Agriculture, Ecosystems and Environment 268 (2018) 70–78

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

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

Re-assessing nitrous oxide emissions from croplands across Mainland China

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A R T I C L E I N F O

Keywords:
Nitrous oxide
Croplands
Nitrogen fertilizers
Greenhouse gas emission
Regression model
Data synthesis
China's agriculture

A B S T R A C T

Reliable quantification of nitrous oxide emission is a key to assessing efficiency of use and environmental impacts of N fertilizers in crop production. In this study, N_2O emission and yield were quantified with a database of 853 field measurements in 104 reported studies and a regression model was fitted to the associated environmental attributes and management practices from China's croplands. The fitted emission model explained 48% of the variance in N_2O emissions as a function of fertilizer rate, crop type, temperature, soil clay content, and the interaction between N rate and fertilizer type. With all other variables fixed, N_2O emissions were lower with rice than with legumes and then other upland crops, lower with organic fertilizers than with mineral fertilizers. We used the subset of the dataset for rice - covering a full range of different typical water regimes, and estimated emissions from China's rice cultivation to be 31.1 Gg N_2O-N per year. The fitted yield model explained 35% of the variance in crop yield as a function of fertilizer rate, temperature, crop type, and soil clay content. Finally, the empirical models for N_2O emission and crop yield were coupled to explore the optimum N rates (N rate with minimum N_2O emission per unit yield) for combinations of crop and fertilizer types. Consequently, the optimum N application rate ranged between 100 kg N ha^{-1} and 190 kg N ha^{-1} respectively with organic and mineral fertilizers, and different crop types. This study therefore improved on existing empirical methods to estimate N_2O emissions from China's croplands and suggests how N rate may be optimized for different crops, fertilizers and site conditions.

1. Introduction

Nitrogen (N) plays a key role in enhancing food production to support the world's growing population – being an essential nutrient supporting plant growth for food and feed (Zhang et al., 2013; Sutton et al., 2013). Apart from the natural conversion from nitrogen gas (N_2) by lightning fixation and bacterial fixation, reactive nitrogen (Nr) is increasingly produced through the Haber-Bosch process in industry of nitrogen fertilizers developed since early 20th century. Being a pivotal player in crop production, the ever-increased application of N fertilizers had dramatically increased food production albeit at significant environmental cost (Gruber and Galloway, 2008). Fertilized N in cropping systems could find its way to the atmosphere and aquatic systems via ammonia (NH_3) volatilization, leaching of nitrate/nitrite and emission of nitrous oxide (Wrage et al., 2001; Ju et al., 2009). These end-products of lost N are known to cause secondary inorganic aerosol formation and thus haze pollution (Liu et al., 2017), and destruction of the stratospheric ozone layer (Ravishankara and Portmann, 2009), and again impact on human health (Galloway et al., 2008; Farnworth et al., 2017).

As a potent greenhouse gas, production and emission of nitrous oxide (N_2O) in global nitrogen (N) cycle is particularly important for

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https://doi.org/10.1016/j.agee.2018.09.003
Received 19 December 2017; Received in revised form 13 August 2018; Accepted 2 September 2018

climate change (Mosier et al., 1998). With a global warming potential (GWP) approximately 265 times as CO_2 over a 100-year time horizon (IPCC, 2013), N_2O emissions were around 8.4 Tg N_2O yr^{-1} globally, with, for example, 58% estimated to be contributed by agriculture in 2005 (Smith et al., 2007). Since global application of N fertilizer is projected to increase in world agriculture to meet the food demand of the increasing world population, N_2O emissions in global agriculture are also projected to increase in the coming decades (Reay et al., 2012). The key challenge this presents to the agricultural sector is to maximize crop productivity while minimizing N_2O emissions from fertilized field (Galloway et al., 2008).

In recent decades, a large number of field studies have been carried out to characterize N losses, including N_2O emissions, and exploring N use efficiency in various agricultural systems. Bouwman et al. (2002) created a global database of field N_2O emissions from a total of 388 studies, of which however only 3% of the data was from China. The existing field data has facilitated development of ecosystem N models to predict N_2O emissions from agricultural systems (Heinen, 2006), including, for example, the dynamic process-based models of DNDC (Li et al., 1992), SUNDIAL (Smith et al., 1997) and DAYCENT (Ogle et al., 2010). The dataset had also been used directly by Bouwman et al. (2002) to develop an empirical model of N_2O emissions as a function of several field and management variables, which informed the choice of the emission factor of 1% (meaning 1% of fertilizer N is emitted as N_2O-N) adopted in the IPCC Tier I methodology (IPCC, 2006).

Accurate and precise prediction of N_2O emissions in croplands is difficult since the biotic and abiotic factors influencing N_2O emission in field are temporally dynamic and spatially heterogeneous, and influenced by a number of factors related to climate, soil quality, fertilizer application, cropping systems and management practices (Ladha et al., 2016; Tang et al., 2016; Lam et al., 2016; Yue et al., 2017). For instance, N_2O emission rates were lower for flooded or paddy rice than upland crops as the anaerobic conditions in wetland soils tend to encourage complete denitrification to N_2 (Gerber et al., 2016). Also, many existing models predicting N_2O emission from croplands were developed and parameterized in regions where agriculture was well-developed and fertilizer use efficiency was relatively high. However, much of the projected increased in food production, and thus N use, is expected to occur in the developing countries (Holland et al., 1999; Tilman et al., 2001), particularly in the populous regions of the Indo-Gangetic Plain (IGP), southwest Asia and Yangtze and Yellow river plain of eastern Asia. Thus, quantifying N_2O emissions and developing more robust models suitable in these regions is critical to enable better prediction of global agricultural N_2O emission and identify improved management practices in these regions.

China is a country representing 19% of the world's population and 7% of net GHG emission from Agriculture, Forestry and Other Land Use (AFOLU) in 2014 (FAOSTAT, 2017). Total annual N_2O emissions from fertilized croplands in China had previously been estimated (Zou et al., 2007; Gerber et al., 2016), using the aforementioned existing models calibrated with global data in which China was under-represented. China's agriculture covered 166 M ha croplands and 23.6 Mt N was used for food production in 2015 (NBSC, 2017). Between 2002 and 2014, China had achieved a crop yield increase of 21% with an increase by 23.4% of N fertilizer application. The increase in N fertilizer application resulted in decreased N use efficiency (NUE) in China's croplands, resulting in negative environmental impacts such as soil acidification (Guo et al., 2010), water eutrophication (Le et al., 2010), air pollution (Sapkota et al., 2014; Liu et al., 2017), and severe human health risks (Farnworth et al., 2017; Gu et al., 2012; Galloway et al., 2008). Better knowledge of the impacts of crop nitrogen use can be used to identify more efficient and lower emitting N management practices in China's agriculture which would in turn not only help the state to cut its GHG emissions as part of its commitments to the Paris Agreement (UNFCCC, 2015), but also to reduce other N losses while sustaining food production.

It is critical to identify ways to balance quantity of grain, NUE, and environmental impacts in China, given the increasing human population and limited resources (Galloway et al., 2008; Liu et al., 2016; Xia et al., 2017). Additional increase in N fertilization over the existing high rates might result in marginal yield benefits (Brentrup et al., 2004; Liu et al., 2016) but at the cost of proportionally higher N_2O emissions (Bellarby et al., 2014). As suggested by Van Groenigen et al. (2010), since yield response curves tended to flatten for higher N rates, above a certain point yield-scaled N_2O emissions increased progressively with N application rate. Yet, it is still unclear precisely how such yield based N_2O emissions change with N application for a given crop system, and soil and climate characteristics in the context of Chinese agriculture. Moreover, it was also questionable if the default global fertilizer-induced emission factor of 1% in Tier I approach by IPCC (2006) applies to croplands of China given that it the underpinning data contained few studies (only 3% of the total dataset) from China.

We hypothesized here that N_2O emissions from croplands varied with crop type, N fertilizer type and rate and climate, across various agricultural systems of China. We also hypothesized that such variation could be modeled to predict N_2O emissions and explore the main drivers for N_2O emissions from key Chinese croplands. In this study, field data of N_2O emissions in reported studies were reviewed to create a country-level database and a multi-variate empirical model fitted to predict N_2O emissions in China. Using the model, N_2O emission rates were compared between different fertilizer and crop types and the Emission Factors (EF) for China's croplands were derived for comparison to the IPCC default factors. Furthermore, a cross-system variability was elucidated with the model calculation of the cumulative N_2O emission for rice cultivation in 2014. With an additional multi-variate empirical model of crop yield derived from our database, yield-scaled N_2O emission were identified for different crops and fertilizer types to explore approaches to optimize N use efficiency in China's crop production.

2. Materials and methods

2.1. Database creation

A dataset with a total of 853 seasonal cumulative N_2O field emission measurements from 104 studies in China's agricultural fields was compiled for this study. A primary dataset was compiled from the scientific literature reporting field measurements of N_2O emissions from cropping systems of China published over a time span of 2001-2016. Firstly, papers were collected and archived via searching the databases of CNKI (China National Knowledge Infrastructure), ISI-Web of Knowledge and Google Scholar with keywords of "nitrous oxide" "emission" "chamber" "fertilizer" and "China". From the collected literature, data pairs of N_2O emissions under a fertilizer treatment and a non-fertilized control were retrieved and archived, retaining a total of 71 studies. In addition, 33 studies meeting our criteria in the dataset used by Albanito et al. (2017) were checked and added to the primary dataset. Finally, a dataset comprising 853 data pairs from a total of 104 studies were constructed and used in this study. The reported measurements were located across the mainland China, between the longitude of 85.0° to 139.6° and latitude of 21.9° to 47.4° (Fig. 1).

Information in the dataset included geographic location (latitude and longitude); climate data - annual average temperature (ranging between -0.4℃ and 21.3℃), annual average precipitation (values from 193 mm to 1795 mm); soil characteristics - including clay content, organic carbon and nitrogen content, bulk density, and pH; soil type - classified into 8 soil texture classes (Clay loam, Loam, Sand, Sandy clay loam, Sandy loam, Silt loam, Silty clay, Silty clay loam) following the United State Department of Agriculture (USDA) classification; cropping system; crop types aggregated into 4 broad categories (Table 1); fertilizer types classified into 3 broad categories (Table 1); fertilizer application rate; management practices - including water management,