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Nitrous oxide and methane emissions from optimized and alternative cereal cropping systems on the North China Plain: A two-year field study

Bing Gao [a], Xiaotang Ju [a,*], Fang Su [a], Qingfeng Meng [a], Oene Oenema [b], Peter Christie [a,c], Xinping Chen [a], Fusuo Zhang [a]

[a] College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, China
[b] Wageningen University and Research, Alterra, Wageningen, The Netherlands
[c] Agri-Environment Branch, Agri-Food and Biosciences Institute, Belfast BT9 5PX, UK

HIGHLIGHTS

- Yields, resource use efficiency and $N_2O + CH_4$ emission differ among cropping systems.
- An alternative cropping system is recommended for the North China Plain region.
- A rotation cycle of it is in sequence winter wheat, summer maize and spring maize.
- This alternative is better than an optimized winter wheat–summer maize system.
- It is sustainable due to saving water and N, maintaining yields and reducing GHG.

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ABSTRACT

The impacts of different crop rotation systems with their corresponding management practices on grain yield, greenhouse gas emissions, and fertilizer nitrogen (N) and irrigation water use efficiencies are not well documented. This holds especially for the North China Plain which provides the staple food for hundreds of millions of people and where groundwater resources are polluted with nitrate and depleted through irrigation. Here, we report on fertilizer N and irrigation water use, grain yields, and nitrous oxide (N_2O) and methane (CH_4) emissions of conventional and optimized winter wheat–summer maize double-cropping systems, and of three alternative cropping systems, namely a winter wheat–summer maize (or soybean)–spring maize system, with three harvests in two years; and a single spring maize system with one crop per year. The results of this two-year study show that the optimized double-cropping system led to a significant increase in grain yields and a significant decrease in fertilizer N use and net greenhouse gas intensity, but the net greenhouse gas N_2O emissions plus CH_4 uptake and the use of irrigation water did not decrease relative to the conventional system. Compared to the conventional system the net greenhouse gas emissions, net greenhouse gas intensity and use of fertilizer N and irrigation water decreased in the three alternative cropping systems, but at the cost of grain yields except in the winter wheat–summer maize–spring maize system. Net uptake of CH_4 by the soil was little affected by cropping system. Average N_2O emission factors were only 0.17% for winter wheat and 0.53% for maize. In conclusion, the winter wheat–summer maize–spring maize system has considerable potential to decrease water and N use and decrease N_2O emissions while maintaining high grain yields and sustainable use of groundwater.

1. Introduction

Nitrous oxide (N_2O) and methane (CH_4) are two important greenhouse gases with global warming potentials 298 and 25 times that of carbon dioxide (CO_2) on a 100-year time scale. The atmospheric concentrations of N_2O and CH_4 are increasing at rates of 0.26% and 0.4% per year, respectively (Forster et al., 2007). Together they account for 24% of total anthropogenic radiative forcing (Denman et al., 2007). Moreover, N_2O is involved in the destruction of stratospheric ozone (O_3) (Forster et al., 2007). There is an urgent need to reduce N_2O and CH_4 emissions from different sources because of climate change.

Agriculture is an important emitter of N_2O and CH_4 (Robertson et al., 2000; Reay et al., 2012), accounting for 60% and 50% of global anthropogenic N_2O and CH_4 emissions, respectively (Forster et al., 2007). Emissions of N_2O from croplands are strongly influenced by nitrogen (N) fertilizer and animal manure applications (Bouwman et al., 2002; Qin et al., 2012), soil temperature and soil moisture (Hu et al., 2013),

* Corresponding author. Tel.: +86 10 62732006; fax: +86 10 62731016.
E-mail address: juxt@cau.edu.cn (X. Ju).

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tillage and straw management practices (Dendooven et al., 2012) and crop rotations (Huang et al., 2013a). Upland soils act as a sink for atmospheric CH_4, depending on soil temperature (Whalen and Reeburgh, 1996), soil moisture (Dunfield, 2007) and ammonium-N fertilization (Glatzel and Stahr, 2001). Agriculture is rightly recognized as a large source of greenhouse gas emissions with various opportunities for mitigation (Burney et al., 2010). Recently van Groenigen et al. (2010) proposed the concept of yield-scaled N_2O emissions (emissions expressed as g N_2O-N per kg aboveground N uptake) and found that the lowest emissions occur at the optimum range of N application rates without sacrificing yield. Yield-scaled N_2O emissions will be relatively high when insufficient N application rates are accompanied by low yields (as in many parts of Africa) and very high when excessive N is applied (as in most intensive agricultural systems in China).

The North China Plain (NCP) is the largest agricultural plain in China, comprising about 39% of the arable land (Wei et al., 2007). The common winter wheat–summer maize double-cropping system in this area accounts for 61% of the total winter wheat yield and 33% of the maize yield in China (Cui et al., 2008). The double cropping system and especially current farming practices are under scrutiny because of the overuse of N fertilizers (Ju et al., 2009), the pollution of groundwater with nitrate (Ju et al., 2006), and the depletion of groundwater resources due to irrigation (Foster and Garduno, 2004). Several studies have examined yields and use of water and N when one season of winter wheat is replaced by fallow due to the high consumption of groundwater by winter wheat (e.g., Liu et al., 2008; Meng et al., 2012a). It has been suggested that an integrated management system comprising a winter wheat–summer maize–spring maize rotation, with three crop harvests over two years, has considerable potential to reduce N and water use and maintain similar net economic return as the conventional winter wheat–summer maize double-cropping system and this new cropping system should be considered for economic and sustainable agricultural development on the North China Plain (Meng et al., 2012a).

Previous studies have indicated that N_2O emissions occur mainly within the one-to-two-week period after N fertilization in conventional cropping systems in this region (Ju et al., 2011; Bao et al., 2012; Hu et al., 2013). Emissions are controlled mainly by the chemical form and application rate of the fertilizer N (Ju et al., 2011; Bao et al., 2012) but irrigation and precipitation events (Ju et al., 2011) and straw management practices (Huang et al., 2013b) have also shown some effects on N_2O emissions. The mean N_2O emission factors ranged from 0.11 to 0.21% and 0.45 to 0.59% for winter wheat and summer maize, respectively, in different fertilizer N treatments (Ju et al., 2011; Hu et al., 2013). The recommend integrated management practices significantly reduced N_2O emissions by about 30–50% and maintained grain yields relative to the conventional winter wheat–summer maize system. Management strategies include optimum fertilizer N and water inputs, use of nitrification inhibitors and careful crop management (Ju et al., 2011; Bao et al., 2012; Hu et al., 2013). The agricultural soils represented a weak sink for atmospheric CH_4 with an annual CH_4 uptake of only about 1 kg CH_4-C ha^{-1} yr^{-1} in this double-cropping system and different fertilizer N rates and other management practices had no significant effect on CH_4 uptake in one cereal rotational cycle (Hu et al., 2013; Shi et al., 2013). Clearly, N fertilization and irrigation regimes, other crop management practices, and soil temperature and soil moisture will change after conversion to alternative cropping systems. However, no studies have yet been conducted on N_2O emissions or CH_4 uptake in alternative cropping systems on the North China Plain and it still unclear which cropping system might maintain or increase grain yields and achieve sustainable use of groundwater at the same time as producing low N_2O emissions. We therefore hypothesized that a winter wheat–summer maize (or summer soybean)–spring maize rotation with three crop harvests over two years and a single spring maize system with one crop per year will produce lower N_2O emissions than the conventional double-cropping system due to lower fertilizer N and irrigation water inputs, and the optimized double-cropping system will produce the highest yields due to, *inter alia*, careful management of fertilizer N and irrigation, tillage and straw together with other agronomic aspects of the management package. The fertilizer N and irrigation regimes will be the main factors controlling N_2O emissions, and straw return will accelerate N_2O emissions but increases carbon storage by the soil.

The objectives of the present study were therefore to evaluate the performance of an optimized double-cropping system (involving different fertilizer and irrigation practices but the same crop rotations) and alternative cropping systems in terms of N_2O emissions, CH_4 uptake, fertilizer N and irrigation water use, and grain yields over a two-year period, to further understanding of the factors controlling N_2O emissions and CH_4 uptake in different cropping systems, and to elucidate which cropping systems can produce low N_2O emissions while maintaining or increasing grain yields and the sustainable use of groundwater.

2. Materials and methods

2.1. Experimental site

A long-term field experiment was set up at Quzhou experimental station (36.87°N, 115.02°E) in Hebei province in October 2007. The site is at an altitude of 40 m and has a temperate monsoon climate. The annual mean temperature was 13.2 °C and the annual mean precipitation was 494 mm from 1980 to 2010 (range 213–840 mm), with 68% of the annual precipitation falling between June and September (Meng et al., 2012a). The surface 30 cm of the Fluvo-aquic soil has a bulk density of 1.37 g cm^{-3}, a pH of 7.72 (soil:water ratio 1:2.5), an organic matter content of 12.6 g kg^{-1}, total N of 0.7 g kg^{-1}, Olsen-P of 4.8 mg kg^{-1} and available K of 72.7 mg kg^{-1}. These values were determined on one composite soil sample across the whole experimental field before the start of the long-term field experiment.

2.2. Experiment treatments and field management

A completely randomized design was employed with five treatments and four replicates. Each plot is 1800 (30 × 60) m^2. The control is the conventional winter wheat–summer maize double-cropping system (Con.W/M). The other four cropping systems were designed with optimized crop, water and fertilizer N management, namely (i) an optimized winter wheat–summer maize double-cropping system (Opt.W/M), (ii) a winter wheat–summer maize–fallow–spring maize system (W/M-M), (iii) a winter wheat–summer soybean–fallow–spring maize system (W/S-M), with three harvests in two years, and (iv) a single spring maize system with one crop per year (M). Detailed field management practices in the five different treatments over the two-year study period are shown in Table 1.

The three cultivars used, all commonly used in this region, were winter wheat Shijiazhuang 8 sown at the beginning of October, summer maize Zhengdan 958 and summer soybean Yudou 25 planted in mid-June. Spring maize cultivar Denghai 605 was planted at the end of May. In the Con.W/M treatment, wheat (225 kg ha^{-1}) and maize (75,000 plants ha^{-1}) were seeded in rows at distances of 15 and 60 cm, respectively. In the alternative systems, wheat (188 kg ha^{-1}), summer maize (75,000 plants ha^{-1}) and spring maize (85,000 plants ha^{-1}) were seeded in rows at distances of 15, 60 and 60 cm, respectively, and soybean had a planting density of 235,000 plants ha^{-1} and was seeded in rows at a distance of 40 cm.

Nitrogen application and the irrigation rate were system-dependent (Table 1). In Con.W/M the management followed current farming practice on the North China Plain. Total N input was 300 kg ha^{-1} yr^{-1} for winter wheat and 250 kg ha^{-1} yr^{-1} for summer maize, and the ratios of basal and topdressed applications were 1:1 and 1:1.5, respectively (Cui et al., 2010; Meng et al., 2012a). The basal fertilizer for winter wheat was surface broadcast just before tillage and the topdressed