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Three-year measurements of nitrous oxide emissions from cotton and wheat–maize rotational cropping systems

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HIGHLIGHTS

- Three-year N_2O fluxes are reported for cotton and wheat–maize cropping systems.
- The fertilizer rate is not always an effective indicator of annual N_2O emissions.
- Leaching significantly contributes to fertilizer losses in irrigated croplands.
- N_2O emission inventory should consider leaching effects.
- Optimized sampling protocols enhance the reliability of discrete flux measurements.

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ABSTRACT

The remarkable expansion of fertilization and irrigation may stimulate nitrous oxide (N_2O) emissions from cropping systems in northern China. High-resolution measurements were conducted in irrigated cotton and wheat–maize rotational systems in Shanxi Province, P.R. China, between 2007 and 2010 (three year-round crop cycles, hereinafter referred to as Y1, Y2 and Y3) to investigate the impacts of natural inter-annual variations and agricultural management on annual N_2O emissions and direct emission factors (EFs). Overall, N_2O emissions fluctuated diurnally, seasonally and inter-annually in the fertilized treatments. The hourly N_2O fluxes closely followed the daily air temperature patterns. The daily mean fluxes corresponded to these hourly fluxes, which were observed between 09:00–10:00 and 19:00–20:00. An optimized sampling protocol could improve the reliability of discrete measurements when estimating cumulative emissions. The N_2O emissions for the fertilized treatments were 2.7 ± 0.2 (Y1) and 1.6 ± 0.1 kg N ha^{-1} yr^{-1} (Y2) from the cotton field and 6.2 ± 0.4 (Y1), 4.5 ± 0.3 (Y2) and 4.5 ± 0.2 kg N ha^{-1} yr^{-1} (Y3) from the wheat–maize field. Peak N_2O emissions after fertilization and irrigation/rainfall lasted one to three weeks and accounted for 16–55% of the annual emissions. Leaching losses were estimated at 10.4 ± 3.0 (Y1) and 12.5 ± 3.4 kg N ha^{-1} yr^{-1} (Y2), which accounted for 16–17% of the fertilizer-N applied to the cotton field. Annual N_2O emissions did not increase with increasing fertilization rates or water inputs because significant amounts of fertilizer-N were lost through leaching. Background emissions amounted to one-third to one-half of the total N_2O emissions from the fertilized treatments. The direct EFs were $2.2 \pm 0.3\%$ (Y1) and $0.9 \pm 0.2\%$ (Y2) in the cotton field and $1.3 \pm 0.2\%$ (Y1), $0.8 \pm 0.1\%$ (Y2) and $0.7 \pm 0.1\%$ (Y3) in the wheat–maize field. The large inter-annual variations in N_2O emissions and direct EFs emphasize the importance of multiple-year continuous observations.

1. Introduction

Globally, maize and wheat are the first and third most important cereal crops, respectively, accounting for 50–65% of planted areas and yields for cereal crops in China (China Statistical Yearbook, 2012; FAO, 2013). Cotton is grown for fiber and seed, and global cotton lint and seed production were 26 and 49 million tons, respectively, in 2011 (FAOSTAT, 2013). In China, annual cotton lint production amounts to 6.6 million tons, which represents 25% of global cotton lint production (China Statistical Yearbook, 2012). Wheat, maize and cotton production in China increased by 30, 59 and 34%, respectively, between 2002 and 2011 (China Statistical Yearbook, 2012). These increases have been largely driven by the

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intensification of agricultural management, i.e., the application of more fertilizer, expansion of irrigation and establishment of multiple cropping systems.

The winter wheat-summer maize double-cropping system has been widely adopted in northern China, which is a major region for wheat and maize production in Asia. This cropping system receives fertilizer of 550–600 kg N ha^{-1} yr^{-1} and irrigation water of 90–690 mm yr^{-1} (Wang et al., 2008; Ju et al., 2009). Northern China is also an important area of cotton production. Fertilizer rates for irrigated cotton are typically between 60 and 140 kg N ha^{-1} yr^{-1} (Liu et al., 2010). The application of synthetic nitrogen fertilizers and additional irrigation water creates favorable conditions for microbial nitrification and denitrification processes in soils and may stimulate nitrous oxide (N_2O) emissions. Indeed, significant N_2O emissions of 0.8–6.9 kg N ha^{-1} yr^{-1} were observed in wheat–maize rotational cropping systems (Ju et al., 2009; Li et al., 2010; Cui et al., 2012; Cai et al., 2013; Hu et al., 2013). In contrast, N_2O measurements in cotton fields are scarce in China and elsewhere, although cotton may significantly contribute to emissions of this important greenhouse gas (Liu et al., 2010; Scheer et al., 2013).

The direct emission factor (EF) is defined as the fraction of the anthropogenic nitrogen inputs that are released as N_2O emissions on a seasonal or annual scale. Emission factors are used extensively for compiling the national inventory of N_2O emissions from croplands (Zheng et al., 2004; Lu et al., 2006; Zou et al., 2010). However, reliable EF data are scarce, and most of the reported EFs have large errors due to improper sampling schedules such as low-frequency measurements and a lack year-round measurements, inter-annual replicates and unfertilized control treatments (Zheng et al., 2004). Recent studies have identified the systematic and random errors of N_2O flux measurements and have provided solutions to these errors. First, the improper scheduling of low-frequency measurements may result in a significant under- or over-estimation of annual N_2O emissions and EFs (Parkin, 2008; Liu et al., 2010). High-frequency measurements or optimized sampling schedules with low measurement frequencies should be adopted to eliminate such deviations (Smith and Dobbie, 2001; Liu et al., 2010). Second, gas chromatographic set-ups that used nitrogen as a carrier gas significantly overestimated N_2O emissions because carbon dioxide (CO_2) from the sample air was insufficiently removed and interfered with N_2O detection in the electron capture detector (Zheng et al., 2008). Thus, analytical set-ups using a mixture of argon and methane as the carrier gas or injecting buffer gas containing a high concentration of CO_2 when using nitrogen as the carrier gas should be implemented (Zheng et al., 2008). Third, the dimensions and spatial positioning of the measuring chambers can significantly affect the flux measurements. For example, when fluxes were measured only in the inter-rows of a maize crop, the annual N_2O emissions were 25–67% lower than the fluxes that were measured in both the plant rows and inter-rows (Cai et al., 2012). To ensure the representativeness of fluxes, the dimensions and spatial positioning of measurement chambers must be specially designed for different cropping systems.

To avoid the errors described above and to accurately estimate annual N_2O emissions and direct EFs in wheat–maize and cotton cropping systems, N_2O fluxes were measured at high resolution (hourly) over several years. Both fertilized and unfertilized treatments were studied with typical crop management systems in northern China. The aims of the present study were to (a) accurately quantify inter-annual variations of N_2O emissions and EFs, (b) assess the importance of background emissions for calculating EFs, (c) evaluate the reliability of low-frequency measurements and recommend optimized solutions and (d) determine the effects of field management and environmental factors on diurnal, seasonal and annual N_2O emissions.

2. Materials and methods

2.1. Experimental site

The experimental site (34°55.51′N, 110°42.59′E) is located on Dong Cun Farm in Yongji City, Shanxi Province, northern China. The primary cropping systems of this farm are cotton and winter wheat-summer maize rotations. The cotton growing season begins in early April and ends in early November. Cotton lint is usually harvested once every 1–2 weeks between the end of August and early November. Maize grows between early June and mid-October, and wheat grows during the remainder of the year. The two cropping systems are usually rotated every 3–5 years to avoid the negative effects of monoculture on crop yield. The investigated cotton (10.6 ha) and wheat–maize fields (10.4 ha) were adjacent and were planted with these crops for 3 and 2 years, respectively, prior to the experimental measurements. A sprinkler system was used to irrigate the crops with groundwater pumped from a depth of 130–140 m. Herbicides (Atrazine or Trifluralin) were applied to each crop once per growing season. Pesticides (acetamiprid or a mixture of emamectin benzoate and chlorpyrifos) were applied once-per-week between mid-May and mid-August for cotton and only once during July for maize. After harvest, the wheat, maize and cotton stubble were mechanically chopped into pieces (5–10 cm length) before being ploughed into the soil (0–20 cm). Meteorological data and soil properties for the experimental site were previously published by Liu et al. (2010, 2012).

Eight experimental plots (6 × 6 m) were set up in each of the cotton and maize–wheat fields before October 11, 2007. In addition, two treatments, fertilized and unfertilized, with four replicates each were randomly allocated to individual plots. The unfertilized treatments received no nitrogen fertilizer in a given year. In the fertilized treatments, nitrogen fertilizer was applied three times per year: during sowing (end of October) and the greening stage (mid-March) for wheat, at the 18- to 19-leaf stage (mid of July) for maize and at the flowering and boll-setting stage (end of June) for cotton. Phosphate (P) and potassium (K) fertilizers in the form of calcium superphosphate and potassium sulfate were applied during wheat planting (60–30 kg P–K ha^{-1}) and during the flowering and boll-setting stage of cotton (8–6 kg P–K ha^{-1}) in the fertilized and unfertilized treatments. The synthetic fertilizers were either tilled into the soil (20 cm depth) after surface broadcasting at planting or covered by the soil (0–5 cm depth) after band application along the plant row. The nitrogen fertilizer application rates are provided in Table 1. Due to increasing crop prices, the farm manager increased the fertilizer and irrigation water application rates over the experimental period.

2.2. Nitrous oxide fluxes

Nitrous oxide fluxes were determined from October 11, 2007, to October 15, 2009, for cotton and from October 11, 2007, and October 15, 2010, for wheat–maize. An automatic monitoring system for exchanges of nitrogen and carbon trace gases (AMEG), with eight translucent chambers (four replicate chambers per cropping system), was used to measure the N_2O fluxes in the fertilized plots for both crops. The automated chambers were made of polycarbonate (thickness: 1 mm) and stainless steel and measured 90 × 90 × 45 and 70 × 70 × 45 cm (length × width × height) for the cotton and wheat–maize cropping systems, respectively. The height of each chamber was expanded with one or two additional chamber parts to adapt the chamber height to the height of the growing crops. The final chamber heights were 90 and 135 cm in the wheat–maize and cotton fields, respectively. When the maize reached a height of 90 cm at the end of July (i.e., 10–15 days after the final fertilization), the measuring