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The effect of fertilizer practices on N balance and global warming potential of maize–soybean–wheat rotations in Northeastern China

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ABSTRACT

Long-term agronomic studies are useful to determine cropping system nitrogen (N) use efficiency and the fate of applied fertilizers. We used a subtractive fertilizer experiment incorporating N, phosphorous (P), potassium (K) and swine manure to determine long-term changes in grain yield, soil organic carbon (SOC), total soil nitrogen (N), as well as carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions. The experiment was conducted on a 22-year maize–soybean–wheat rotation in Northeastern China. Crop residues were removed for cooking fuel and forage according to local practices. Five fertilizer treatments were applied annually: control (no fertilizer), NK, NP, NPK, and NPKOM (N, P, K and manure). The NPKOM treatment increased SOC and total soil N by 4.59 and 0.45 Mg ha^{-1}, respectively. In contrast, SOC decreased by 10.6 and 6.64 Mg ha^{-1} in the control and NK treatments, respectively. The NPKOM treatment had an average of 2.9 times more N_2O emissions than the other fertilizer treatments. The cropping system balances for N and SOC, together with fuel use for farming practices and manure handling, were used to calculate the global warming potential (GWP) of the different fertilizer treatments. Due to SOC sequestration, the GWP of the NPKOM treatment (6.77 Mg C equivalent ha^{-1}) was significantly lower than that of both the control (14.4 Mg C equivalent ha^{-1}) and the NK treatment (12.8 Mg C equivalent ha^{-1}). The results suggest that in rainfed agricultural systems in Northeastern China, the application of manure supplemented with NPK can simultaneously achieve higher grain yield and lower GWP compared to mineral fertilizers alone.

1. Introduction

The performance of cropping systems is often based on yield potential, ignoring other criteria such as minimizing global warming potential (GWP) and loss of nutrients to the environment. The input of fertilizers, especially nitrogen (N), has promoted consistent and increasing crop yields; however, its inefficient use has lead to environmental issues such as degraded water quality and increased greenhouse gas (GHG) emissions (Li et al., 2007; Davidson, 2009; Van Groenigen et al., 2010; Yang et al., 2011). Nitrous oxide (N_2O) is a long-lived GHG that accounts for approximately 6% of total anthropogenic greenhouse warming from all sectors (Lashof and Ahuja, 1990; Rodhe, 1990; Mackenzie, 1998). Greenhouse gas emissions and soil C loss can be major components of the net GWP of rainfed agricultural systems, particularly where manure use supplements N inputs (Davidson, 2009). It is therefore prudent to develop practices and crop rotations that increase nutrient use efficiency and lower the GWP while at the same time maintaining crop productivity.

Increasing soil organic carbon (SOC) storage is one approach to lower the GWP of cropping systems (Chirinda et al., 2010). In addition, increases in SOC can also maintain and increase yield potential (Ladha et al., 2005). In agricultural systems, the relationship between changes in SOC and N_2O emissions is typically a major driver of net GWP (Robertson et al., 2000). Nitrous oxide is primarily produced through denitrification and ammonia oxidation (nitrifier nitrification, nitrifier denitrification, and nitrification-coupled denitrification) processes (Wrage et al., 2001; Zhu et al., 2013a). Previous studies on N_2O emissions have shown that these microbial processes are strongly affected by agricultural decisions such as crop rotation, residue management, N application rate and N fertilizer type (Skiba and Smith, 2000; Bouwman et al., 2002; Snyder et al., 2009; Chirinda et al., 2010; Linquist et al., 2012). Managing for maximum yield potential by promoting N use efficiency has been

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Table 1
Total input of N, P and K fertilizer in each crop season and treatment (kg ha^{-1}).

Treatment	Maize			Soybean			Wheat		
	N	P	K	N	P	K	N	P	K
Control	–	–	–	–	–	–	–	–	–
NK	113	–	25	20	–	16	113	–	25
NP	113	20	0	20	23	–	113	20	0
NPK	113	20	25	20	23	16	113	20	25
NPKOM[a]	149	24	79	56	27	70	149	24	79

[a] The amount of N, P and K show in this treatment include manure input of 36 kg ha^{-1} N, 4.4 kg ha^{-1} P and 54 kg ha^{-1} K.

shown to increase SOC and the efficiency of N uptake from soils by crops, thereby providing the potential for avoiding large N_2O emissions (Adviento-Borbe et al., 2007).

The efficient use of N fertilizers has proven to be a major challenge due to factors associated with variable management practices and soil properties, both locally and at larger scales (Ladha et al., 2005; Devkota et al., 2013). Cropping systems that utilize N more efficiently are often characterized by diverse crop rotations, use of cover crops, crop residue management, and prudent use of alternative inputs such as manures, resulting in increased SOC and N storage (Clark et al., 1998; Drinkwater et al., 1998). To assess the GWP of agricultural systems, several factors need to be considered collectively, primarily emission of GHG, but also including net changes in SOC and intrinsic C costs associated with agricultural machinery, manure management, and other inputs such as pesticides.

Rainfed maize–soybean–wheat rotations account for more than half of China's food production (Jia, 1990). To meet the increasing food demand of China's growing population and to alleviate poverty, increasing amounts of mineral fertilizer N are being used to increase crop yield potential. We used a subtractive fertilizer (N, P, K and manure) trial in a 22-year traditional maize–soybean–wheat rotation in the northeast of China to determine N use efficiency, importance of P and K, and the value of manure as a source of N. The effect of the different fertilizer treatments and estimates of GWP were determined to develop a quantitative understanding of N balance, SOC sequestration, GHG emissions and the GWP of rainfed maize–soybean–wheat rotations in China. Our main goal is to make recommendations for optimal fertilizer management practices that sustain maximum yield potential and have a low GWP compared to traditional management practices.

2. Materials and methods

2.1. Site description

The field site is located at the Hailun State Key Agro-ecological Experiment Station, Hailun County, Heilongjiang Province (N47°26′, E126°38′). The location is in the Mollisol region of Northeastern China. The soil texture is a silty clay loam with about 40% clay (Xing et al., 2004). A maize–soybean–wheat rotation using a random design with three replicates was established in 1990 on a 3-year cycle with maize being planted in 1990. The soil properties in 1990 in the top 15 cm were as follows: 28 g kg^{-1} organic C, 2.2 g kg^{-1} total N, 0.7 g kg^{-1} total phosphorus (P), 21 g kg^{-1} total potassium (K) and pH 7.0. The mean annual temperature is 1.5 °C and annual precipitation is 550 mm with 65% occurring during the growing season (June to August) over the last 30 years. The 3-year period from 2006 to 2008 (complete rotation cycle with all crop phases) was used to measure soil N_2O and CO_2 emissions. The period experienced average temperature and precipitation amounts according to the 30-year record.

2.2. Experimental design

Within each replicate of the maize–soybean–wheat rotation, subplots with five fertilizer treatments were established: control (no fertilizer), NP, NK, NPK and NPKOM (fertilizer NPK plus organic fertilizer as swine manure). The subtractive fertilizer trial plots were randomized within the three main treatment plots for a total of 15 plots. Each subplot measured 15 m × 4.2 m. The soybean cultivar was Hefeng 25, and changed to Heinong 35 in 2004. The maize cultivar was Haiyu 6 and wheat cultivar was Longmai 28, which remained unchanged since the beginning of the experiment. The fertilizer application rates were based on local recommendations for cereal crops determined in 1990. The total N, P and K fertilizer input in each crop season and treatment are summarized in Table 1. Fertilizer N, P and K were applied as urea, [$(NH_4)_2HPO_4$] and K_2SO_4, respectively. The decomposed swine manure (OM) contained 150 g C kg^{-1}, 16 g N kg^{-1}, 2.0 g P kg^{-1} and 24 g K kg^{-1}. All inorganic fertilizers were applied as basal fertilizer except N in maize cultivation, for which 63 kg ha^{-1} N was supplied as basal fertilizer and 50 kg ha^{-1} N was supplied as supplemental fertilizer. This supplemental fertilizer in maize was applied at the elongation stage. The OM was applied yearly at 2.25 Mg ha^{-1}, supplying an additional 33 kg N ha^{-1}. The OM was applied by even spreading onto the soil surface by hand followed by immediate incorporation into the soil.

2.3. SOC and total soil N measurements

Composite soil samples were collected every other year before fertilizer application from all experimental plots by homogenizing 20 soil auger borings from the 0 to 15 cm soil depth, representing the plow layer. Total soil C and N were determined on an ELEMENT III CHNSO analyzer (Perkin Elmer, Shelton, CT). The SOC content was estimated after accounting for $CaCO_3$, determined separately as described by Santi et al. (2006).

2.4. N_2O and CO_2 measurements

The N_2O and soil CO_2 emission data collected from 2006 to 2008 were considered typical emission estimates, and it was assumed that after 16 years, the maize–soybean–wheat rotation had reached a relative equilibrium. A static vented chamber method was used to determine fluxes of N_2O and CO_2 (Hutchinson and Mosier, 1981). For N_2O measurements, a PVC chamber base (70 cm × 20 cm) was inserted into the soil about 2 cm deep within the rows of maize, soybean plants, and between the rows in the wheat system. The chamber tops, also PVC, were tightly fitted onto the base by inserting the flange of the chamber top into a water trough at the top edge of the chamber base. The chamber top included a small, silicon-sealed vent for sampling. Gases were sampled twice a week (Monday and Tuesday) during the growing season, and once every 10 days in the non-growing season. To collect a gas sample from the chamber, headspace air was removed by inserting a gas-tight syringe through a septum of the sampling port. For each sample