldi S (2000) Responses of nitrous oxide, dinitrogen and carbon dioxide production and oxygen consumption to temperature in forest and agricultural light-textured soils determined by model experiment. Biol Fertil Soils 32:67–72
Chang C, Jenzen HH, Cho CM, Nakonechny EM (1998) Nitrous oxide emission through plants. Soil Sci Soc Am J 62:35–38
Ciarlo E, Conti M, Bartoloni N, Rubio G (2007) The effect of moisture on nitrous oxide emissions from soil and the $N_2O/(N_2O + N_2)$ ratio under laboratory conditions. Biol Fertil Soils 43:675–681
Colwell JD (1965) An automatic procedure for the determination of Phosphorus in sodium hydrogen carbonate extracts of soils. Chem Ind 893–895
Crutzen PJ (1981) Atmospheric chemical processes of the oxides of nitrogen, including nitrous oxide. In: Delwiche CC (ed) Denitrification, nitrification, and atmospheric nitrous oxide. Wiley, New York, pp 17–44
Dalal RC, Weijin W, Robertson GP, Parton WJ (2003) Nitrous oxide emission from Australian agricultural lands and mitigation options: a review. Aust J Soil Res 41:165–195
Davidson EA (1992) Sources of nitric oxide and nitrous oxide following wetting of dry soil. Soil Sci Soc Am J 56: 95–102
Di HJ, Cameron KC (2005) Reducing environmental impacts of agriculture by using fine particle suspension nitrification inhibitor to reduce nitrate leaching from grazed pasture. Agric Ecosyst Environ 109:202–212
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 Manag 23:1–9
Fageria NK, Ballgar VC, Wright RJ (1988) Aluminium toxicity in crop plants. J Plant Nutr 11:303–319
Francis GS (1995) Management practices for minimising nitrate leaching after ploughing temporary leguminous pastures in Canterbury, New Zealand. J Contam Hydrol 20:313–327
French RJ, Schultz JE (1984) Water use efficiency of wheat in a Mediterranean-type environment I. The relationship between yield, water use and climate. Aust J Agric Res 35:743–764
Gioacchini P, Nastri A, Marzadori C, Giovannini C, Vittori Antisari L, Gessa C (2002) Influence of urease and nitrification inhibitors on N losses from soils fertilised with urea. Biol Fertil Soils 36:129–135
Halvorson AD, Nielsen DC, Reule CA (2004) Nitrogen fertilization and rotation effects on no-till dryland wheat production. Agron J 96:1196–1201
Huang B, Johnson JW, NeSmith DS, Bridges DC (1994) Root and shoot growth of wheat genotypes in response to hypoxia and subsequent resumption of aeration. Crop Sci 34:1538–1544
IPCC (2006) IPCC guidelines for national greenhouse gas inventories. Prepared by the national greenhouse gas inventories programme. Institute for Global Strategies, Hayama
Isbell RF (2003) 'The Australian soil classification' revised edition. CSIRO, Melbourne
Lashof DA, Ahuja DR (1990) Relative contributions of greenhouse gas emissions to global warming. Nature 344: 529–531
Linn DM, Doran JW (1984) Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils. Soil Sci Soc Am J 48:1267–1272
Malla G, Bhatia A, Pathak H, Prasad S, Niveta J, Singh J (2005) Mitigating nitrous oxide and methane emissions from rice-wheat systems of the Indo-Gangetic plain with nitrification and urease inhibitors. Chemosphere 58:141–147
McTaggart IP, Clayton H, Parker J, Swan L, Smith KA (1997) Nitrous oxide emissions from grassland and spring barley, following N fertiliser application with and without nitrification inhibitors. Biol Fertil Soils 25:261–268
Mosier AR, Duxbury JM, Freney JR, Heinemeyer O, Minami K (1998) Assessing and mitigating N_2O emissions from agricultural soils. Clim Change 40:7–38
Naidu R, Rengasamy P (1993) Ion interactions and constraints to plant nutrition in Australian sodic soils. Aust J Soil Res 31:801–819
Nuttall JG, Armstrong RD, Connor DJ (2003) Evaluating physicochemical constraints of Calcarosols on wheat yield in the Victorian southern Mallee. Aust J Agric Res 54:487–497
Officer S, Kearney G, Kelly K, Graham J (2012) Large nitrous oxide emissions after conversion from pasture to cropping in temperate south eastern Australia. Paper presented at the SSA-NZSSS Conference, Hobart, pp 2–7 December
Officer SJ, Phillips F, Armstrong R, Kelly K (2008) Nitrous oxide emissions from dry-land wheat in south-eastern Australia. In: Proceedings of the 14th Australian Agronomy Conference. Australian Society of Agronomy, Adelaide. http://www.survey.regional.org.au/au/asa/2008/poster/farming-uncertain-climate/5831_officerj.htm
Parkin TB (1987) Soil microsites as a source of denitrification variability. Soil Sci Soc Am J 51:1194–1199
Passioura JB (1991) Soil structure and plant growth. Aust J Soil Res 29:717–728
Peoples MB, Hauggaard-Nielsen H, Jensen ES (2009) The potential environmental benefits and risks derived from legumes in rotations. In: Emerich DW, Krishnan HB (eds) Agronomy monograph 52. Nitrogen fixation in crop production. American Society of Agronomy, Crop Science

Society America, and Soil Science Society of America, Madison, pp 349–385
Rayment GE, Higginson FR (1992) Ion exchange properties. Australian laboratory handbook of soil and water chemical methods. Inkata Press, Melbourne
Ridley AM, Christy BP, White RE, McLean T, Green R (2003) North-east Victoria SGS National Experiment site: water and nutrient losses from grazing systems on contrasting soil types and levels of inputs. Aust J Exper Agric 43: 799–815
Robertson MJ, Kirkegaard JA (2005) Water use efficiency of dryland canola in an equi-seasonal rainfall environment. Aust J Agric Res 56:1373–1386
Rochester IJ (2003) Estimating nitrous oxide emissions from flood irrigated alkaline grey clays. Aust J Agric Res 41:197–206
Searle PL (1984) The Bertholet or indophenol reaction and its use in the analytical chemistry of nitrogen. Analyst 109:549–568
Slyvester-Bradley R, Makepeace RJ (1984) A code of stages of development in oilseed rape (*Brassica napus* L.). Aspects Appl Biol 6:399–419
Soussana JF, Tallec T, Blanfort V (2010) Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands. Animal 4: 334–350
Stefanson RC (1973) Evolution patterns of nitrous oxide and nitrogen in sealed soil-plant systems. Soil Biol Biochem 5:167–169
Stehfest E, Bouwman L (2006) N_2O and NO emissions from agricultural fields and soil under natural vegetation: summarizing available measurement data and modelling of global annual emissions. Nutr Cycl Agroecosyst 74:207–288
Tiedje JM (1994) Denitrifiers. In: Weaver RW, Angel JS, Bottomley PS (eds) Methods of soil analysis, Part 2. Microbialogical and Biochemical Properties'. Soil Science Society of America: Madison, pp 245–267
Trought MCT, Drew MC (1980) The development of waterlogging damage in wheat seedlings (Triticum aestivum L.) 1. Shoot and root growth in relation to the changes in the concentration of dissolved gases and solutes in the soil solution. Plant Soil 54:77–94
Vallejo A, Diez JA, Lopez-Valdiva LM, Gasco A, Jimenez C (2001) Nitrous oxide emission and denitrification nitrogen losses from soils treated with isobutylenediurea and urea plus dicyandiamide. Biol Fertil Soils 34:248–257
Walkley A, Black IA (1934) An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci 37:29–38
Watson ER, Lapins P, Barron BFW (1976) Effect of waterlogging on growth, grain and straw yield of wheat, barley and oats. Aust J Exper Agric Anim Husb 16:115–121
Weir KL, Doran JW, Power JF, Walters DT (1993) Denitrification and the dinitrogen/nitrous oxide ratio as affected by soil water, available carbon, and nitrate. Soil Sci Soc Am J 57:66–72
Weiske A, Benckiser G, Herbert T, Ottow JCG (2001) Influence of the nitrification inhibitor 3,4-dimethylppyrazole phosphate (DMPP) in comparison to dicyandiamide (DCD) on nitrous oxide emissions, carbon dioxide fluxes and methane oxidation during 3 years of repeated application in field experiments. Biol Fertil Soils 34:109–117
Zadoks JC, Chang TT, Konzak CF (1974) A decimal code for the growth stages of cereals. Weed Res 14:415–421
Zhang X, Evans PM, Riffkin PA (2004) Performance of annual pasture legumes in cropping rotations in the cool temperate zone of south-eastern Australia. Aust J Exper Agric 44:863–871