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Maize yield and soil fertility with combined use of compost and inorganic fertilizers on a calcareous soil on the North China Plain

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ABSTRACT

Excessive N fertilization is a problem in the intensive cropping systems on the North China Plain. Proper N management is essential to maximize N efficiency and sustain agricultural production while minimizing negative impacts on the environment. The aim of the present study was to investigate N dynamics, maize yields and soil fertility in response to short term compost application and straw return vs. inorganic fertilization. A field experiment (2012–2014) was conducted for three years on a calcareous soil in Quzhou county, Heibei province, north China. There were four treatments: unfertilized control (T1), inorganic fertilizer (100% NPK, T2), compost (cattle wastes) + 70% NPK (T3), T3 + wheat straw (T4). No significant differences in biomass accumulation or N uptake among the fertilized treatments were observed across the maize growing season. Compost application for three years tended to increase grain yields particularly in the second and third years, and the average yield increase was approximately 7–15% over T2. Residual N_{min} down the soil profile (1 m) in the compost treatments (T3 and T4) decreased by 50% deeper in the soil (60–100 cm depth) at the maize harvest in 2014. Compared to T2, the compost treatments significantly increased NUE and soil available P and K contents. Correlation analysis indicates that maize yield in 2014 was significantly correlated with soil available P and K and with soil organic carbon (SOC). Overall, straw return did not have a significant influence on any measured parameters in either soil or plant samples. Our results demonstrate that 30% replacement of N fertilizer by compost is an effective nutrient management strategy to maintain N uptake and yield of maize, reduce N loss and also increase soil fertility. A considerable increase in invertase activity in the compost treatments highlights that the critical importance of integrating the management of carbon and nitrogen for sustainable agricultural production in this region of highly intensive production.

1. Introduction

The North China Plain (NCP) is one of the most intensive major grain producing agricultural regions in China where about 35 million ha of crops are cultivated and at least 14 million ha are dominated by the winter wheat-summer maize rotational cropping system (Liu et al., 2013; Michalczyk et al., 2014). The NCP accounts for 50 and 33%, respectively, of the country's total yields of winter wheat and summer maize (Wang et al., 2012). The crop yields and the sustainability of agriculture in this region therefore have great implications for China's food security. The importance of this cropping system on the NCP for Chinese agriculture in the near future has been further emphasized recently due to the increasing human population and a shift in the diet of the Chinese in the future for more livestock produce (Jiang et al., 2006).

The NCP is experiencing the intensification of agricultural production typical of rapid growth in the demand for food by an increasing population and rapid economic development. Historically the soil has had inherent low soil fertility and farmers have traditionally amended the soil with farmyard manure to maintain crop yields. Since 1980 manures have been replaced by synthetic fertilizers because of the lower cost of fertilizers and their transport and application (Yang et al., 2015). Excessive use of fertilizers, and in particular of N, as an 'insurance' for reliable yield and income became a common practice in this region. During the past 30 years (1980–2008), crop yields on the NCP increased by a factor of 2.8 (2200–6200 kg ha^{-1}), grain production by a factor of 2.6 (23–59 million tons) and application rate of chemical fertilizers

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increased by a factor of 5.1 (68–350 kg ha^{-1}) (Pei et al., 2013). The annual total application rate of synthetic N for conventional agricultural practices ranges from 550 to 600 kg N ha^{-1} for the winter wheat–summer maize double cropping system (Zhao et al., 2006), while the minimal soil nitrate-N content needed to achieve maximum grain yields and N uptake was about 180 kg ha^{-1} (Cui et al., 2008b). As a result, the apparent N recovery (ANR) of cereal grain production decreased from 30% to 35% in the 1980s (Yan et al., 2014) and to less than 20% in the 2000s (Cui et al., 2008a). The partial factor productivity from applied N (PFP_N) decreased from 55 kg kg^{-1} in 1978 (Zhu and Chen, 2002) to 30 kg kg^{-1} in 2011 (Jin et al., 2012). Excessive N application leads to environmental pollution in terms of soil acidification (Guo et al., 2010) eutrophication (Zhang et al., 2011), and greenhouse gas emissions and N deposition (Liu et al., 2013; Ju et al., 2009). There is therefore a major challenge to ensure food security while reducing environmental costs in this region.

Recently there has been increasing interest in incorporating manure nutrient management towards sustainable agricultural intensification in China (Chadwick et al., 2015). There is a wealth of data from long-term observation experimental sites in China and in other countries (Ai et al., 2012; Maillard and Angers, 2014) showing that continuous application of NP fertilizer plus organic materials including straw (Lu et al., 2009) and composts (Rasool et al., 2008), significantly increases crop yields and soil quality, particularly soil organic matter (SOM) content (Demelash et al., 2014). For example, a mixed application of inorganic fertilizers and crop residues for 22 years substantially increased soil organic carbon (SOC) by 11% and corn yields by 75% on the NCP (Yang et al., 2015). Previous studies in Henan province on the NCP have shown that SOC increased by about 92% from 4.47 to 8.61 g C g^{-1} after 13 years under long-term combined organic and mineral fertilizer application (Ding et al., 2007). Körschens et al. (2013) found that combined mineral and organic fertilization resulted in a 6% yield benefit compared with mineral fertilizers alone by summarizing the results of 20 European long-term experiments. After five years in an experiment, the yield and SOC in the organic fertilizer treatment increased by 126% and 7%, respectively, compared with the chemical fertilizer treatment (Bedada et al., 2014).

Since the mid-1990s there has been increasing agricultural mechanization, particularly the use of combine harvesters and field straw choppers and local farmers now return straw to the field instead of burning it in situ or using it as a fuel (Zhang et al., 2008). In addition, larger quantities of manure nutrients will be generated over the next 20 years with the increasing demand for livestock produce and changes in dietary preferences towards animal proteins (Chadwick et al., 2015). However, in practice as organic manures may not always be available on site, an important question is whether or not straw can as good as organic manures for the maintenance of soil fertility and high crop yields. It is known that application of organic matter (OM) may take a long time to have a significant influence on soil fertility. Long-term experiments have the advantage of studying changes in soil properties and processes over time (Rasmussen et al., 1998). Similarly, the temporal monitoring of changes in soil nutrients, particularly N, can be important for long-term manure management and may potentially avoid long-term undesirable negative impacts on the environment. Understanding N dynamics associated with short-term compost application and straw return can therefore be instructive for the long-term management of organic resources. The objective of the present study was to monitor temporal N uptake by maize over three years under different N management practices. Crop yields, N efficiency and soil nutrients were compared in current conventional practice and 30% replacement of inorganic N fertilizer by compost or by compost + straw.

2. Materials and methods

2.1. Experimental site

An experiment was carried out for three years (2012–2014) in a summer-maize and winter-wheat double cropping system close to the experimental station of China Agricultural University (36°42′N, 114°54′E, 40 m a.s.l.) in Quzhou county, Heibei province. The soil is classified as a Cambisol with a silt loam texture according to IUSS Working Group WRB (2007). It has the following properties (Table 1): pH 7.24 (H_2O), 0.90 g kg^{-1} total N, 13.7 g kg^{-1} OM, 12.01 mg kg^{-1} Olsen-P, and 176.2 mg kg^{-1} available K (NH_4OAc-K). The climate is considered to be monsoon associated with steppe, with mean temperature and annual precipitation of 13.2 °C and 494 mm, respectively (1980–2011). The precipitation during the wheat and maize growing seasons was 132 mm and 367 mm in 2012. The corresponding values were 107 mm and 327 mm in 2013, and 112 mm and 274 mm in 2014.

2.2. Fertilization and treatments

The experiment was set up in 2012 and data were collected over three consecutive years (2012–2014). The experiment comprised four treatments (Table 2): (1) T1 as control, the soil received no fertilizer; (2) T2 inorganic NPK, the N application rates were based on conventional farming practice (FCP) with 250 kg N ha^{-1} for maize (100 kg N ha^{-1} before planting and 150 kg N ha^{-1} at V12 stage), PK rates of 45 kg P_2O_5 ha^{-1} and 45 kg K_2O ha^{-1}, the fertilizers broadcast before sowing and urea, super-phosphate and potassium sulphate used as sources of N, P and K; (3) T3 compost + 70% NPK, the NPK fertilizer replaced by a commercial compost (30% of fertilizer N replaced) and the compost mainly derived from cow wastes, compost moisture content 30% containing 33.2% C, 2.0% N, 0.8% P and 0.7% K (Yong et al., 2011), compost application rate 3000 kg ha^{-1}; and (4) T4 compost + 70% NPK + straw return, the wheat straw chopped to about 2-4 cm when wheat crops were harvested. The wheat straw rates for maize in 2012, 2013 and 2014 were 7, 6, and 5 Mg ha^{-1} respectively due to yield variations among different years. For T3 and T4 the compost was applied before planting and the 70% NPK was applied as in T2. The N content of wheat straw for each year was shown in Table 2. The contents of total P and K in 2012 were 9 kg ha^{-1} and 182 kg ha^{-1} respectively. The corresponding values were 2 kg ha^{-1} and 102 kg ha^{-1} in 2013, and 1 kg ha^{-1} and 129 kg ha^{-1} in 2014. Each treatment had four replicates randomly distributed in blocks with a plot size of 5 × 10 m.

The summer maize (cv. ‘Zheng dan 958′) was sown at a density of ca. 63,000 seeds ha^{-1} with a row spacing of 60 cm and intra-row spacing of 27 cm in the middle of June and was harvested in early October. All of the basic fertilizers were broadcast and incorporated into the upper 20 cm of the soil profile by rotary tillage prior to sowing. The management of herbicides, insecticides and irrigation was based on local conventional farming practice.

Table 1
Selected physicochemical properties of the soil at depths 0–20, 20–40 and 40–60 cm prior to the start of the experiment.

Soil depth (cm)	pH	TN (%)	TC (%)	AK (mg kg^{-1})	AP (mg kg^{-1})	SOM (g kg^{-1})
0–20	7.24	0.09	1.50	176.22	12.01	13.7
20–40	7.21	0.07	1.35	150.00	6.95	10.2
40–60	7.23	0.0	1.25	145.00	1.91	6.8

*TN, total nitrogen; TC, total carbon; AK, available potassium; AP, available phosphorus; SOM, soil organic matter.