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Reducing greenhouse gas emissions while maintaining yield in the croplands of Huang-Huai-Hai Plain, China

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ABSTRACT

Agroecosystems face double pressures of producing more food to feed growing global population and reducing greenhouse gas (GHG) emissions to mitigate climate change. The Huang-Huai-Hai (HHH) plain produces ~1/3 wheat and maize of China with very high resource inputs, particularly synthetic nitrogen (N) fertilizers since the 1980 s. Although fertilizer input has substantially increased crop yield and enhanced biomass carbon (C) input to the soil and thus stimulating soil C sequestration, GHG emissions (e.g., nitrous oxide (N_2O)) relating to the fertilizers have been also dramatically increased. Yet, a systematic regional assessment on the trade-offs between crop yield, soil C sequestration and N_2O emissions as impacted by management practices and environmental conditions is lacking. Here we calibrated a farming system model to conduct comprehensive assessment on crop yield and GHG emissions (soil CO_2 and N_2O emissions) during the period 1981–2010 across the HHH plain at the resolution of 10 km. We found that soil in HHH plain was a C sink with an annual C sequestration rate of 1.53 CO_2-eq ha^{-1} yr^{-1} (0–30 cm soil layer) during the period under current typical agricultural practices, but this sink could only offset about 68% of global warming potential from contemporary N_2O emissions. By reducing the annual N input rate (from current more than 300 to ~250 kg N ha^{-1} yr^{-1}) and enhancing crop residue retention rate (from current 30% to 100%), the HHH plain could act as a net sink of GHG without sacrificing grain yield. Apart from management, the effects of three key environmental factors, i.e., mean annual rainfall and temperature and initial soil organic carbon stock on dynamics of crop yield, soil CO_2 and N_2O emissions were also studied. The results will have important implications for the development of management strategies to maintain yield while reducing GHG emissions.

1. Introduction

Global agricultural intensification has induced significant environmental problems such as soil acidification and degradation, water eutrophication and greenhouse gas (GHG) emissions (Horrigan et al., 2002; Moss et al., 2008). Among the GHGs, soil carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions are dominant in dryland cropping systems. Up to half of the soil organic carbon in the top 30 cm soil can be emitted to the atmosphere as CO_2 after land clearing for agricultural production. For N_2O emissions from agroecosystems, they contribute around 60% to the global N_2O emissions, mainly induced by the use of synthetic nitrogen (N) fertilizers (Smith et al., 2007; Zhang et al., 2014). In the context of global change, modern agriculture faces a big challenge to not only produce enough food to feed increasing global population but also reduce environmental footprints, particularly greenhouse gas (GHG) emissions (Bradford et al., 2016). To overcome this challenge, we need a detailed understanding of the response of crop production and GHG emissions to various management practices, therefore facilitating development of win-win management strategies.

Nitrogen fertilizer application plays a core role in determining crop yield as well as GHG emissions. Crop yield generally increases with N fertilizer application rates until reaching a plateau (Fig. 1). Beyond this plateau, additional N inputs will lead to no yield benefits, while resulting in tremendous N_2O emissions and other sources of N loss from the agricultural systems. In China, agroecosystems are intensively managed with very high N fertilizer inputs. During the period 1981–2010, the use of synthetic N fertilizers was increased from 10.9 Tg yr^{-1} in the earlier 1980 s to 28.1 Tg yr^{-1} in the later 2000 s (Zhang et al., 2014), while the N use efficiency has decreased (Ju et al., 2009; Liu and Diamond, 2008). For example, Ju et al. (2009) reported that increased N use across the North China Plain did not significantly increase crop yields but caused two times larger N losses to the

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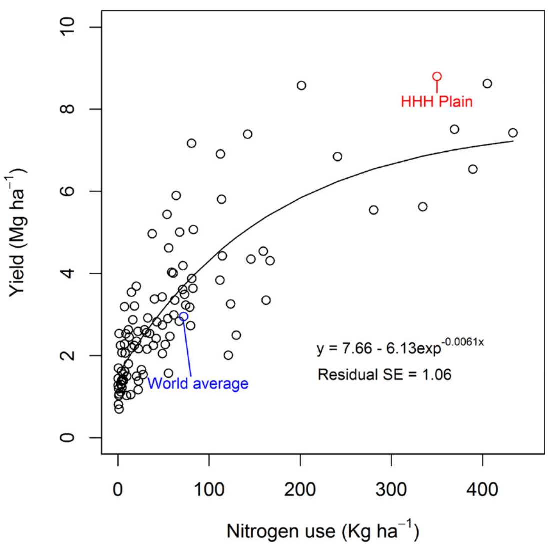

Fig. 1. The global-scale impact of nitrogen use on cereal crop yield on a country level from 2006 to 2010. The data for Huang-Huai-Hai Plain (red circle) is sum of the regional average yields of maize and wheat (the two main staple food crops in this region), which was derived from Zhang et al. (2014). The global country-level data (black circles) was obtained from FAOSTAT (http://faostat3.fao.org/home/E) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

environment. The rapid increase of N fertilizer inputs has caused a rapid increase in N_2O emissions that has outstripped the enhancement in crop production (Zhang et al., 2014; Tian et al., 2011; Lu and Tian, 2013; Tian et al., 2012). For example, the average N input rate in the Huang-Huai-Hai (HHH) Plain has exceeded 300 kg ha^{-1} which is much higher than some regions with the similar levels of crop yield (Fig. 1). Although this high level of N use can ensure high cereal yield (Fig. 1), it also causes serious environmental problems including dramatically enriched N_2O emissions (Ju et al., 2009). In a field trial in the HHH region, Yan et al. (2015) reported that increasing N use rate from 420 to 600 kg ha^{-1} yr^{-1} resulted in 50% increase in annual N_2O emissions without increment in crop yields. These results highlight that sustainable agriculture intensification should take into account the negative effect of N fertilizers on environment such as GHG emissions.

Apart from N fertilization, crop residue management and manure application (i.e., organic amendments) complicate the assessment on the trade-offs between crop production and GHG emissions (Wang et al., 2014b). It is possible that the mineralization of organic amendments may release N for crop growth and thus reduce the requirement of synthetic N. On the contrary, organic amendments (they usually have high C:nutrient ratios) may be stabilized to form new SOC (they usually have low C:nutrient ratios), i.e., carbon sequestration, and thus require additional nutrient including N to maintain stoichiometric balance. The long-term magnitude and direction of the effects of organic amendments on N management, crop yield and GHG emissions depends on the quantity and quality of organic amendments, other management and climate and soil conditions, which is needed to be quantified using a systematic approach.

Modelling approaches have already been used to quantitatively assess both crop production and the associated environmental footprints in response to different agronomic management, particularly the use of chemical N fertilizers (Tian et al., 2012; Lu and Tian, 2013). For example, based on simulations with an Earth system model (i.e., DLEM), Lu and Tian (2013) reported that N-induced N_2O emissions has offset the benefits from soil C sequestration in N overused areas of China. By contrast, using the same model, Tian et al. (2012) suggested that reducing current N fertilizer level by 60% in the 'over-fertilized' areas can substantially decrease N_2O emission without significantly influencing crop production. However, the detailed agronomic management such as planting, harvesting, fertilizing, crop residue management, manure incorporation and irrigation can hardly well represented by Earth system models because of the complexity in implementation and the large uncertainty at the global scale (Samuel, 2014). A process-based farming system model with implementing these detailed complex processes can potentially be used to more accurately simulate crop productivity, nutrient cycling and environmental impacts as influenced by environmental variability and management interventions. For example, Zhang et al. (2014) used an agricultural production model to quantify the net GHG emissions in China's croplands by considering specific temporally varied rates of crop residue retention, manure and nitrogen applications. However, there still lacks a comprehensive, high resolution strategic assessment on the potential of maintaining crop production and soil organic carbon accumulation while reducing GHG emissions through improving agronomic management across the high nutrient input and GHG emission regions in China.

In this study, we first calibrated the performance of the Agricultural Production System sIMulator (APSIM) in simulating crop yield and SOC dynamics in HHH plain. And then the calibrated APSIM was used to simulate the crop growth and soil nutrient cycling of the winter wheat-summer maize double cropping system across the whole HHH plain. The HHH plain in China is a typical region with intensive agricultural management involving N fertilizers, organic manure application and crop residue retention, providing a good opportunity to characterize the detailed spatial patterns and explicitly evaluate the relationships between N use, crop yield and soil CO_2 and N_2O emissions at the regional scale. Specifically, the objectives of this study were to: 1) assess the crop production, soil C sequestration and N_2O emissions during the past three decades; 2) target potential opportunities for maintaining crop production with maximum reduction in GHG emissions; and 3) identify the key management and environmental factors regulating yield and GHG emissions.

2. Materials and methods

2.1. Study region and long-term experimental sites

This study focuses on the croplands across the Huang-Huai-Hai Plain in China (Fig. 2). The HHH Plain includes the areas of five provinces and two municipalities: the entire Shandong, major parts of Hebei, Beijing and Tianjin and Henan; and the northern parts of Anhui and Jiangsu. The croplands in this region constitute around one-six of China's total cultivated area, and produce 35–40% and 60–80% of China's wheat and corn (Liu et al., 2015), respectively. Consequently, the HHH Plain is described as the "food bowl" of China (Kong et al., 2014).

Data from three long-term experimental sites (Fig. 2 and Table 1) located within the HHH Plain as a part of the National Long-term Fertilisation Experimental Network in China (Zhao et al., 2010) were used to constrain the APSIM model for accurately simulating soil organic carbon changes and crop productions under various management practices. Data from another two-year field experiment at Huantai (Table 1) was used to test the model's performance in simulating soil N_2O emissions. The mean annual temperature and precipitation at these sites varies from 11 to 15 °C and from 547 to 848 mm, respectively. The initial soil organic carbon stock varies from 20 to 40 Mg C ha^{-1} (0–30 cm soil profile). The multi-year average crop yields vary from 4.8 to 7.4 Mg ha^{-1} for maize and from 3.8 to 6.3 Mg ha^{-1} for wheat, respectively, under the farmers' conventional management practices. Both soil and land use history at the three sites are representative of the HHH plain. The double cropping system of winter wheat and summer maize were adopted at these sites, which is in line with the typical cropping practices in the croplands of the HHH Plain. In general, among these sites, several treatments involving synthetic nitrogen fertilization, manure application and crop residue retention were included in the