Science of the Total Environment 595 (2017) 371–379

Contents lists available at ScienceDirect

Science of the Total Environment

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

Trade-off between soil organic carbon sequestration and nitrous oxide emissions from winter wheat-summer maize rotations: Implications of a 25-year fertilization experiment in Northwestern China

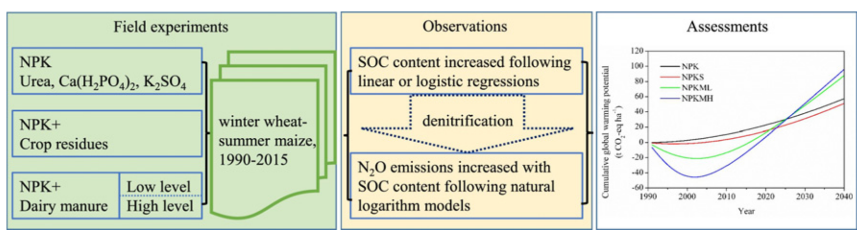
Jiangxin Gu *, Mengxuan Yuan, Jixuan Liu, Yaoxu Hao, Yingtian Zhou, Dong Qu, Xueyun Yang *

College of Natural Resources and Environment, Northwest A&F University, 712100 Yangling, PR China
Key Laboratory of Plant Nutrition and the Agri-environment in Northwest China, Ministry of Agriculture, 712100 Yangling, PR China

HIGHLIGHTS

- Field measurements suggest that large N_2O fluxes were mainly due to denitrification.
- Time stage relative to SOC saturation seemed critical to estimate C sequestration rate.
- About 88–151% of the sequestered C was offset by N_2O emissions over 1990–2015.
- All fertilization regimes in this study were greenhouse gas sources over 1990–2040.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 31 October 2016
Received in revised form 27 March 2017
Accepted 30 March 2017
Available online 6 April 2017

Editor: D. Barcelo

Keywords:
Agricultural soil
Global warming potential
Greenhouse gas mitigation
N_2O
Organic amendment
SOC

ABSTRACT

The primary aims of this study were to (i) quantify the variations in nitrous oxide (N_2O) emissions and soil organic carbon (SOC) sequestration rates under winter wheat-summer maize cropping systems in Guanzhong Plain and (ii) evaluate the impact of organic amendments on greenhouse gas mitigation over a long-term period. We measured N_2O fluxes during the maize season in 2015 under four fertilizer regimes in a long-term fertilization experiment. Soil was treated with only synthetic fertilizers in the maize season and with synthetic fertilizers, synthetic fertilizers plus crop residues and synthetic fertilizers plus low and high levels of dairy manure in the winter wheat season from 1990. The SOC content (0–20 cm) was collected annually at the same site between 1990 and 2015. Synthesis of our measurements and previous observations (between 2000 and 2009) within the investigated agricultural landscape revealed that cumulative N_2O emissions increased with the SOC content following natural logarithm models during both the maize and winter wheat seasons ($r^2 > 0.77$, $p < 0.001$), implying a trade-off between N_2O emissions and SOC sequestration. The SOC content increased under all fertilizer regimes, and the dynamics were well fitted by the linear and logistic regression models ($r^2 > 0.74$, $p < 0.001$), indicating that all the fertilizer treatments in this study sequestered SOC. By applying these regression models, we estimated that the two manure-amended treatments accumulated a negative global warming potential (ranging from -1.9 to -12.9 t CO_2-equivalent ha^{-1}) over the past 25 years. However, this benefit would most likely be offset by high N_2O emissions at saturated SOC levels before 2020. Our estimates suggest that organic amendments may not be efficient for greenhouse gas mitigation in Guanzhong Plain over a long-term period. We recommend efforts to inhibit N_2O production via denitrification as being critical to resolving the conflict between SOC sequestration and N_2O emissions.

* Corresponding authors at: College of Natural Resources and Environment, Northwest A&F University, 712100 Yangling, PR China.
E-mail addresses: gujiangxin@nwsuaf.edu.cn, jiangxin.gu@yahoo.com (J. Gu), xueyunyang@nwsuaf.edu.cn (X. Yang).

http://dx.doi.org/10.1016/j.scitotenv.2017.03.280
0048-9697/

1. Introduction

Nitrous oxide (N_2O) is almost 298 times more heat absorptive than carbon dioxide (CO_2) over a 100-year time horizon and contributes approximately 6% to global radiative forcing (IPCC, 2013). Its atmospheric concentration has increased by 20% since 1750, mostly as a result of nitrogen (N) fertilizer application in agricultural soils (Davidson, 2009; Park et al., 2012). Soil N_2O originates mainly from microbial nitrification and denitrification, which are primarily controlled by inorganic N substrates and soil aeration (Davidson, 1991). Large N_2O fluxes following N fertilizer application and precipitation/irrigation have been widely observed in various agroecosystems (Gu et al., 2011, 2016; Bell et al., 2015; Jain et al., 2016). Annual and seasonal N_2O emissions have been shown to respond positively to N input rates, leading to the development of the concept of a direct emission factor (EF; Bouwman, 1996; Zheng et al., 2004; Li et al., 2013). EF is the fraction of N fertilizer lost as N_2O for a given year or season and has been widely used to estimate global and regional N_2O emissions (Bouwman, 1996; Zheng et al., 2004; Davidson, 2009). However, N_2O emissions do not always relate to the N input rate, due to the influence of site-specific factors such as climate, soil and field managements (Wei et al., 2010; Gu et al., 2013; Jain et al., 2016). The relative importance of these factors varies greatly due to their complex relations with microbial activities and soil gas diffusivity (Davidson, 1991; Smith et al., 2003). The synthesis of field observations representative in space and time is crucial for identifying major controls of N_2O emissions within a given region.

Guanzhong Plain is a major food production area in Northwestern China. This extensive farming region is located on the south edge of the Loess Plateau, where soil erosion, degradation and frequent droughts have long been the major environmental problems threatening the crop production. The combination of synthetic fertilizer with manure and crop residues has been widely adopted in the local region with promising benefits to increase soil fertility and grain yields (Yang et al., 2011; Zhang et al., 2015; Li et al., 2016a). With additional input of organic materials, these practices have inevitably led to an increase in soil organic carbon (SOC) content and had important implications on carbon (C) sequestration (Yang et al., 2011; Zhang et al., 2015; Li et al., 2016a). However, the overall impacts of organic amendments on greenhouse gas mitigation may largely depend on the trade-offs between SOC turnover and N_2O emissions over a long-term period (Shang et al., 2011; Jain et al., 2016). In comparison to synthetic fertilizers, organic amendments have been observed to stimulate N_2O emissions by providing more N and C substrates to microbial organisms that play roles in nitrification and denitrification processes (Rochette et al., 2008; Li et al., 2013). Organic amendments have also been reported to reduce N_2O emissions by regulating the soil C:N ratio and subsequently governing microbial activities in soils (Frimpong and Baggs, 2010; Ding et al., 2013); conversely, other studies showed that such effects were not obvious (Lopez-Fernandez et al., 2007; Wei et al., 2010). These divergent findings were mostly due to the quantity and quality of the applied organic materials, the site-specific crops and soil properties, and variations in climatic conditions (Huang et al., 2004; Pelster et al., 2012; Li et al., 2013). In particular, the region-specific relation between N_2O emissions and SOC sequestration is not clear in Guanzhong Plain, leading to a misunderstanding of the potential trade-off between organic amendments and greenhouse gas mitigation.

We measured N_2O fluxes during the summer maize season in 2015 under four fertilizer regimes within a long-term fertilization experiment in Guanzhong Plain. To interpret the variations in N_2O emissions over sites and years, we went through the literature and summarized field observations about N_2O emissions from winter wheat-summer maize cropping systems throughout the local region during the past few decades. The SOC content was also collected annually at the long-term fertilization experiment site between 1990 and 2015. The primary aims of this study were to (i) quantify the variations in N_2O emissions and SOC sequestration rates and (ii) evaluate the impact of organic amendment on greenhouse gas mitigation over a long-term period.

2. Material and methods

2.1. Site description and field management

Field measurements were conducted at the "Chinese National Soil Fertility and Fertilizer Efficiency Monitoring Base of Loessial Soil" (34°17′51″N, 108°00′48″E), locating in Yangling, Shaanxi Province. The semi-humid region, which is prone to droughts, is representative of the Guanzhong Plain, with a typical warm temperate continental monsoon climate. The site displays a mean annual temperature of 13.0 °C, a mean annual precipitation of 550 mm, and potential evaporation of 1400 mm. Approximately 60% of precipitation occurs during July to September. The silty loam soil is derived from loess material and is classified as Eumorthic Anthrosol, with a soil pH (1:1 v/v water) approximately 8.6 (Yang et al., 2012).

A long-term fertilization experiment (hereafter refers to LTFE) commenced in 1990 under a winter wheat-summer maize rotation (Yang et al., 2012). The field experiment was arranged in a series of randomly distributed plots with a relatively large area (14 m × 14 m), each of which was separated by ridges approximately 1 m in width. However, the treatment was replicated once for practical reasons. Three successive crops of winter wheat and maize were sown without fertilizer and manure over the whole area to homogenize the soil fertility before the fertilizer treatments were applied. Considering that representative soil properties of all plots, such as the SOC and total N (TN) contents, the bulk density (BD) and the pH, displayed small spatial heterogeneity ($CV < 6\%$, $n = 33$) at the beginning of the experiment (Yang et al., 2012), we assumed that any significant differences subsequently observed between plots could be attributed to the treatment effects. In the winter wheat season (between October and May in the next year), fertilizer was applied as synthetic urea (N), super phosphate (P) and potassium sulfate (K) fertilizers (NPK), NPK plus crop residues (NPKS), and NPK plus low (NPKML) and high (NPKMH) levels of dairy manure. All fertilizers and organic materials were surface applied and incorporated into the soil (0–20 cm) with rotary tiller before winter wheat sowing. The NPK treatment received synthetic N, P and K at 165 kg N ha^{-1}, 57 kg P ha^{-1} and 68 kg K ha^{-1}, respectively. The NPKS treatment received the same quantity of synthetic fertilizers as the NPK treatment and an additional wheat straw (approximately 4.5 t dry weight ha^{-1} yr^{-1}) from 1990 to 1998. From 1999 on, the wheat straw was substituted by aboveground maize stalk from the plot (ranging from 2.6 to 6.0 t dry weight ha^{-1} yr^{-1} over the experimental years, with a mean 4.4 t dry weight ha^{-1} yr^{-1}). The NPKML treatment received the same rates of synthetic P and K and 30% of N compared to the NPK treatment, with the remaining 70% of N from dairy manure. The NPKMH treatment involved 1.5 times as much applications of synthetic N, P, K and dairy manure as NPKML. The dairy manure input rates averaged 11.8 ($CV = 61\%$) and 17.5 ($CV = 63\%$) t dry weight ha^{-1} yr^{-1} in the NPKML and NPKMH treatments, respectively, over the past 25 years. The total C and N contents of the applied manure averaged 304.9 g C kg^{-1} dry weight ($CV = 18\%$) and 15.5 g N kg^{-1} dry weight ($CV = 59\%$), respectively. In the maize season (between June and September), all treatments received the same amount of synthetic N, P and K at 185 kg N ha^{-1}, 25 kg P ha^{-1} and 78 kg K ha^{-1}, respectively. The fertilizers were manually incorporated into the soil (0–20 cm) between plants along a row approximately one month after the maize sowing. All treatments were flood irrigated once or twice each crop season, depending on the precipitation pattern. The water input rate for each irrigation event was similar to a rainfall event of 80 mm. All above-ground crop residues were removed after harvest unless otherwise specified. In 2015, maize crops were sowed, fertilized, irrigated and harvested on June 7, July 17, July 25 and October 2, respectively.