Nitrous oxide fluxes from cropping soils in a semi-arid region in Australia: A 10 year perspective

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Abstract

Understanding nitrous oxide (N_2O) fluxes from agricultural soils in semi-arid regions is required to better understand global terrestrial N_2O losses. Nitrous oxide fluxes were measured from three rain-fed, cropped soils in a semi-arid region of south-western Australia on a sub-daily basis from 1995 to 2014 using automated chambers. Western Australia's grain-belt includes 7 million hectares of arable land, with cropping confined to winter and soils fallow at other times. Nitrogen fertilizer (up to 100 kg N ha^{-1} yr^{-1}) was applied at planting and during the growing season depending on crop requirements. *In situ* N_2O measurements were consistently small from all sites (0.04–0.27 kg N ha^{-1} yr^{-1}), representing 0.01 to 0.12% of applied N fertilizer. Increasing soil organic matter (OM) increased soil N_2O fluxes, but losses represented <0.12% of the N fertilizer applied. While including grain legumes in cropping rotations also did not enhance soil N_2O fluxes in the growing season or post-harvest. Developing strategies for mitigating N_2O fluxes from cropping soils in our region is challenging as most losses occur post-harvest, when there is no active plant growth, and in response to summer rainfall. Increasing the efficiency of the nitrification process by increasing soil pH (via liming) decreased N_2O fluxes from sandy, acidic soils following summer rainfall, and is a potential strategy for mitigating N_2O fluxes from nitrification. Accurately accounting for N_2O fluxes in our region has refined Australia's national greenhouse gas inventory and demonstrated annual fluxes can be low from cropped soils in semi-arid regions.

Key Words

Emission factor, semi-arid climate, sandy-textured soils, nitrogen mineralisation, nitrification, wheat

Introduction

Semi-arid and arid regions cover approximately half of the global agricultural area (The World Bank 2008) and are important to food production and associated nutrient management. Understanding N_2O fluxes from agricultural soils in these regions is necessary if we are to improve our knowledge of global terrestrial N_2O losses. Annual N_2O fluxes from rain-fed, N fertilized cereal crops in semi-arid regions have not been widely reported (Stehfest and Bouwman 2006). Instead, *in situ* measurements of N_2O fluxes from semi-arid environments had been mainly confined to irrigated cereal crops and rain-fed grasslands (Barton et al. 2008).

The south-western Australian grain belt consists of approximately 7 million hectares of arable land in a semi-arid region, and is responsible for up to 40% of Australia's annual grain production (Australian Bureau of Agricultural and Resource Economics (ABARE), www.abareconomics.com). The region has a strong seasonality that is characterized by cool, wet winters and hot, dry summers; although, significant rainfall events (> 10 mm) occur infrequently during the summer months. Inorganic N fertilizer is used extensively for crop production in the region, and its use has been increasing. Nitrous oxide fluxes resulting from the application of N fertilizer to soils in this region were unknown due to a lack of measurements. Furthermore, extrapolating findings [including the Intergovernmental Panel on Climate Change (IPCC) default emission factor for the application of N fertilizer to land] from overseas studies to the south-western Australian was not considered appropriate due to differences in N fertilizer management, soil types and climate; factors known to influence annual agricultural N_2O fluxes (Stehfest and Bouwman 2006).

The aim of the following paper is to synthesize a decade of field-based research quantifying and characterizing sub-daily N_2O fluxes from rain-fed, cropped soils in a semi-arid region, and explore potential strategies for mitigating these losses.

Methods

Study locations and experimental designs

Annual N_2O fluxes have been reported from three locations in the region, Buntine (30.01 S, 116.34 E), Cunderdin (31.6 S, 117.22 E) and Wongan Hills (31.48 S, 116.2 E), and over successive years (Barton et al. 2008; Barton et al. 2010; Barton et al. 2011; Li et al. 2012; Barton et al. 2013b; Barton et al. 2016). The long term average rainfall at the study sites ranged from 291 to 374 mm depending on location, while the mean daily maximum temperature ranges averaged 25.6 °C across the sites, and the mean daily minimum temperature averaged 11.6 °C (Commonwealth Bureau of Meteorology, www.bom.gov.au/climate). The three study sites included two contrasting soil types: a free-draining sand overlying a poorly draining clay [Yellow or Brown Sodosol, Cunderdin; classified using the Australian soil classification (Isbell 2002)] and a deep sand (Basic Regolithic Yellow-Orthic Tenosol, Buntine; Acidic Ferric Yellow-Orthic Tenosol, Wongan Hills). Nitrogen fertilizer rates ranged from 0 to 100 kg N ha^{-1}, and was generally applied as urea. The experimental design differed between each study site as described in each of the associated papers (Table 1).

Measuring nitrous oxide fluxes

Nitrous oxide fluxes were measured at each study location using soil chambers connected to a fully automated system that enabled *in situ* determination of N_2O fluxes (Barton et al. 2008). Briefly, the system consisted of a gas chromatograph equipped with an electron capture detector for N_2O analysis, an automated sampling unit for collecting and distributing gas samples, and a series of six to 12 chambers. Chambers (0.5 m x 0.5 m) were placed on metal bases inserted into the ground (0.1 m), and fitted with a top (0.15 m in height) that could be automatically opened and closed by means of pneumatic actuators. The height of the chambers was progressively increased to accommodate crop growth to a maximum height of 0.95 m. Furthermore, the chambers were programmed to open if the air temperature in the chamber exceeded a set value (42 °C when plants were growing in the chamber, 60 °C at other times) or if rainfall occurred (> 0.4 mm in five minutes) while the chambers were closed. The automated gas sampling unit enabled N_2O to be monitored continuously, providing up to eight (hourly) flux rates per day. Specific N_2O measurement details for each study site are described in the associated papers (Table 1).

Calculations

Hourly N_2O fluxes (μg N_2O-N m^{-2} h^{-1}) were calculated from the slope of the linear increase in N_2O concentration during the chamber lid closure period, and corrected for chamber air temperature, air pressure and the ratio of cover volume to surface area. Flux rates were converted to zero if the regression coefficient (r^2) was < 0.80. Annual fluxes for each plot were calculated by integrating hourly losses over time. The emission factor for the application of N fertilizer to the soil was calculated using two different approaches depending on the study location. For Buntine and Cunderdin it was calculated by dividing the difference in cumulative N_2O flux for the plus N treatment and the nil N treatments (kg N_2O-N ha^{-1} yr^{-1}), by the total amount of N fertilizer applied during the study (kg N ha^{-1}). While at Wongan Hills, the emission factor was calculated by dividing the difference in cumulative N_2O flux for the plus N treatment (wheat) and the nil N treatment (grain legume, no N fertilizer applied), by the total amount of N fertilizer applied to the wheat crop. Nitrous oxide fluxes from plots planted to grain legume were used as the nil N treatment as an earlier study in the region showed growing grain legumes did not enhance cumulative N_2O fluxes in comparison to bare soil (Barton et al. 2011).

Results and discussion

Annual N_2O fluxes are low in a semi-arid region in south-western Australia in comparison to losses reported nationally (The National Agricultural Nitrous Oxide Research Program, www.n2o.net.au/publications/) and globally. In our studies nitrous oxide fluxes ranged from 0.04 to 0.27 kg N_2O-N ha^{-1} yr^{-1}, whereas globally, and across a variety of climatic regions, annual N_2O losses from cropped mineral soils have ranged from 0.3 to 16.8 N_2O-N ha^{-1} yr^{-1} (Stehfest and Bouwman 2006). Nitrous oxide emission factors ranged from 0.01 to 0.12 in the present study region and included eight values based on annual measurements (Table 1). However, in some instances, N_2O fluxes from N fertilized treatments did not differ statistically from non-fertilised treatments (e.g., Barton et al. 2008; Barton et al. 2016). The lowest emission factor occurred from a deep sand cropped to barley, while the greatest emission factor occurred from the same study site where the soil had been amended with OM (Table 1). Emission factors reported for south-western Australia were often a magnitude less than the value currently used by the Australian government to calculate N_2O from N fertilizer applied to rain-fed crops (0.2%; Department of Environment, 2013), and were significantly less than the international default value (1.0%; IPCC. 2006).

Table 1. Annual N_2O fluxes and emission factors reported for cropped soils in south-western Australia.

Location, year	Crop	N application (kg N ha^{-1} yr^{-1})	Annual N_2O flux (kg N ha^{-1} yr^{-1})	Emission factor (%)
Cunderdin, 2005[a]	Wheat	0	0.09	0.02
		100	0.11	
Cunderdin, 2006[b]	Wheat	0	0.07	0.02
		75	0.09	
Cunderdin, 2007[c]	Canola	0	0.08	0.06
		75	0.13	
Cunderdin, 2008[d]	Lupin	0	0.13	NA
Wongan Hills, 2009[e]	Lupin	0	0.04	0.03
	Wheat	75	0.06	
Wongan Hills, 2010[e]	Wheat	20	0.06	NA
	Wheat	50	0.07	
Buntine, 2012[f]	Canola	0	0.01	0.01
	Canola	100	0.02	
Buntine, 2012[f]	Canola (+OM)	0	0.06	0.08
	Canola (+OM)	100	0.14	
Buntine, 2013[f]	Barley	0	0.01	0.01
	Barley	100	0.02	
Buntine, 2013[f]	Barley (+OM)	0	0.15	0.12
	Barley (+OM)	100	0.27	

[a]Barton et al.(2008); [b]Li et al.(2012); [c]Barton et al.(2010); [d]Barton et al.(2011); [e]Barton et al. (2013b), non-limed treatment only presented; [f]Barton et al. (2016), no organic matter treatment only NA, not applicable.

A large proportion, and up to 80%, of the N_2O fluxes from cropped soils in south-western Australia have been measured in response to summer rainfall events (Barton et al. 2008; Barton et al. 2013b) rather than following N fertilizer applications. Summer rainfall elevated soil water contents at times when surface soils were mild to warm (i.e., >15°C), resulting in the rapid mineralisation of soil OM and the production of mineral N. Furthermore, during these periods there was no active plant growth to compete with soil microbial processes for available soil N. It has been hypothesised that the increased N_2O fluxes following the summer rainfall were probably coupled with an increase in ammonium availability and nitrification activity; although, the contribution of denitrification in the region cannot be ruled out (Barton et al. 2013a). Nitrous oxide fluxes following summer rainfall were often unpredictable and short-lived (<24 h) and would have not been characterised without using an automated measuring system (Barton et al. 2015).

Increasing soil OM in sandy textured soils or including grain legumes in cropping rotations is unlikely to significantly increase soil N_2O fluxes from N fertilized soils in semi-arid environments similar to our study region. Although increasing soil OM at a study site (Buntine) increased the N_2O fluxes and the emission factor in comparison to values previously reported for the region, losses were still relatively conservative (Table 1). Similarly, including grain legumes in cropping rotations did not enhance soil N_2O fluxes during the growing season or post-harvest. Instead N_2O fluxes from grain-legume crops were similar to losses from rain-fed, N fertilised crops grown in the same environment. For example, the annual N_2O flux from a legume (lupin) crop at Cunderdin was similar to those rates reported from the same site when previously cropped to N fertilised wheat and canola (Table 1). Similarly including a grain legume in the cropping rotation with wheat did not enhance soil N_2O at a second site (Wongan Hills) with total N_2O losses were approximately 0.1 kg N_2O-N ha^{-1} after two years for both lupin-wheat and wheat-wheat rotation (Barton et al. 2013b). Our findings are consistent with the general consensus that N_2O fluxes from grain legume crops are similar, if not less than, those from fertilised non-legume crops (e.g. Rochette and Janzen 2005).

Developing strategies for mitigating N_2O fluxes from cropping soils in our region is challenging as losses occur post-harvest, when there is no active plant growth, and in response to summer rainfall rather than N fertilizer additions. Strategies that control soil N supply from nitrification, or immobilise excess mineral N via soil microbial or plant uptake, would be expected to decrease the availability of N for subsequent N_2O loss in semi-arid regions. Indeed, previous studies have demonstrated that increasing the efficiency of the nitrification process by increasing soil pH (via liming) could in turn decrease N_2O losses from sandy, acidic soils following summer rainfall (Barton et al. 2013a; Barton et al. 2013b). A laboratory-based study also suggested nitrapryin, a nitrification inhibitor, may also have the potential to limit N_2O losses from nitrification in the study region (Fisk et al. 2015b), but requires field-based verification. Controlling the supply and immobilisation of mineral N through the incorporation of crop residues has proven to be difficult in our region (Hoyle and Murphy 2011; Fisk et al. 2015a). Instead, the presence of root exudates has been shown to be more effective at increasing microbial N immobilization relative to N supply (nitrification) than long term additions of crop residues (Fisk et al. 2015a). The potential for plants to both utilise mineral N and stimulate soil N immobilisation during the summer-autumn fallow, and respond to rainfall during these months, therefore warrants further attention in semi-arid, rain-fed cropping systems.

Conclusion

Nitrous oxide fluxes were consistently small (0.04–0.27 kg N ha^{-1} yr^{-1}) in our semi-arid region, representing <0.12% of applied N fertilizer. Largest daily N_2O fluxes occurred in response to summer rainfall rather than following N fertilizer applications. Neither increasing soil OM nor including grain legumes in cropping rotations enhanced soil N_2O fluxes in the growing season or post-harvest. Increasing the efficiency of the nitrification process by increasing soil pH (via liming) is a potential strategy for mitigating N_2O fluxes from nitrification. Accurately accounting for N_2O fluxes in our region has refined Australia's national greenhouse gas inventory and demonstrated annual fluxes can be low from cropped soils in semi-arid regions.

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