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Hierarchy of factors driving N_2O emissions in non-tilled soils under different crops

V. R. N. Cosentino[a,b,c], S. A. Figueiro Areggui[b,d] & M. A. Taboada[a,b,c]

[a]*Cátedra de Fertilidad y Fertilizantes, Facultad de Agronomía, Universidad de Buenos Aires, Av. San Martín 4453, C1417DSE Buenos Aires, Argentina,* [b]*CONICET, Av. Rivadavia 1917, C1033AAJ, Buenos Aires, Argentina,* [c]*Instituto de Suelos Castelar, INTA, Buenos Aires, Argentina, and* [d]*Cátedra de Edafología, Facultad de Agronomía, Universidad de Buenos Aires, Av. San Martín 4453, C1417DSE Buenos Aires, Argentina*

Summary

Nitrous oxide (N_2O) is emitted to the atmosphere as a by-product of nitrification and denitrification by soil microbial processes. Differences in climate, soil and management regulate these processes, causing N_2O emissions to vary in space and time. This study aimed to identify and rank the soil properties that control N_2O emissions in non-tilled soils under different crops. Over a period of 2 years, gas samples were taken from closed chambers and soil properties were determined once per season. N_2O emission rates were highly variable (from -15 to 314 μg N_2O-N m^{-2} $hour^{-1}$). A regression tree analysis allowed us to classify soil N_2O emissions into three groups, separated by topsoil temperature (primary factor) and water-filled pore space (WFPS, secondary factor). N_2O emissions were small (mean 4.22 μg N_2O-N m^{-2} $hour^{-1}$) with topsoil temperature less than 14°C (Group 1), large (mean 61.87 μg N_2O-N m^{-2} $hour^{-1}$) with topsoil temperature between 14 and 23°C and WFPS more than 58.5% (Group 2) and moderate (mean 21.4 μg N_2O-N m^{-2} $hour^{-1}$) with topsoil temperature more than 23°C and WFPS less than 58.5% (Group 3). These emission groups allow for more efficient sampling of N_2O emissions in the field: in winter, when topsoil temperatures are less than 14°C and N_2O emissions are expected to be small or even negligible, sampling frequency can be reduced; in autumn and spring, when topsoil temperatures are more than 14°C and WFPS is more than 60–70%, sampling frequency should be increased.

Introduction

Nitrous oxide (N_2O) is the main greenhouse gas (GHG) generated by cropping systems and is the main focus of efforts aimed at mitigating GHG emissions from agricultural soils (IPCC, 2007; Snyder *et al.*, 2009). Soil N_2O emissions are variable in space and time, giving rise to 'hot spots' and 'hot moments' that are difficult to predict (McClain *et al.*, 2003). This large variability results from the complex set of environmental variables, such as soil and microbial community heterogeneity, which control the nitrification and denitrification processes responsible for N_2O emissions (Firestone & Davidson, 1989). Often, the cause of the large N_2O emission rates in 'hot spots' and 'hot moments' can be linked to only one variable.

There is considerable controversy about the main variable driving N_2O emission rates and about the way a given variable can promote or limit N_2O emissions in different situations. For example, Shelton *et al.* (2000) found a linear relationship between N_2O emissions and soil water content between field capacity (60% water-filled pore space, WFPS) and water saturation (100% WFPS). On the other hand, Schindlbacher & Zechmeister-Boltenstern (2004) observed maximum emissions between 80 and 95% of WFPS, with decreasing N_2O emission rates at more than 95% WFPS. Dobbie & Smith (2001) and Schindlbacher & Zechmeister-Boltenstern (2004) observed a positive relationship between N_2O emissions and topsoil temperature when the WFPS percentage remained large, while Almaraz *et al.* (2009) found a negative relationship between the two variables in a field trial in which N_2O emissions were related to rainfall. Under field conditions, agricultural traffic and zero tillage may increase soil bulk density and give way to anaerobic zones in surface horizons (Sasal *et al.*, 2006). This may give rise to N_2O emissions caused by denitrification processes (Beare *et al.*, 2009).

Nitrous oxide emission rates depend on the sum of variables required by soil microbial populations to carry out nitrification and denitrification processes. These variables can be divided into components such as substrate availability (NO_3^-, NH_4^+,

Correspondence: M. A. Taboada. E-mail: mtaboada@cnia.inta.gov.ar

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NO_2^- and labile carbon, C) and factors (O_2 availability, soil moisture and temperature) whose actions are often hierarchical. If one or more of these variables is affected, N_2O emissions are likely to diminish. The ecological stoichiometry controlling emissions is the balance of multiple chemical substances, energy and materials in ecological interactions and processes. This conceptual framework has been successfully applied to topics ranging from population dynamics to biogeochemical cycling. This approach provides a tool for analysing how the balance of the multiple factors required by soil organisms affects N_2O production (Sterner & Elser, 2002; Hessen *et al.*, 2004). Our study aimed to identify and rank the soil variables driving N_2O emission rates across seasons in non-tilled soils under different crops. It was hypothesized that the conceptual framework of ecological stoichiometry would be a useful approach to understanding the variation of N_2O emissions under field conditions.

Materials and methods

A non-manipulative field trial was conducted between April 2009 and February 2011 to determine N_2O emission rates and their main driving factors, in an agricultural field in the Province of Buenos Aires, Argentina (34°57′29″S, 60°13′11″W). The soil was a loamy Typic Argiudoll (clay 190 g kg^{-1}; silt 400 g kg^{-1}) from the O'Higgins series (INTA, 2012) with 35.2 g kg^{-1} organic matter and pH (1:2.5 soil:water suspension) of 5.7 in the A horizon. The field was under continuous no-till farming with a three-year crop sequence composed of wheat/double crop soyabean–maize/full season soyabean. In this sequence 85–95 kg N ha^{-1} as urea was added at the time of wheat sowing and when maize was at the V_{3-5} phenological stage.

Measurements were performed following a systematic stratified design. In the 30-ha experimental area (Figure 1), six field plots were seasonally sampled (approximately every three months) over two years. Measurements were performed in two temporally-shifted three-year crop sequences: (i) Sequence 1, starting with full season soyabean residues; and (ii) Sequence 2, starting with double cropped soyabean residues (Table 1). These cropping sequences allowed for simultaneous measurement of the response variables of interest in the various crops of the typical cropping sequence of the region. In this way, we expected to capture the possible variability in N_2O emissions across seasons. In order to capture the variability caused by the passage of farm machinery typical of a non-tilled topsoil, six samples were taken, within each cropping sequence, at two positions in the plot: (i) border (large traffic intensity); and (ii) away from the border (small traffic intensity). The three chambers in the same position within the plot were 10 m apart; those in different positions were 50 m apart (Figure 1). Each field chamber was considered as an experimental unit.

Gas samples were taken from within static, closed and non-vented chambers (surface = 0.13 m^2, height = 0.125 m), inserted into the soil to a depth of 0.05 m. Each chamber had a metal base and an aluminum-coated plastic top. As the field trial was carried out on a production farm, we had to remove the chambers after sampling and re-insert them 24 hours before the subsequent sampling. After each insertion, 15 mm tap water was added to each chamber in order to ensure an adequate seal between the soil and the chamber base before gas sampling. This addition of water sometimes resulted in a small increase in WFPS values at each sampling date.

Sampling was carried out in the morning, as described by Cosentino *et al.* (2012). Gas samples were taken from the chamber headspace at 0, 20 and 40-minute intervals after closing the chambers. Gases were extracted using a vacuum pump, and injected into previously evacuated 25-cm^3 vials sealed with rubber stoppers fixed to the vial with an aluminum flange. We followed this procedure on each sampling date and for each of the six chambers within each plot.

Within seven days of sampling, N_2O was measured in the laboratory with a GC 6890 Agilent Technologies Network gas chromatograph, fitted with a ^{63}Ni electron capture detector (Agilent Network GC System, ÁECD, Santa Clara, CA, USA) and a 30 m × 530 µm × 25 µm Molsieve HP-Plot column. The oven, injector and detector temperatures were 150, 100 and 300°C, respectively. The carrier gas was N_2 and the injection volume was 0.5 cm^3.

The N_2O fluxes (f) were calculated as:

$$f = \frac{\Delta C}{\Delta t} \times \frac{V}{A} \times \frac{m}{V_m}, \quad (1)$$

where $\Delta C/\Delta t$ is the change in N_2O concentration in the chamber during the incubation time Δt, V is the volume of the chamber (16.7 dm^3), A is the soil area (0.13 m^2) covered by the chamber, m is the molecular mass of N_2O and V_m is molar volume of N_2O. Gas fluxes were calculated as the increase in concentration during the incubation period. A linear function was fitted to the N_2O emission/incubation time relationship. When the coefficient of determination (R^2) of the fitted linear function was greater than 0.7 the slope of the function was taken to be the rate of N_2O flux over the 0–40 minutes interval. When R^2 was smaller than 0.7 and a linear function could not be fitted, N_2O flux over the interval was considered to be null. In this study, the minimum detectable limits (distinguishable from zero) were either more than 0.3 µg N_2O-N m^{-2} hour^{-1} or less than −0.3 µg N_2O-N m^{-2} hour^{-1}. All measured N_2O emission values were included in the analysis.

At the same time as the flux measurements, topsoil temperature was measured at 0.10 m depth beside each chamber. After gas sampling, soil samples (0–0.2 m in depth) from inside the chamber perimeter were taken. Nitrate-N was extracted from wet soil samples with a solution of $CuSO_4$ (Jackson, 1958) and nitrate concentration was determined by colorimetry (Keeney & Nelson, 1982) after reduction of nitrate to nitrite (Markus *et al.*, 1985). Topsoil structural types or classes in each site were described according to Soil Survey Staff (1999). Soil bulk density (BD; 100 cm^3 cylinders; 0.05 m diameter) and gravimetric water content (GWC) were determined on samples taken within the perimeter of each field chamber. Both BD and GWC values

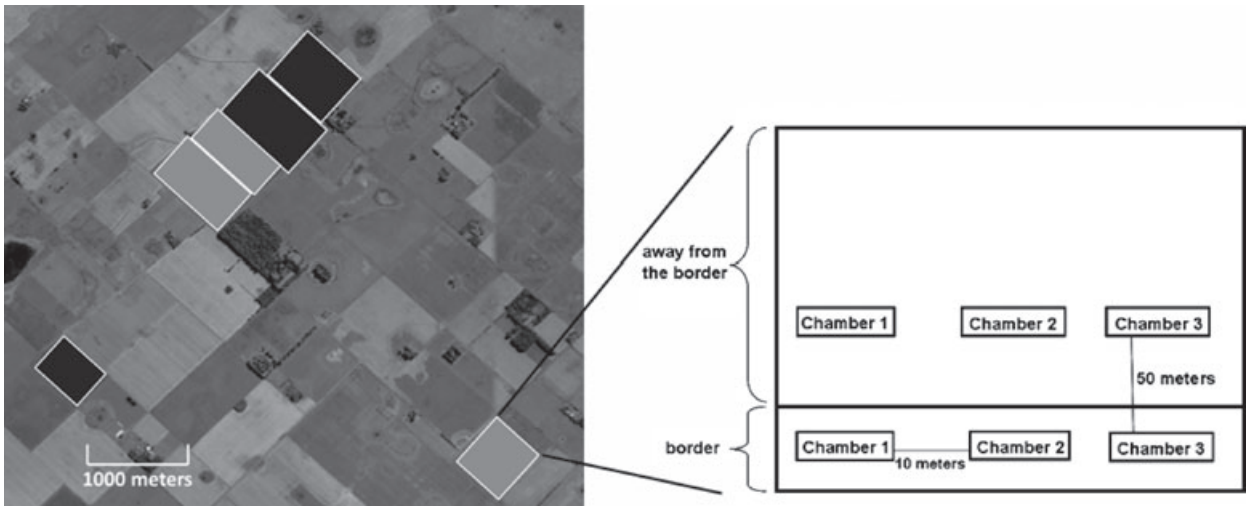

Figure 1 Experimental plot locations within fields (left) and chamber locations within each plot (right). Grey squares correspond to sequence 1, black squares correspond to sequence 2.

Table 1 Chronogram of sampling, sowing, N fertilizer and harvest of the two crop sequences over 2 years

Sequence 1	Soyabean res.			Wheat				W res.	Double crop. soyabean				Soyabean residue				Maize						
	2009								2010												2011		
Date of	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Sampling		X		X			X				X			X				X		X		X	
Sowing				X					X										X				
N fertilization				X																X			
Harvesting							X					X											

Sequence 2	Soyabean res.			Maize					Maize residue				Full season Soyabean										
	2009								2010												2011		
Date of	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Sampling		X		X			X				X			X				X		X		X	
Sowing							X												X				
N fertilazation							X																
Hervesting											X												

w. res. = wheat residue; crop. = cropping.

were used to calculate porosity (P), assuming a particle density (Dp) of 2.65 Mg m^{-3}, and volumetric water content (VWC) using Equations (2) and (3):

$$P = 1 - (BD/Dp)\,, \tag{2}$$

$$VWC = GWC \times BD. \tag{3}$$

The percentage of WFPS was calculated by subtracting VWC from P.

A decision tree analysis, based on a procedure originally proposed by Morgan & Sonquist (1963) and later used by others (cited by Lemon *et al.*, 2003), was used to separate a single group of values into more homogeneous subgroups. This analysis involves a series of decisions, given that a sample is considered as a single group. The parent group is transformed into two new subgroups to minimize the sum of squares; each subgroup becomes more homogenous in the response variable (N_2O emission rate). In such a way, each subgroup turns into a new parent group. These divisions may be repeated as many times as necessary.

Linear regression analysis was used to fit functions to the relationship between subgroup N_2O emission rates and soil NO_3^--N concentration. Each point in the regression scatter was the result of the individual measurement of each chamber. The Infostat package was used for decision tree and linear regression analysis (Infostat, 2002).

Results

Away from the border locations, topsoils had mainly granular and subangular blocky aggregates, while those in border locations had

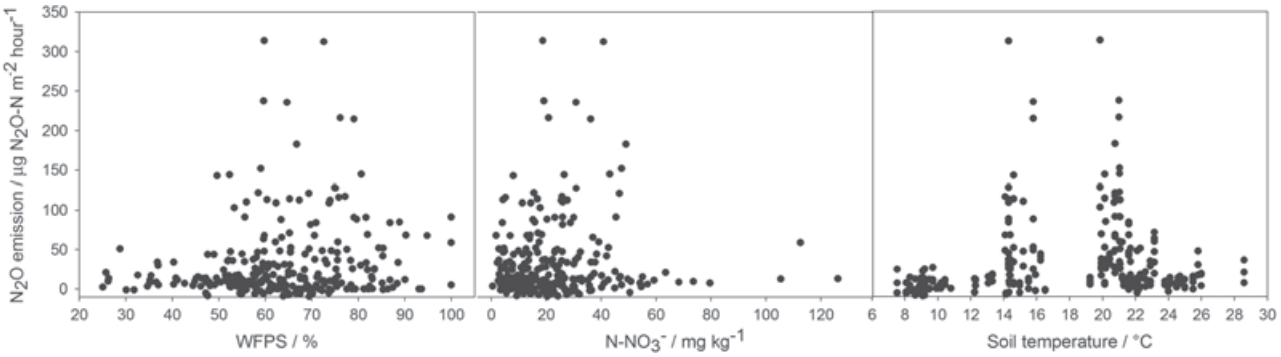

Figure 2 Distribution pattern of N_2O emission rates as a function of water-filled pore space (WFPS), soil NO_3^--N concentration and topsoil temperature (left to right).

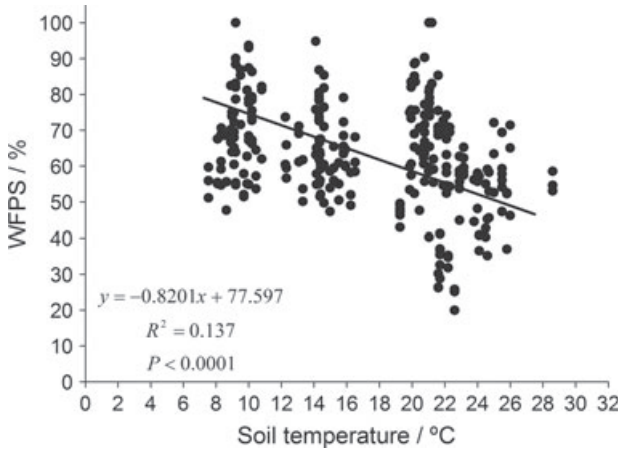

Figure 3 Relationship between water-filled pore space (WFPS) and topsoil temperature.

mainly planar, massive and subangular blocky aggregates. Despite these different structural types, similar topsoil bulk densities (from 1.2 to 1.4 Mg m^{-3}) were observed in both locations in the plots: N_2O emission rates were also similar away from the border and in border locations.

During the study period, N_2O emission rates ranged between −15 and 314 µg N_2O-N m^{-2} $hour^{-1}$, with large variability among replicates. When plotted against all measured soil properties, no relationship between emission rates and WFPS or soil NO_3^--N concentration was observed, but N_2O emission rates showed a clearer response pattern across the topsoil temperature range (Figure 2). Nitrous oxide emission rates were very variable in the 14–23°C topsoil temperature range, whereas they were smaller and less variable at topsoil temperatures less than 14°C and more than 23°C. A negative relationship between soil temperature and WFPS was observed with $R^2 = 0.137$ and $P < 0.0001$ (Figure 3).

The regression tree analysis showed three groups of N_2O emission rates which differed significantly ($P < 0.001$): Group 1, small N_2O emission rates, 4.22 ± 4.11 µg N_2O-N m^{-2} $hour^{-1}$; Group 2, large N_2O emission rates, 61.87 ± 4.07 µg N_2O-N m^{-2} $hour^{-1}$; and Group 3, moderate N_2O emission rates, 21.4 ± 5.01 µg N_2O-N m^{-2} $hour^{-1}$ (Figure 4). These emission groups coincide with the distribution pattern of topsoil temperature (Figure 2).

The small N_2O emission rates (Group 1) occurred during winter, when topsoil temperatures were always less than 14°C, as was found in both crop sequences in June and August 2009 and 2010 (Figure 5). In this case the rate of N_2O emissions showed no relationship with any of the measured variables. The large N_2O emission rates (Group 2) were associated with topsoil temperatures of more than 14°C and WFPS of more than 58.5% (Figure 4), observed in November 2009 (crop sequence 2, Figure 5) and March and October 2010 (crop sequences 1 and 2, Figure 5). The moderate N_2O emission rates (Group 3) occurred at topsoil temperatures of more than 23°C and WFPS less than 58.5% (Figure 4). They were observed in November 2009 (crop sequence 1, Figure 5), December 2010 and February 2011 (crop sequences 1 and 2, Figure 5).

The large and moderate N_2O emission rates (Groups 2 and 3) were positively related to soil NO_3^--N concentration. However, the slope of fitted straight lines describing these relationships was different for each emission group and crop (Figure 6). Good relationships were found for maize and wheat, and in fallow periods with soyabean residues (Figure 6). No clear relationship was found for periods under soyabean crops, regardless of the N_2O emission group and temperature range considered.

Discussion

N_2O emission values were divided into three groups, each of which was associated with one or more of the study variables. The first limiting variable was topsoil temperature, which separated the small emission group (Group 1) from the remainder (Figures 4, 5). In this emission group, topsoil temperature (less than 14°C) had a direct effect, probably because of reduced microbial activity at these temperatures, which influences N_2O emissions (Keeney *et al.*, 1979; Trumbore *et al.*, 1996; Farquharson & Baldock, 2008; Maljanen *et al.*, 2009).

The results of this study are consistent with those observed by others (Trumbore *et al.*, 1996) who found a decrease in microbial

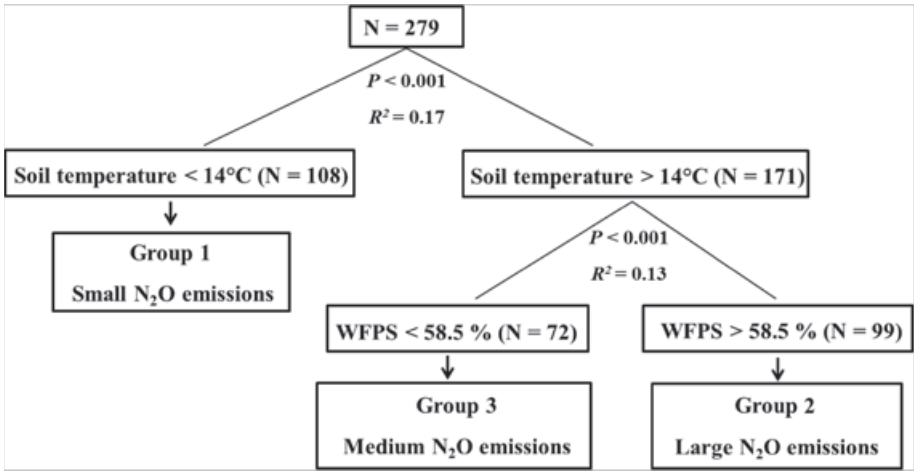

Figure 4 Results of the regression tree analysis, showing the main variables affecting N_2O emission rates.

activity with decreasing topsoil temperature. However, Maljanen *et al.* (2009) found that even in sub-zero temperatures (−6.8°C) N_2O emissions were observed in soils that undergo freezing processes regularly, and where an adaptation of the microbial community to low temperatures could be expected. This is not the case in a temperate region such as the Argentine Pampa, which suggests that, at our study site, microbial communities are probably not adapted to produce N_2O at low temperatures because the soils are never frozen.

Nitrous oxide emissions were large and very variable with topsoil temperatures between 14 and 23°C and WFPS more than 58.3% (Group 2, Figures 4, 5). These variations were positively related to soil NO_3^-–N concentration, as shown by the fitted relationships for maize and soyabean residues (Figure 6). Events characterized by both large temperature and large WFPS could favour relatively large rates of N_2O production, provided sufficient NO_3^- was present in the soil (Castaldi, 2000). In fact, measured NO_3^--N concentrations were always more than 5 mg kg^{-1} in the study site, suggesting that soil nitrate never limited N_2O emissions totally, as has been shown by Dobbie *et al.* (1999).

According to Dalal *et al.* (2003) denitrification rate increases with increasing NO_3^- content, when the soil is wet and temperature and carbon availability are not limiting. This occurs because the presence of NO_3^- inhibits N_2O to N_2 reduction, resulting in a relatively large N_2O:N_2 ratio at similar humidity and oxygen content. Dalal *et al.* (2010) found a positive correlation between N_2O emissions and soil NO_3^- content, when topsoil temperature varied between 10 and 30°C and WFPS between 30 and 80%. In contrast, results from a field trial in Denmark with no added fertilizer and WFPS of 50–70% (Ambus, 2005) showed a negative relationship between the rate of N_2O emission and soil NO_3^--N concentration. This different result could be due to the smaller WFPS in the Danish field trial, which is expected to promote nitrification instead of denitrification processes.

N_2O emissions were moderate when topsoil temperature was more than 14°C and WFPS less than 58.3% (Group 3, Figures 4, 5). These moderate N_2O emissions were smaller than those observed in experiments performed under controlled conditions, which showed an increase in N_2O emission rates at temperatures as large as 70°C (Keeney *et al.*, 1979; Schindlbacher & Zechmeister-Boltenstern, 2004). These large N_2O emission values are possible when increasing temperatures lead to an increase in the size of the soil anaerobic zones (Li *et al.*, 2000), as greater respiration rates cause greater O_2 concentration gradients, thus resulting in a greater soil volume devoid of oxygen (Smith *et al.*, 2003). This would lead to an increase in denitrification. Added to this, larger soil temperature causes an increase in microbial activity (Farquharson & Baldock, 2008) and increases gas solubility, causing a greater loss of N_2O to the atmosphere before being reduced to N_2 (Dalal *et al.*, 2010).

Our field results showed that WFPS decreased with topsoil temperature (Figure 3). Soil drying at greater temperatures avoided the development of anaerobic zones, such as those found in experiments where soil water content is controlled (Dobbie & Smith, 2001; Schindlbacher & Zechmeister-Boltenstern, 2004). When a soil dries to less than 60% WFPS, the relative importance of denitrification as a source of N_2O emissions decreases while the relative contribution of nitrification increases (Linn & Doran, 1984). These by-product N_2O emissions from nitrification are usually less than those of denitrification (Castaldi, 2000; Smith *et al.*, 2003), which provides an explanation of why N_2O emission rates in Group 3 were only moderate. In this case, the influence of topsoil temperature was indirect and mediated by soil water content.

The relationship between N_2O emissions and soil NO_3^--N concentration differed from Group 2 to Group 3 and between crops within each Group (Figure 6). In Group 2, linear relationships were fitted when soil was cropped to maize and covered by soyabean residues, while no relationship was found in soyabean-cropped soil (Figure 6a–c). In Group 3, soil NO_3^--N concentration also influenced N_2O emission rates under maize and wheat and again no relationship was found under soyabean (Figure 6d–f). Nitrous oxide emissions under maize and wheat in Group 3 occurred at smaller rates than those in Group 2, which can be ascribed to the smaller N_2O emissions when nitrification instead of denitrification prevails (Castaldi, 2000; Smith *et al.*, 2003).

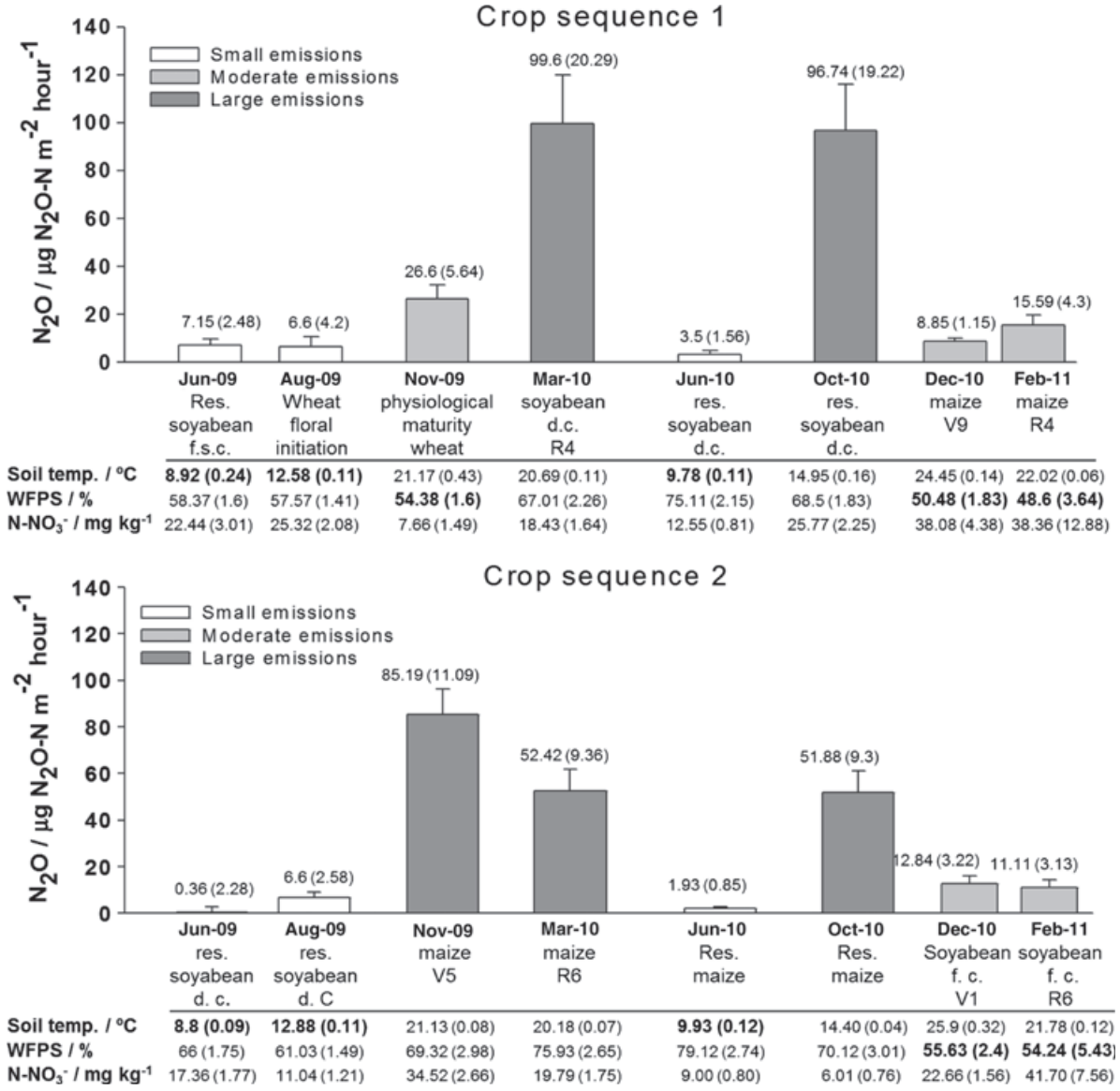

Figure 5 N_2O emissions during the study period for each crop sequence (bars). Capped vertical lines above each bar are one standard error. Values above bars are means and (SE). Below each graph, values for means and (SE) are shown for soil temperature, water-filled pore space (WFPS) and soil NO_3^--N concentration.

It is interesting to note that soyabean crops did not show a linear relationship between N_2O^- and NO_3^--N, regardless of the emission group. It is likely that some unmeasured variable could explain N_2O emissions under soyabean crops, in particular the large variability of N_2O emissions under soyabean in Group 2. Ghosh *et al.* (2002) and Rochette & Janzen (2005) found large N_2O emissions in legume crops, which could be related to other factors such as release of root N exudates. Soil organic C is another possible biophysical factor regulating N_2O emissions. It can influence N_2O emissions in two ways, as a source of energy for denitrifiers and by increasing biological oxygen demand and creating anaerobic zones in the soil ('hot spots'). In fact, additions of degradable organic C may lead to localized depletion of oxygen at microsites and enhanced N_2O production (Helgason *et al.*, 2005). The results of N_2O emissions under soyabean crops need further clarification. It is likely that the inclusion of other biophysical variables would help explain the origin of large N_2O emissions in soyabean crops better.

Conclusions

The most important factor driving soil N_2O emission rates was topsoil temperature, followed by water-filled pore space and soil NO_3^- concentration. From this study of non-tilled soils, a hierarchical arrangement of factors was used to explain N_2O emission rates, which was determined by which particular

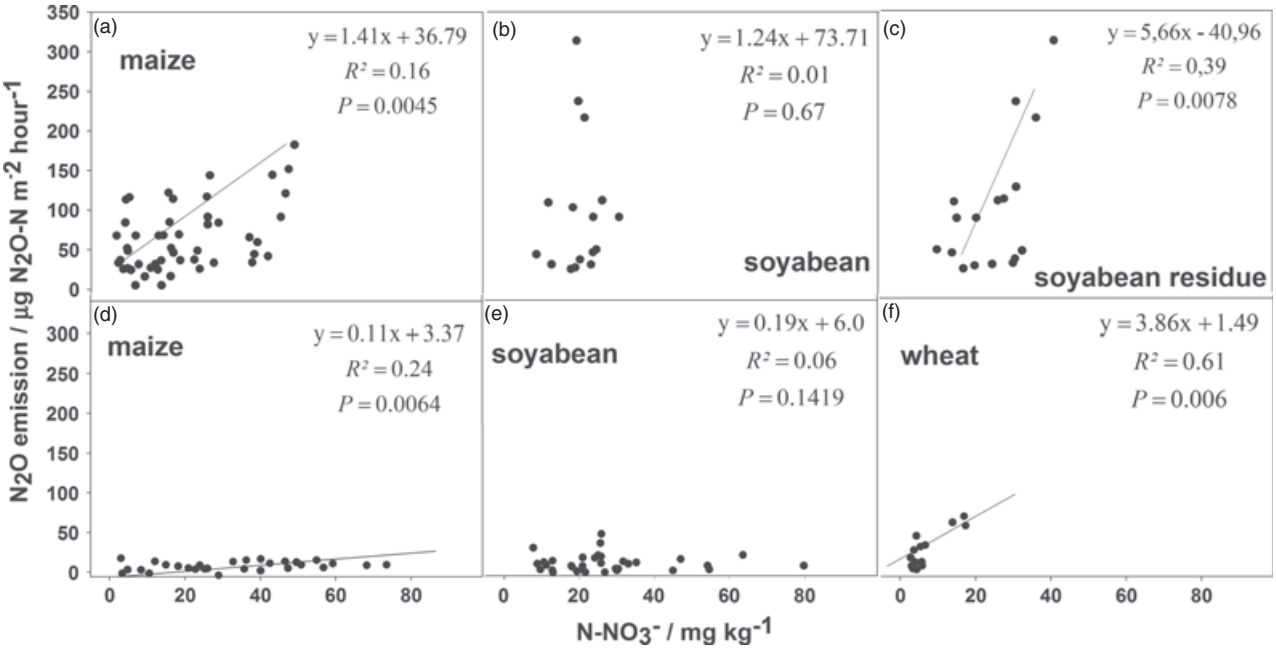

Figure 6 Relationship between N_2O emission rate and soil NO_3^--N concentration for different crops and residues. (a–c) Large emissions with topsoil temperatures between 14 and 23°C (Group 3). (d–f) Moderate emissions with soil temperatures more than 23°C and WFPS less than 58.5% (Group 2).

variable limited N_2O production. This followed the hypothesized conceptual framework of ecological stoichiometry, which provides a useful tool to understand how the balance of these variables affects N_2O production by soil microbes (Hessen *et al.*, 2004).

The results of this study show the variation and driving factors of N_2O emission rates in an agricultural field under zero tillage and temperate climate, arranged in a hierarchical order dominated by topsoil temperature. These results could be extrapolated to other areas supporting similar soil, climate and management conditions. Nitrous oxide emission groups obtained through regression tree analysis could be helpful when deciding when a soil should be sampled for N_2O emissions, saving time and effort during fieldwork. For example, N_2O emissions are likely to be small or even negligible when topsoil temperatures are less than14°C, a common occurrence during winter in temperate regions. In this case, checking topsoil temperature would reduce sampling effort. On the other hand, it is important to make measurements when WFPS is more than 60–70% and topsoil temperature more than 14°C, as often occurs during Autumn and Spring. In this case, more frequent N_2O measurements would be recommended to capture all possible environmental variables.

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References

Almaraz, J.J., Zhou, X., Mabood, F., Madramootoo, C., Rochette, P., Ma, B.L., *et al.* 2009. Greenhouse gas fluxes associated with soybean production under two tillage systems in southwestern Quebec. *Soil & Tillage Research*, **104**, 134–139.

Ambus, P. 2005. Relationship between gross nitrogen cycling and nitrous oxide emissionin grass-clover pasture. *Nutrient Cycling in Agroecosystems*, **72**, 189–199.

Beare, M.H., Gregorich, E.G. & St-Georges, P. 2009. Compaction effects on CO_2 and N_2O production during drying and rewetting of soil. *Soil Biology & Biochemistry*, **41**, 611–621.

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. *Biology & Fertility of Soils*, **32**, 67–72.

Cosentino, V.N.R., Fernandez, P.L., Figueiro Aureggi, S.A. & Taboada, M.A. 2012. N_2O emissions from a cultivated Mollisol: optimal time of day for sampling and the role of soil temperature. *Revista Brasileira de Ciência do Solo*, **36**, 1814–1819.

Dalal, R.C., Wang, W., Robertson, G.P. & Parton, W.J. 2003. Nitrous oxide emission from Australian agricultural lands and mitigation options: a review. *Australian Journal of Soil Research*, **41**, 165–195.

Dalal, R.C., Gibson, I., Allen, D.E. & Menzies, N.W. 2010. Green waste compost reduces nitrous oxide emissions from feedlot manure applied to soil. *Agriculture, Ecosystems & Environment*, **136**, 273–281.

Dobbie, K.E., McTaggart, I.P. & Smith, K.A. 1999. Nitrous oxide emissions from intensive agricultural systems: variations between crops and seasons, key driving variables, and mean emission factors. *Journal of Geophysical Research*, **104**, 26891–26899.

Dobbie, K.E. & Smith, K.A. 2001. The effects of temperature, water-filled pore space and land use on N_2O emissions from an imperfectly drained gleysol. *European Journal of Soil Science*, **52**, 667–673.

Farquharson, R. & Baldock, J. 2008. Concepts in modelling N_2O emissions from land use. *Plant & Soil*, **309**, 147–167.

Firestone, M.K. & Davidson, E.A. 1989. Microbiological basis of NO and N_2O production and consumption in soil. In: *Exchange of Trace Gases Between Terrestrial Ecosystems and the Atmosphere: Report of the Dahlem Workshop on Exchange of Trace Gases Between Terrestrial Ecosystems and the Atmosphere* (eds M.O. Andreae & D.S. Schimel), pp. 7–21. Wiley, New York.

Ghosh, S., Majumdar, D. & Jain, M.C. 2002. Nitrous oxide emissions from *kharif* and *rabi* legumes grown on an alluvial soil. *Biology & Fertility of Soils*, **35**, 473–478.

Helgason, B.L., Janzen, H.H., Chantigny, M.H., Drury, C.F., Ellert, B.H., Gregorich, E.G., *et al.* 2005. Toward improved coefficients for predicting direct N_2O emissions from soil in Canadian agroecosystems. *Nutrient Cycling in Agroecosystems*, **72**, 87–99.

Hessen, D.O., Ågren, G.I., Anderson, T.R., Elser, J.J. & De Ruiter, P.C. 2004. Carbon sequestration in ecosystems: the role of stoichiometry. *Ecology*, **85**, 1179–1192.

Infostat 2002. *Software estadístico*. Grupo InfoStat, Facultad de Ciencias Agropecuarias, Universidad Nacional de Córdoba, Córdoba.

Instituto Nacional de Tecnología Agropecuaria 2012. [WWW document]. URL http://anterior.inta.gov.ar/suelos/cartas/ [accessed on 26 November 2012].

IPCC 2007. *Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007* (eds B. Metz, O.R. Davidson, P.R. Bosch, R. Dave & L.A. Meyer). [WWW document]. URL http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg3_report_mitigation_of_climate_change.htm [accessed on 27 June 2013].

Jackson, M.L. 1958. *Soil Chemical Analysis*. Prentice-Hall, Englewood Cliffs, NJ.

Keeney, D.R. & Nelson, D.W. 1982. Nitrogen-inorganic forms. In: *Methods of Soil Analysis, Part 2* (eds A.L. Page, R.H. Miller & D.R. Keeney), pp. 643–698. American Society of Agronomy – Soil Science Society of America, Madison, WI.

Keeney, D.R., Fillery, I.R. & Marx, G.P. 1979. Effect of temperature on the gaseous nitrogen products of denitrification in a silt loam soil. *Soil Science Society of America Journal*, **43**, 1124–1128.

Lemon, S.C., Roy, J., Clark, M.A., Friedmann, P.D. & Rakowski, W. 2003. Classification and regression tree analysis in public health: Methodological review and comparison with logistic regression. *Annals of Behavioral Medicine*, **26**, 172–181.

Li, C., Aber, J., Stange, F., Butterbach-Bahl, K. & Papen, H. 2000. A process-oriented model of N_2O and NO emissions from forest soils: 1. Model development. *Journal of Geophysical Research*, **105**, 4369–4384.

Linn, D.M. & Doran, J.W. 1984. Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils. *Soil Science Society of America Journal*, **48**, 1267–1272.

Maljanen, M., Virkajärvi, P., Hytönen, J., Öquist, M., Sparrman, T. & Martikainen, P.J. 2009. Nitrous oxide production in boreal soils with variable organic matter content at low temperature – snow manipulation experiment. *Biogeosciences*, **6**, 2461–2473.

Markus, D.K., McKinnon, J.P. & Buccafuri, A.F. 1985. Automated analysis of nitrite, nitrate and ammonium nitrogen in soils. *Soil Science Society of America Journal*, **49**, 1208–1215.

McClain, M.E., Boyer, E.W., Dent, C.L., Gergel, S.E., Grimm, N.B., Groffman, P.M., *et al.* 2003. Biogeochemical hot spots and hot moments at the interface of terrestrial and aquatic ecosystems. *Ecosystems*, **6**, 301–312.

Morgan, J.N. & Sonquist, J.A. 1963. Problems in the analysis of survey data, and a proposal. *Journal of the American Statistical Association*, **58**, 415–434.

Rochette, P. & Janzen, H. 2005. Towards a revised coefficient for estimating N_2O emissions from legumes. *Nutrient Cycling in Agroecosystems*, **73**, 171–179.

Sasal, M.C., Andriulo, A.E. & Taboada, M.A. 2006. Soil porosity characteristics and water movement under zero tillage in silty soils in Argentinian Pampas. *Soil & Tillage Research*, **87**, 9–18.

Schindlbacher, A. & Zechmeister-Boltenstern, S. 2004. Effects of soil moisture and temperature on NO, NO_2, and N_2O emissions from European forest soils. *Journal of Geophysical Research*, **109**, D17302.

Shelton, D.R., Sadeghi, A.M. & McCarty, G.W. 2000. Effect of soil water content on denitrification during cover crop decomposition. *Soil Science*, **165**, 365–371.

Smith, K.A., Ball, T., Conen, F., Dobbie, K.E., Massheder, J. & Rey, A. 2003. Exchange of greenhouse gases between soil and atmosphere: interactions of soil physical factors and biological processes. *European Journal of Soil Science*, **54**, 779–791.

Snyder, C.S., Bruulsema, T.W., Jensen, T.L. & Fixen, P.E. 2009. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. *Agriculture, Ecosystems & Environment*, **133**, 247–266.

Soil Survey Staff 1999. *Soil Taxonomy*, *2nd edn.* U.S. Government Printing Office, Washington.

Sterner, R.W. & Elser, J.J. 2002. Stoichiometry and homeostasis. In: *Ecological Stoichiometry: The Biology of Elements from Molecules to the Biosphere* (eds R.W. Sterner & J. Elser), pp. 1–42. Princeton University, Princeton, NJ.

Trumbore, S.E., Chadwick, O.A. & Amundson, R. 1996. Rapid exchange between soil carbon and atmospheric carbon dioxide driven by temperature change. *Science*, **272**, 393–396.