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Global nitrous oxide emission factors from agricultural soils after addition of organic amendments: A meta-analysis

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ABSTRACT

Agricultural soils receiving synthetic fertilizers and organic amendments containing nitrogen contribute a large part to anthropogenic nitrous oxide (N_2O) emissions. As a source of nitrate that undergoes reduction to N_2O, organic amendments also change soil C availability and redox potential, which influences the N_2O emission factor (EF) of organically-amended soils. The objective of this study was to conduct a meta-analysis of N_2O EF from agricultural soils receiving organic amendments. A global survey of peer-reviewed literature resulted in the selection of 38 studies including 422 observations at 43 sites in 12 countries. The analysis yielded a global EF for all organic sources, EForg, equal to $0.57 \pm 0.30\%$, which is lower than the IPCC default EF of 1 for synthetic fertilizers. Three groups of organic amendments with similar EFs were identified: the high-risk group including animal slurries, waste waters and biosolids ($1.21 \pm 0.14\%$); the medium-risk group including solid manure, composts + fertilizers, and crop residues + fertilizers ($0.35 \pm 0.13\%$); and the low-risk group including composts, crop residues, paper mill sludge and pellets ($0.02 \pm 0.13\%$). The EF was higher when soils received organic amendments in combination with synthetic fertilizers, such as liquid manures + fertilizers ($2.14 \pm 0.53\%$), composts + fertilizers ($0.37 \pm 0.24\%$), and crop residues + fertilizers ($0.59 \pm 0.27\%$). The EF was modulated by amendment (C/N ratio), soil (texture, drainage, organic C and N) and climatic (precipitation) factors. For example, EFs were on average 2.8 times greater in fine-textured than coarse-textured soils. We recommend site-specific EFs that consider organic amendment chemistry, soil characteristics, climate conditions and whether the organic amendment is applied alone or in combination with synthetic fertilizers.

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1. Introduction

Nitrous oxide (N_2O) is an important greenhouse gas, with 298 times the global warming potential of carbon dioxide (CO_2) (Foster et al., 2007). Nitrous oxide emissions are also a major source of ozone-depleting nitrogen oxides (NO and NO_2) in the stratosphere (Ravishankara et al., 2009). Agricultural sources of N_2O make a prominent contribution to the global budget. For example, Syakila and Kroeze (2011) estimated agricultural emissions owing to N fertilizer use and manure management (4.3–5.8 Tg N_2O–N yr^{-1}) represented 23–31% of all global N_2O sources (19 Tg N $year^{-1}$ in 2006). Human population growth and increasing global prosperity demands greater N fertilizer inputs to sustain the global food supply, and also generates more N-rich organic waste that is returned to agricultural soils as organic amendments (OAs). As a result, the N_2O emissions from agricultural soils are predicted to increase in the future, which is cause for concern.

Most N_2O emissions from agricultural soils are the result of nitrification and denitrification of mineral N following application of synthetic fertilizers and OAs. In Canada, 34% of direct soil N_2O emissions are attributed to OAs such as animal manure and crop residues (Rochette et al., 2008). OAs have multiple roles in the microbially-mediated reactions leading to N_2O production, resulting in positive or negative effects. Mineralization of organic N contained in OAs releases ammonium (NH_4^+), with subsequent nitrification (NO_3^-) processes leading to N_2O production. As an organic C substrate for microbial growth, OAs may also stimulate

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microbial N assimilation, which can increase competition for NH_4^+ between heterotrophic microorganisms and autotrophic nitrifiers (Chen et al., 2013), resulting in temporary reduction of N_2O production. In soils with high N availability but low organic C, OAs may stimulate nitrifier denitrification, the oxidation of ammonia to nitrite (NO_2^-) and its subsequent reduction to NO and N_2O by autotrophic ammonia oxidizing microorganisms under low O_2 availability (Butterbach-Bahl et al., 2013). Under anaerobic conditions, organic C provided by OAs enhances denitrification and N_2O production. The ratio of N_2O to N_2 produced during denitrification increases with increasing soil NO_3^- availability, which is influenced by the microbial consumption and production of NO_3^- due to C and N substrate availability in OA-amended soils (Terry and Tate, 1980; Weier et al., 1993; Miller et al., 2008). Finally, OAs such as animal slurries modulate O_2 availability in soil microsites because the labile C input enhances soil respiration; as slurries are mostly water (up to 97% moisture content), their addition saturates soil micropores in the short-term. Given the multiple ways that OAs impact the activity of microorganisms involved in N_2O production, their influence on soil N_2O emissions cannot be predicted from simple measures such as the total N application rate, which is a reasonably good estimator of the EF from synthetic fertilizers (Kim and Dale, 2008).

Although simplified EF values are used in calculating the contribution of agricultural soils to national N_2O inventories following the Tier 1 methodology of the Intergovernmental Panel on Climate Change (IPCC EF_1), they can result in erroneous conclusions. There are four major weaknesses associated with simplified EF_1 values: (1) they assume a linear relationship between total N input and N_2O emissions, not considering that biological thresholds for N_2O emissions might exist (Kim et al., 2013; Shcherbak et al., 2014); (2) the large range of uncertainty that varies from 0.3% to 3%; (3) the dataset used to generate the EF_1 is biased towards mid-latitude and temperate regions (Bouwman et al., 2002a); and (4) the simplified EF_1 values do not account for differences between N inputs from synthetic fertilizer and organic amendments on N_2O emission across soil types, agronomic systems and environmental conditions (Buckingham et al., 2014; Rochette et al., 2008). As signatory countries to the United Nations Framework Convention on Climate Change move to define region- and site-specific EF values (Tier 2 and Tier 3 methodologies) for calculating the N_2O emissions from their agricultural soils, the lack of quantitative information on how OAs contribute to N_2O emissions emerges as a research gap of global significance.

Soil N_2O emissions from agricultural soils receiving OAs can be summarized at global and regional scales using systematic reviews (Bouwman et al., 2002a; Novoa and Tejeda, 2006; Aguilera et al., 2013; Buckingham et al., 2014) or meta-analyses techniques (Liu and Powers, 2012; Chen et al., 2013; Shan and Yan, 2013; Bouwman et al., 2002b). Manure-amended soils had a mean global N_2O EF of 0.8%, i.e. 20% lower than the default IPCC EF_1, with an uncertainty range of −40% to +70% in the N_2O emissions, using Residual Maximum Likelihood (REML)-based models and 846 N_2O cumulative emissions measurements (Bouwman et al., 2002b). In the United-Kingdom, the DNDC mechanistic model generated an EF for manure ranging from +0.01 to +1.53% with an average of $0.43 \pm 0.34\%$ (standard deviation) (Cardenas et al., 2013). A meta-analysis of N_2O emissions from OAs in soils of the Mediterranean region presented an average EF of $0.97 \pm 1.17\%$ for solid OAs (e.g., crop residues, manure, composted municipal solid waste, composted cattle and sheep manure, and composted solid fraction of digested pig slurries), and an average EF of $1.75 \pm 1.34\%$ for liquid manure (Aguilera et al., 2013). Still, another meta-analysis suggested that the EF for pig slurry was similar to EF_1 (Liu and Powers, 2012). Decomposing crop residues generate N_2O emissions, and a global EF of 1.055% was calculated using a simple linear regression of soil N_2O emitted on residue-N applied (kg ha^{-1}) (Novoa and Tejeda, 2006). However, sensitivity analysis revealed that removing the two highest observations would decrease the EF to 0.6%, indicating the uncertainty of the estimate. A global meta-analysis by Chen et al. (2013) also concluded that crop residues produced comparable or greater N_2O emissions than synthetic fertilizer, whereas Shan and Yan (2013) reported that crop residue addition with synthetic fertilizer inhibited N_2O emissions by 11.7% compared to synthetic fertilizers alone. The variability in EF of agricultural soils receiving OAs warrants more investigation to determine how key factors, such as the OA type and its properties, soil and climate conditions, modulate the EF responsible for soil N_2O emissions.

The aim of this study was to provide a comprehensive and quantitative analysis of a dataset containing 422 EFs reported in 38 studies that measured soil N_2O emissions after OA addition in perennial and annual cropping systems. The analysis was done using (1) a systematic review and (2) a REML model. These two approaches allowed us to compare EF for OAs and OAs combined with synthetic fertilizers, to categorize the global EF according to OA types and properties, and to determine how the global EF for OAs was influenced by environmental and management-related factors.

2. Material and methods

2.1. Global database

The systematic review summarises the results of publications relevant to the objectives, while minimizing publication bias (i.e., bias towards particular publication journals, authors or study type) as much as possible by following six main steps: (1) determination of search terms, (2) conducting searches and obtaining literature, (3) development of screening criteria, (4) extraction and data assimilation protocol, (5) quality assurance and (6) post extraction data summary and analysis (Buckingham et al., 2014).

A detailed review of literature was carried out until June 13, 2014 with Scopus (1960–2014) and *CAB Abstracts* (1910–2014) research databases using the key words listed in Tables S1 combined with Boolean Operators. It retrieved 1064 papers published in peer-reviewed journals (Fig. S1). The following inclusion criteria were applied to screen studies in a standardized manner; which resulted in the retention of 38 studies:

- N_2O fluxes were measured from agricultural soils for at least 30 d (modelling outputs excluded, grazing pasture and paddy soils excluded).
- Unamended soils that received no fertilizer/amendment addition were used as control.
- Soils were amended with organic by-products with or without synthetic fertilizers.
- Information on chemical properties of amendments and application rates was available to estimate the relative contribution of the applied materials (e.g., total N input) to cumulative N_2O fluxes.

We retained field experiment data only and excluded experiments done under controlled conditions such as disturbed soil and undisturbed soil column incubations. Studies without spatial replication or no replicates reported were excluded from the analysis. Three studies against the selected 38 used micrometeorological instrumentation (Sharpe and Harper, 1997, 2002; Merbold et al., 2014) and were excluded because not in a relatively large number to adequately sub-group the meta-analysis considering methodological aspects in N_2O measurements (Borenstein et al., 2009). Using these criteria, the selected 38 studies reported

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