Agriculture, Ecosystems and Environment 254 (2018) 69–81

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Research Paper

Soil nitrous oxide emissions from agricultural soils in Canada: Exploring relationships with soil, crop and climatic variables

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A R T I C L E I N F O

Keywords:
Soil N_2O emissions
Soil texture
Growing season precipitation
Synthetic N
Organic N
Annual and perennial crop

A B S T R A C T

National scale emissions of nitrous oxide (N_2O) from agricultural soils are often estimated using a unique fertilizer-induced emission factor (EF); thereby neglecting how factors other than nitrogen input could impact emissions. In the present study, we compiled soil N_2O flux data collected since 1990 on agricultural soils in Canada, to identify key soil and climate factors, and management practices that explain variations in N_2O emissions and in EF. Stepwise regression analysis showed that the growing season precipitation was the most important factor impacting N_2O emissions, and that cumulative N_2O fluxes and EFs could be predicted using equations (R^2 from 0.68 to 0.85) including two to five of the following variables: growing season precipitation, ratio of growing season precipitation to potential evapotranspiration, mean annual air temperature, crop type (annual or perennial), soil pH, texture and organic carbon content. We conclude that N_2O EFs could be effectively stratified based on growing season precipitation, soil texture (coarse, medium and fine), type of N (synthetic and organic), and crop type (perennial and annual). We propose EFs that account for the dominant factors that modulate the nitrogen fertilizer-induced emissions and should improve regional and national estimates in Canada. They may also provide useful information for guiding the development of soil N_2O emission quantification in other countries.

1. Introduction

Nitrous oxide (N_2O) is the third largest contributor to radiative forcing among naturally present greenhouse gases (GHGs) after carbon dioxide (CO_2) and methane (CH_4). Increased use of N fertilizer and expansion of fertilized agricultural lands have been recognized as the primary drivers of the increase in N_2O concentration in the atmosphere (Forster et al., 2007).

Emissions of N_2O from cultivated soils account for 3% of anthropogenic sources in Canada (Environment and Climate Change Canada, 2017). Nitrous oxide is produced in soil by the denitrification and autotrophic nitrification processes which are primarily controlled by soil moisture, temperature, labile organic C, oxygen availability, nitrate (NO_3^-) and ammonium (NH_4^+) concentrations and pH (Bouwman, 1990, 1996; Butterbach-Bahl et al., 2013; Farquharson and Baldock, 2008). For croplands, these factors are in turn influenced by soil characteristics (texture, drainage, bulk density), climatic conditions (temperature, rainfall) and cultural practices (fertilization, crop type, tillage) (Kaiser et al., 1996; Jungkuns et al., 2006; Flechard et al., 2007).

The Intergovernmental Panel on Climate Change (IPCC) provides a standard methodology to estimate direct and indirect N_2O emissions from agricultural soils (IPCC, 2006). Direct emissions are estimated as a fraction of soil N inputs. A default value of this fraction or emission factor (EF) has been set to 0.01 kg N_2O−N kg^{-1}N based on a large global dataset (Bouwman et al., 2002a). However, the available dataset was biased towards mid-latitude, temperate regions and a number of studies have shown deviation from the default emission factors (EFs) under different conditions (Freibauer and Kaltsmith, 2003; Gabrielle et al., 2006; Jungkuns et al., 2006; Leip et al., 2011; Berdanier and

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http://dx.doi.org/10.1016/j.agee.2017.10.021
Received 9 August 2017; Received in revised form 23 October 2017; Accepted 25 October 2017

Conan, 2012). The use of the IPCC default EF could indeed result in biased N_2O emission estimates (Brown et al., 2001; Flynn et al., 2005). For this reason, the IPCC encourages the development of country-specific methodologies for key sources of emissions which can account for regional variability and thus provide more accurate estimates of N_2O emissions. Country-specific EFs were determined in the United Kingdom where a mean of 0.0017 ± 0.0002 kg N_2O-N kg^{-1}N was reported based on a meta-analysis of flux data (Buckingham et al., 2014). A similar effort in China yielded EFs from 0.0056 to 0.0154 kg N_2O-N kg^{-1}N with a mean confidence interval (95%) of 0.0092 kg N_2O-N kg^{-1}N for upland crops (Shepherd et al., 2015).

Methodologies to quantify N_2O emissions from agricultural soils have been developed based on numerical modeling (Li et al., 2000; Brown et al., 2002; Butterbach-Bahl et al., 2004; Del Grosso et al., 2005, 2006; Kesik et al., 2005; Neufeldt et al., 2006; Britz and Leip, 2009) or empirical relationships (Skiba et al., 1998; Bouwman et al., 2002a,b; Dämmgen and Grünhage, 2002; Sozanska et al., 2002; Freibauer, 2003; Roelandt et al., 2005; Lu et al., 2006; Dechow and Freibauer, 2011). Empirical methodologies are most often based on multivariate linear regressions using N input, land use, soil temperature, water-filled pore space or soil water content, soil clay, sand, organic C and/or N content, and climate variables such as precipitation (Kaiser et al., 1996; Skiba et al., 1998; Sozanska et al., 2002; Freibauer and Kaltsmith, 2003; Jungkuns et al., 2006; Lu et al., 2006).

In Canada, Rochette et al. (2008c) proposed a methodology using an empirical approach based on data published before 2005. The methodology quantified direct N_2O emissions from agricultural soils by ecodistrict (areas of > 100 kha and characterized by relatively homogeneous biophysical and climatic conditions) as the sum of emissions from N inputs as a function of tillage intensity, irrigation, landscape position and practice of summer fallow. Emission factors were estimated based on experimental results from three regions using the relationship between soil N_2O emissions and ratios of growing season precipitation to potential evapotranspiration. However, for the regions corresponding to the Prairies, the regressions fit could be improved. The use of a larger dataset that includes the most recently published studies since 2005 from a wider variety of experimental sites may improve the representativeness of EFs.

The objective of the present study is to propose updated N_2O EFs and refined relationships of key factors (soil properties, climatic conditions, and management practices) that explain N_2O emissions from fertilized agricultural soils in Canada in light of more recent studies.

2. Methods

The criteria used in this study correspond: i) field experiments on Canadian agricultural soils, ii) flux measurements with at least 50 days of duration, iii) treatments that included control plots (no N input), and iv) experimental results collected after 1990. A literature search was carried out using the Scopus database. The keywords included field; N_2O; nitrous oxide; soil; greenhouse gas; and Canada as affiliation country. The dataset is comprised of 50 peer-reviewed and 4 unpublished studies. A total of 10 peer-reviewed papers were reported both in this dataset and in Rochette et al. (2008c). Five studies used in Rochette et al. (2008c) were excluded from the dataset in this study because one or more requirement criteria were not met. Overall; the updated dataset included 34 peer-reviewed papers not included in Rochette et al. (2008c) as well as 4 new unpublished studies.

The dataset encompassed 1026 treatment-years from various cropping systems, soil types, climatic regions, N fertilizer types and rates (Table 1). In addition to the explanatory variables such as climate, soil and management related variables used in the regression analysis (Table 2), other information/data from these published and unpublished studies was collected and recorded in Microsoft Excel to include study reference number, soil drainage class, soil C:N ratio, rate of biosolid organic N applied, split N application, and tillage type. The majority of the N_2O measurements were made using non-steady state non-flow through chambers placed on the soil surface, or on top of a collar. Micrometeorological measurements were reported otherwise. Many of the studies within the dataset had some missing values of the required variables and were therefore excluded; as a result, only 474 records from 25 different studies were used for modeling the cumulative soil N_2O emissions. Emission factor calculation cannot be done for the zero-N treatments, which resulted in 227 records from 10 studies analyzed.

Total N_2O emissions were calculated in the original studies as point measurements interpolated between measurement dates, summed over the study period and averaged over replicates and years. Emission factors of soil N_2O were calculated using the difference in the cumulative N_2O fluxes between N-treated plots and the control plots (0 kg N ha^{-1}) divided by the amount of N applied.

The explanatory variables were used in the regression analysis including climate, soil and management related variables (Table 2). It is expected that some of these variables, especially within the same group, would be correlated, and therefore principal component analysis was carried out to examine relationships among variables and to summarize the dataset using the principal component analysis [PROC PRINCOMP procedure of SAS (SAS Institute, 1999)]. All regressions were tested for influential values, collinearity (condition index) and other violations of standard regression assumptions, and compared using three basic measures of fit: the adjusted R^2, root mean square error, and the Mallow's C_p statistics. The Mallows' C_p statistics is a measure of model fit using ordinary least squares that aims at balancing model accuracy with variable number; smaller values indicating that the model is more efficient. Collinearity refers to a linear relationship between two explanatory variables.

Cumulative N_2O emissions and N_2O EFs were first examined for normality using the Shapiro-Wilk test and transformed when necessary. Emission factors of soil N_2O by treatments (i.e. soil texture, fertilizer N type, tillage practice, crop type) were deemed significantly different from one another when 95% confidence intervals did not overlap, which is analogous to a 0.05 probability level.

3. Results

Simple correlation analysis was carried out among dependent and independent variables, excluding all binary variables such as soil drainage class, crop type and tillage practice (Table 3). Soil clay content was correlated positively with soil organic C content, cumulative soil N_2O emissions, and N_2O EFs, and negatively with soil sand content (Table 3). Likewise, cumulative soil N_2O emissions and soil N_2O EFs were also correlated positively with soil organic C content, growing season precipitation, ratio of growing season precipitation to potential evapotranspiration, and negatively with soil sand content (Table 3). The principal component analysis for the dataset indicated that the first two principal components explained approximately 84% in eigenvalues of the covariance matrix. Close correlations were identified in the plot of Principal Component two by Principal Component one among P, P2, PPE, PPE2, PE, and PE2 as expected (Fig. 1). Strong correlation between soil pH, and P or PPE likely reflects the interactions among the factors driving soil genesis. Soil types in Eastern Canada are usually associated with high precipitation and low soil pH, whereas in Western Canada (mainly on the prairies) soils developed in low precipitation and high soil pH. Other close correlations between PE and organic N, and between synthetic N and soil clay are more difficult to interpret, but likely also reflect regional study objectives and therefore are indicative of biases in the dataset. Because of correlations among the variables, it is important to recognize that 1) multiple alternative equations for predicting cumulative soil N_2O emissions or N_2O EFs through multi-factorial linear regressions with slightly lower R^2 values are possible, and 2) coefficients of the multiple regressions do not rigorously express the true contribution of the variables to soil N_2O emissions and EF values.