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RESEARCH ARTICLE

Chemical fertilizers could be completely replaced by manure to maintain high maize yield and soil organic carbon (SOC) when SOC reaches a threshold in the Northeast China Plain

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Abstract

The combined use of chemical and organic fertilizers is considered a good method to sustain high crop yield and enhance soil organic carbon (SOC), but it is still unclear when and to what extent chemical fertilizers could be replaced by organic fertilizers. We selected a long-term soil fertility experiment in Gongzhuling, Northeast China Plain to examine the temporal dynamics of crop yield and SOC in response to chemical nitrogen, phosphorus, and potassium (NPK) fertilizers and manure, applied both individually and in combination, over the course of three decades (1980–2010). We aimed to test 1) which fertilizer application is the best for increasing both maize yield and SOC in this region, and 2) whether chemical fertilizers can be replaced by manure to maintain high maize yield and enhance SOC, and if so, when this replacement should be implemented. We observed that NPK fertilizers induced a considerable increase in maize yield in the first 12 years after the initiation of the experiment, but manure addition did not. In the following years, the addition of both NPK fertilizers and manure led to an increase in maize yield. SOC increased considerably in treatments with manure but remained the same or even declined with NPK treatments. The increase in maize yield induced by NPK fertilizers alone declined greatly with increasing SOC, whereas the combination of NPK and manure resulted in high maize yield and a remarkable improvement in SOC stock. Based on these results we suggested that NPK fertilizers could be at least partially replaced by manure to sustain high maize yield after SOC stock has reached 41.96 Mg C ha^{-1} in the Northeast China Plain and highly recommend the combined application of chemical fertilizers and manure (i.e., 60 Mg ha^{-1}).

Keywords: long-term fertilization, manure, maize yield, soil organic carbon, Northeast China

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1. Introduction

The world is facing both a growing demand for food and deteriorating agricultural soils (Godfray *et al.* 2010; Godfray and Garnett 2014). To address this issue, it is urgent to improve soil organic carbon (SOC), which is a ubiquitous soil

quality indicator and key to maintaining soil fertility in order to sustain high crop yields (Martius *et al.* 2001; Bationo *et al.* 2007; Pan *et al.* 2009; Miao *et al.* 2015; Tian *et al.* 2015). Optimizing the application of chemical and organic fertilizers to increase both crop yield and SOC in cropland is of high priority, but it is still unclear how to achieve this goal, as the responses of crop yields and SOC to the application of chemical and organic fertilizers differ depending on climate, soil type, fertilization history, and existing soil carbon and nutrients (Diacono *et al.* 2010; Chivenge *et al.* 2011; Ding *et al.* 2015; Zhao *et al.* 2015).

The application of chemical fertilizer usually improves crop yield in the short-term (Zhang H M 2009), but it barely maintains and even decreases SOC and has negative environmental impacts, such as acidification and nutrient loss (Tarkalson *et al.* 2006; Cai *et al.* 2015). Organic fertilizer application is a widely accepted strategy to sustain or improve crop yield and SOC stock, and has significant effects on climate change mitigation (Manna *et al.* 2007; Lu *et al.* 2015) and also soil fertility sustainability (Harris 2009; Liu *et al.* 2014). Among the types of organic fertilizer applications, manure amendments are favored for increasing SOC stock and supplying nutrients to crops because they have higher SOC sequestration efficiency (Wang *et al.* 2016) and supply more available nutrients to crops (Zhu *et al.* 2007; Zhang W J 2009). However, increases in crop yields are either marginal or increase at a low rate when organic fertilizers are used alone (Manna *et al.* 2005; Seufert *et al.* 2012; Wei *et al.* 2016). Alternatively, the combined use of chemical and organic fertilizers has been proposed to meet the requirements of sustaining crop yield and enhancing SOC at a reasonable rate (Kong *et al.* 2014). The key question is when and to what extent chemical fertilizers should be replaced by organic fertilizers to maintain high crop yield without reducing SOC.

We therefore need to know the temporal dynamics of crop yield and SOC when chemical and organic fertilizers are applied individually and in combination, especially over the long term. Because it takes time for organic amendments in cropland to impact soil properties (e.g., SOC) (Manna *et al.* 2005; Yan and Gong 2010), and the slow release of nutrients from organic fertilizers that is responsible for increases in crop yield cannot be detected in the short-term (Pan *et al.* 2009), mid- and long-term soil fertility experiments are ideal to test the effects of organic and chemical fertilization on crop yield and SOC. Although there are plenty of studies about crop yield and SOC changes under chemical and organic fertilizer application in short-term period (Majumder *et al.* 2008; Aye *et al.* 2009; Liu *et al.* 2010), there are few studies in long-term period as we report here.

In this study, we selected the long-term experiment site in Gongzhuling, Northeast China Plain as our study site. This experiment was initiated in 1980 with a staple crop of maize (*Zea mays cv*. Jidan 101 from 1980 to 1989 and Jidan 209 from 1990 to 2007). The tested black soil is Luvic Phaeozems (Zhang W J 2009), which is a typical soil in Northeast China. There are 44.52×10^5 ha of black soil in Northeast China, accounting for 21.93% of the total arable land area in China (Gao and Wang 2011). The area of land used for maize cropping in Northeast China accounted for 30.82% of the entire maize planting area in China (Gao and Wang 2011). However, after continuous maize cropping for approximately 150 years, the SOC decline in black soils ranges from 1.07 to 22.0 g kg^{-1} (e.g., Heilongjiang Province), and this is likely to threaten maize yield in the near future. In order to restore SOC and to maintain high crop yield in arable land in Northeast China, it is vital to determine the optimal application of chemical and organic fertilizers (Ling *et al.* 2014; Dou *et al.* 2016). The objective of this study is to test: i) which fertilizer application best increases both maize yield and SOC in Northeast China, and ii) whether chemical fertilizers can be replaced by organic fertilizers to maintain high maize yield and increase SOC, and if so, when this replacement should be implemented.

2. Materials and methods

2.1. Description of the experimental site

The long-term (1980–2010) experimental site is located at Gongzhuling, Jilin Province, China (42°57′N, 148°57′E). The site is 220 m above sea level and has a cool-temperate and semi-humid climate. The annual mean precipitation is 525 mm with 60–70% of precipitation occurring in June–September, the annual total evaporation is 1 400 mm, and the annual mean temperature is 4.5°C. Prior to the establishment of the experimental site, the land was used for cereal cultivation for more than 50 years. The soil is Luvic Phaeozems (Zhang W J 2009), consisting of 31% clay, 30% silt, and 39% sand. Before the initiation of experiments in 1980, the soil properties at 0–20 cm depth were as follows: pH 7.6, a bulk density (BD) of 1.19 g cm^{-3}, an organic carbon (C) level of 13.5 g kg^{-1}, total nitrogen (N), phosphorus (P), and potassium (K) levels of 1.53, 1.41, and 23.1 g kg^{-1}, respectively, and available N, Olsen-P, and K levels of 102.0, 20.6, and 160.0 mg kg^{-1}, respectively.

2.2. Experimental design

At the Gongzhuling site we selected six fertilization treatments: (1) no fertilization as the control (CK), (2) application of chemical N, P, and K fertilizers (NPK), (3) farmyard manure addition at ~30 t fresh weight ha^{-1} yr^{-1} (M30), (4) farmyard manure addition at ~60 t fresh weight ha^{-1} yr^{-1} (M60), (5)