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Modelling the response of N_2O emission factor to nitrogen application rates and inter-annual climate variability

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Abstract: Nitrous oxide is one of the primary greenhouse gases contributing to global warming, and its concentration in the atmosphere has increased significantly since 1970. Agricultural soils are regarded as the most important source for emissions nitrous oxide. The Intergovernmental Panel on Climate Change (IPCC) put forward 1.0% as the default country-specific value for emission factor (EF) for estimating country-specific direct nitrous oxide emissions from nitrogen input agriculture. However, the emission factor from soils is based on limited data. Large uncertainty had been found in the EF values as no allowance has been made for the effects of land cover, soil type, climatic conditions or management practices on the values. In this paper we use Agricultural Production Systems simulator (APSIM) to explore the response of EF to N fertilizer applications and climate variations. The model is used to predict emission factor following various N-fertilizer rates over a 120 years (1890-2010) in a semi-arid rain-fed wheat cropping system in New South Wales, Australia. Emission factors following N application to rain-fed wheat ranged from 0.13-0.23%, which was significantly lower than the default emissions factor recommended by IPCC (EF=1.00%). Our long-term simulation results clearly showed that EF increased linearly with N inputs, and there was a highly variable inter-annual climate. In the rain-fed wheat cropping system, highest EF occurred in years with medium rainfall years, which indicated that the proportion of N-fertilizer inputs loss as N_2O emissions was not only highly impacts by annual rainfall amount but also rainfall pattern.

Keywords: *Emission factor, Climate variability, N-fertilizer rate*

1. INTRODUCTION

Nitrous oxide (N_2O) is one of the primary greenhouse gases (GHGs), with about 296 times global warming potential compared to carbon dioxide (CO_2). It contributes approximately 6% of the global warming effect caused by the increasing GHGs concentration in the atmosphere (Dalal et al., 2003; Smith et al., 2008). In 2009, N_2O concentration in the atmosphere was 323 parts per billion (ppb), which was about 20% higher than in the pre-industrial era and 70% of the increase has occurred since 1970 (IPCC, 2007). Estimates are that about 60% of the N_2O emitted from the biosphere to the atmosphere is derived from soil, and about 35% of the global emissions occur from agricultural soils (FAO/IFA, 2001; Mosier et al., 1998). The direct global annual N_2O emission from agricultural soils was about 2.1 Tg N on average, ranging from 0.03 to 3 Tg N (Tg = teragram; 1Tg = 10^{12}g; (Mosier et al., 1998; Watson et al., 1992)). The large range implies that there is a significant uncertainty associated with the estimations of N_2O emissions.

The Intergovernmental Panel on Climate Change (IPCC) adopted the emission factor method to estimate N_2O emissions from fertilized soils. It is based on the empirical method from Bouwman (1996) where annual direct N_2O emissions (E) from N input was estimated as a proportion (EF) of annual N-Fertilizer rate in kg N ha^{-1} yr^{-1}. IPCC recommended 1.00% as the default country-specific value for emission factor (EF) because of limited data (Hamilton et al., 1992). The default country-specific value for EF can be modified by detailed N_2O emission data or models which were well calibrated in the country (Hamilton et al., 1992). IPCC (2006) also pointed out that the uncertainty range of EF is 0.03%-3% base on recent studies (Bouwman et al., 2002a; Bouwman et al., 2002b; Stehfest and Bouwman, 2006). These studies showed that the value of EF could be varied with (i) environmental factors (climate, soil organic C content, soil texture, drainage and soil pH) and (ii) management-related factors (N application rate, crop type, rotations). Studies in Australia indicated that the proportion of N-fertilizer as N_2O emission ranged from 0.02 to 0.11% in Australian dry-land wheat cropping systems (Barker-Reid et al., 2005; Barton et al., 2008; Barton et al., 2010; Dalal et al., 2003; Galbally et al., 2010) , being largely lower than the IPCC default value of 1.00%.

In this study, we use the Agricultural Production Systems simulator (APSIM; (Keating et al., 2003) to simulate the N_2O emissions from nitrification and denitrification in the soil, and their responses to climate patterns and N input rates. The objective is to explore the response of the so-called emission factor (EF) to N fertilizer applications and climate variations.

2. METHOD AND MATERIAL

2.1 Study site and weather data

Wagga Wagga (35.05 °S, 147.35 °E) in Australia was selected as the study site. It has a semi-arid continental climate with annual average temperature of 9.1 °C and mean annual rainfall of 554 mm. Inter-annual variations in rainfall is high. The soil at the study site is classified as a Red Kandosol (Isbell, 1996), a representative soil type in the dominant wheat cropping region. Soil in the surface 0.2 m contained 1.38 % organic carbon and 0.09% nitrogen. The soil hydraulic properties are presented in Table 1, which extracted from the APSoil database.

Table 1 Soil hydraulic properties at Wagga Wagga site, NSW, Australia

Soil layer (cm)	Bulk density (g cm^{-3})	Air dry water content (cm^3 cm^{-3})	Water content at lower limit of 15-bar suction (LL15) (cm^3 cm^{-3})	Water content at drained upper limit (DUL) (cm^3 cm^{-3})	Saturated soil water content (SAT) (cm^3 cm^{-3})
0-20	1.45	0.055	0.11	0.22	0.37
20-40	1.55	0.088	0.11	0.21	0.36
40-60	1.45	0.22	0.22	0.35	0.41
60-80	1.50	0.22	0.22	0.33	0.39
80-100	1.55	0.22	0.22	0.3	0.37
100-120	1.60	0.22	0.22	0.3	0.35
120-140	1.60	0.22	0.22	0.28	0.35
140-160	1.60	0.22	0.22	0.28	0.35

Daily weather variables, including maximum and minimum air temperature, solar radiation and rainfall from 1890 to 2010 for the study site were obtained from the SILO Patched Point Dataset, managed by Queensland Department of Natural Resources and Mines (http://www.longpaddock.qld.gov.au/silo/ppd/).

2.2 Modeling of N_2O emissions with APSIM

We applied the farming systems model APSIM to simulate the N_2O emission from soil in response to climate variation and management changes. APSIM is a process-oriented model that simulates the key processes of water, carbon (C) and nitrogen (N) in soil-plant system (Keating et al., 2003). It has been well tested and widely used to analyze the impacts of agricultural managements and climate change on wheat yield in Australia (Asseng et al., 1996; Wang et al., 2011). The dynamics of soil C and N are simulated in the SoilN sub-module, which is described in detail at Keating et al. (2003). In the SoilN module, soil organic carbon (SOC) is partitioned into four SOC pools, that is fresh organic carbon pool (FOM), microbial biomass pool (BIOM), more stable humus pool (HUM) and an inert carbon pool (INERT). Decomposition of these pools lead to loss of carbon into the atmosphere, carbon and nitrogen transformation between the pools, and nitrogen mineralization or immobilization. The performance of the model to simulate SOC dynamics was tested by Luo et al. (2011). The ability to simulate N_2O emission from nitrification and denitrification processes was recently developed and tested by (Thorburn et al., 2010; Xing et al., 2011).

In this study, the approach developed by Xing et al (2011) was used to simulate the N_2O emissions from nitrification and denitrification processes under a dry-land continuous wheat cropping system. In the simulations, Wheat (cv. Hartog) was sown every year within a sowing window between 20 April and 30 June. The sowing date was determined when (i) the accumulated rainfall in seven consecutive days was greater than 20 mm or (ii) when 30^{th} June was reached (Wang et al., 2009).

Five N fertilizer application rates were used for the simulations, namely zero N application (N0), 75 kg urea ha^{-1} (N75), 100 kg urea ha^{-1} (N100), 150 kg urea ha^{-1} (N150), and a non-N limiting fertilizer treatment which aims to reach the highest wheat yield for each year (NCD). In NCD scenario, the fertilizer rate varied every year with the average of 185 kg urea ha^{-1} yr^{-1} (range from 67 to 324 kg urea ha^{-1} yr^{-1}). In N75 and N100 scenarios, 25 kg urea ha^{-1} was applied at a soil depth of 50mm with the seed and the remainder applied to soil surface at the jointing stage of growth. In N150 and NCD scenarios, the fertilizer was applied in three splits at sowing, jointing and flowering stage of growth.

2.3 Emission factor and its response to climate and management variations

Emission factor is defined as the proportion of N loss as N_2O from the applied N fertilizer:

$$EF = \frac{N_{N_2O(+N)} - N_{N_2O(0N)}}{N_{fertliser}} \times 100\%$$

Where EF is the emission factor (%), $N_{N2O(+N)}$ and $N_{N2O(0N)}$ are the cumulative annual N_2O emission from the treatment with and without N-fertilizer application (kg N ha^{-1} yr^{-1}) respectively, and $N_{fertiliser}$ is the amount of N fertilizer applied (kg N ha^{-1}).

In order to analyse the impact of climate variations on EF, the 120 years (1891-2010) were grouped as dry, wet and medium years to analyze the impacts of rainfall variations on N_2O emissions. Wet years were defined as years with annual rainfall higher than 1.25 times of the average annual rainfall, while dry years defined with annual rainfall lower than 0.75 times of the average annual rainfall. The remaining years were referred to as medium years.

3. RESULT AND DISCUSSION

3.1 Impacts of fertilizer application rates on N_2O emissions

The simulated long-term average value of emission factor (EF) for the dry-land wheat cropping system was 0.13%, 0.15%, 0.20% and 0.23% for N75, N100, N150 and NCD scenarios, respectively (Fig.1). The simulated EF values were consistent with the value of 0.02 - 0.11% reported from rain-fed wheat crop fields in Western and South-eastern Australia (Barker-Reid et al., 2005; Barton et al., 2008). They were significantly lower comparing the default EF value recommended by IPCC (1.00%).

Our simulation results clearly show that EF is not a constant proportion of N-fertilizer application rates, but linearly increases with N fertilizer application rates from 75 kg urea ha^{-1} to 185 kg urea ha^{-1} (Fig. 1). Higher N-fertilizer application rates lead to more available mineral N in the soil profiles for nitrification and denitrification, resulting in increased N_2O emissions from soil. These simulated result supported the studies of Clayton et al. (1994) and Lilly et al. (2003), where they reported that EF was impacted by soil nitrate concentrations and N-fertilizer rates.

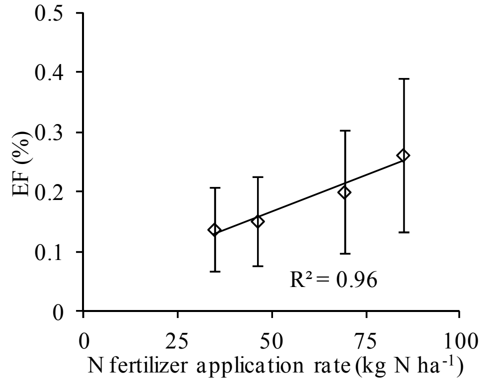

Figure. 1 Impact of N fertilizer application rates on N_2O emission factor (EF).

3.2 Impacts of climate variability on N_2O emissions

The value of EF in the dry land wheat cropping system also varied in response to inter-annual climate variations (Fig.2). The range of EF based on the long-term simulation results was 0.0-0.39%, 0-0.46%, 0.02-0.6% and 0.08-0.73% for N75, N100, N150 and NCD scenarios, respectively (Fig. 2). These findings are consistent with the results of Flynn et al. (2005) and Flechard et al. (2007). Flynn et al. (2005) reported that EF increased with the increasing annual rainfall. However, our results show that the average EF in medium years was the highest under all N application rates (Fig.3), especially in NCD scenario ($P<0.05$). This may be caused by the rainfall pattern at the study site. At Wagga Wagga, the number of annual storms (≥10mm/d) and the amount of rainfall with storm to annual rainfall increase with the annual rainfall (data not showed). Although N_2O production will increase with rainfall amount due to the increases in Water-Pore-Filled-Space (WFPS) in soil, high rainfall in wet years also causes increased drainage and lower nitrogen concentration in the surface soil layers because of nitrogen leaching. This leads to significantly lower N_2O emissions from surface soil layers and increase the N_2O production from deep soil layers, but the contribution of the contribution of N_2O products in the deep soil layer is very small as the short of the denitrifers and the reduction during its diffusion (Clough et al., 2005). Therefore, high rainfall with more storm events decreases N_2O emissions from soils.

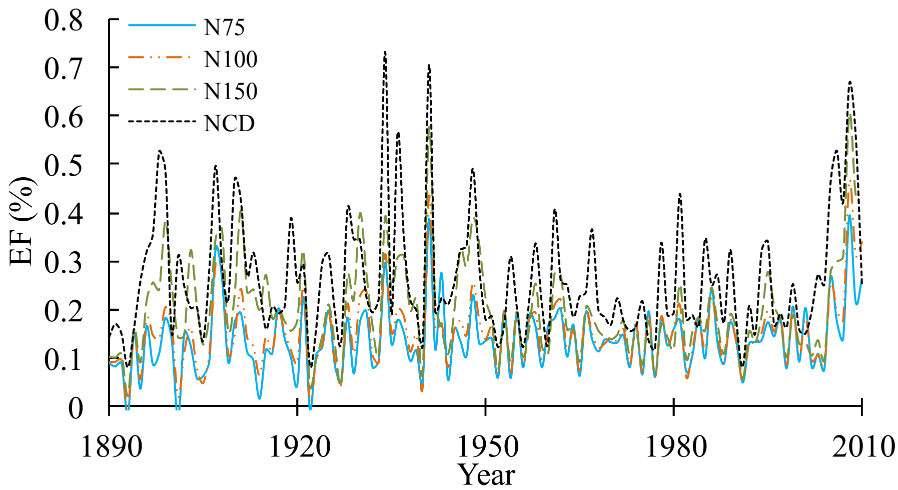

Figure.2 The impacts of climate variations on EF from 1890 to 2010.

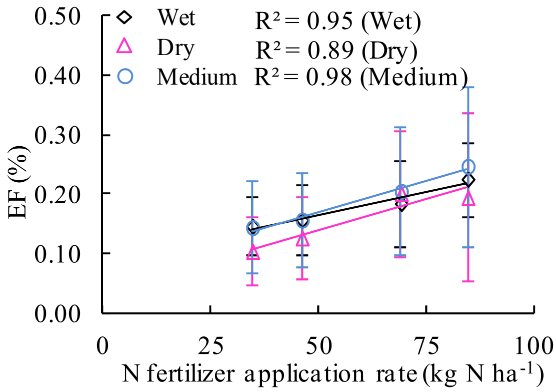

Figure. 3 Impact of N fertilizer application rates on EF under different annual rainfall years.

4. CONCLUSION

Nitrous oxide EF following N fertilization of rain-fed wheat at Wagga Wagga was significantly lower than the default emissions factor recommended by IPCC (EF=1.00%). Our simulation results clearly showed that EF linearly increased with N fertilizer application rates and varied with inter-annual climate variations. In the rain-fed wheat cropping system, highest EF was found to occur in medium rainfall years, thus higher annual rainfall did not always lead to higher proportion of N-fertilizer loss as N_2O emissions.

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