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Effect of Long-Term Fertilization on Soil Productivity on the North China Plain

WANG Jing-Yan[1,2], YAN Xiao-Yuan[2] and GONG Wei[1,2,*]

[1] *Sichuan Provincial Key Laboratory of Ecological Forestry Engineering, Sichuan Agricultural University, Ya'an 625014 (China)*
[2] *State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, Nanjing 210008 (China)*

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ABSTRACT

Soil productivity is the ability of a soil, in its normal environment, to support plant growth and can be evaluated with respect to crop production in unfertilized soil within the agricultural ecosystem. Both soil productivity and fertilizer applications affect crop yields. A long-term experiment with a winter wheat-summer maize rotation was established in 1989 in a field of the Fengqiu State Key Agro-Ecological Experimental Station, a region typical of the North China Plain, including seven treatments: 1) a balanced application of NPK chemical fertilizers (NPK); 2) application of organic fertilizer (OM); 3) application of 50% organic fertilizer and 50% NPK chemical fertilizers (1/2OMN); 4) application of NP chemical fertilizers (NP); 5) application of PK chemical fertilizer (PK); 6) application of NK chemical fertilizers (NK); and 7) unfertilized control (CK). To investigate the effects of fertilization practices on soil productivity, further pot tests were conducted in 2007–2008 using soil samples from the different fertilization treatments of the long-term field experiment. The soil sample of each treatment of the long-term experiment was divided into three pots to grow wheat: with no fertilization ($\mathrm{Pot_{unf}}$), with balanced NPK fertilization ($\mathrm{Pot_{NPK}}$), and with the same fertilizer(s) of the long-term field experiment ($\mathrm{Pot_{ori}}$). The fertilized soils of the field experiment used in all the pot tests showed a higher wheat grain yield and higher nutrient uptake levels than the unfertilized soil. Soil productivity of the treatments of the field experiment after 18 years of continuous fertilizer applications were ranked in the order of OM > 1/2OMN > NPK > NP > PK > NK > CK. The contribution of soil productivity of the different treatments of the field experiment to the wheat grain yield of $\mathrm{Pot_{ori}}$ was 36.0%–76.7%, with the PK and NK treatments being higher than the OM, 1/2OMN, NPK, and NP treatments since the soil in this area was deficient in N and P and rich in K. Wheat grain yields of $\mathrm{Pot_{NPK}}$ were higher than those of $\mathrm{Pot_{ori}}$ and $\mathrm{Pot_{unf}}$. The N, P, and K use efficiencies were higher in $\mathrm{Pot_{NPK}}$ than $\mathrm{Pot_{ori}}$ and significantly positively correlated with wheat grain yield. Soil organic matter could be a better predictor of soil productivity because it correlated more strongly than other nutrients with the wheat grain yield of $\mathrm{Pot_{unf}}$. Wheat yields of $\mathrm{Pot_{NPK}}$ showed a similar trend to those of $\mathrm{Pot_{unf}}$, indicating that soil productivity improvement was essential for a further increase in crop yield. The long-term applications of both organic and chemical fertilizers were capable of increasing soil productivity on the North China Plain, but the former was more effective than the latter. The balanced application of NPK chemical fertilizers not only increased soil productivity, but also largely increased crop yields, especially in soils with lower productivity. Thus, such an approach should be a feasible practice for the sustainable use of agricultural soils on the North China Plain, particularly when taking into account crop yields, labor costs, and the limited availability of organic fertilizers.

Key Words: balanced fertilization, chemical fertilizer, crop yield, soil fertility, nutrient use efficiency, organic fertilizer, soil organic matter

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The North China Plain is one of the major grain-producing regions in China, with an area of 178 700 km^2, of which 88 500 km^2 is farmland (Lin *et al.*, 2000). It is a highly productive agricultural area with a main cropping system of winter wheat and summer maize, and is often referred to as "China's breadbasket" (Shi, 2003). Insufficient farmland to cope with the overpopulation is a problem in China, and will continue to get worse during the course of the 21st century (Yang *et al.*, 2003); thus, the sustainable use of agricultural soils in this area could be crucial in terms of China's food security. The traditional organic agricultural methods of this region dating back thousands of years have been changing since the 1980s, with more chemical fertilizers and less organic fertilizers being applied due to increased accessibility to chemical fertilizers and rising labor costs (Wang and Lu, 1998). However, little information is available on the response of soil productivity to these changes in fertilization practices on the North China Plain.

Soil organic matter (SOM) is a reservoir of carbon (C) in the biosphere as well as a reservoir of nutrients

*Corresponding author. E-mail: gongwei@sicau.edu.cn.

in soil, and contains nearly all nutrients necessary for plant growth (Gong *et al.*, 2008). The SOM in farmland soils has been recognized as an important indicator of soil productivity (Yang *et al.*, 2003), and thus increasing SOM levels through farming practices is essential for improving soil productivity (Bhattacharyya *et al.*, 2010). An overall increase in the SOM content has been found in China's agricultural soils in the past 30 years by direct measurements, with the largest increase being in soils of the North China Plain (Yan *et al.*, 2011). The results of previous long-term fertilization experiments have shown that both organic and chemical fertilizers are the likely reason for the increased SOM content and crop yields in this region since the 1980s (Gong *et al.*, 2009; Zhang, H. M. *et al.*, 2009). Gong *et al.* (2012) suggested that the resulting high crop yields lead to high crop inputs to soil in the form of residues and exudates, such that plant SOM derivation overwhelms SOM decomposition.

The crop yield of each season in long-term experiments is the result of soil productivity and fertilizer application during the crop growing season. It is difficult to differentiate the effects of soil productivity and fertilizer application based on the crop yield data because both the soil productivity and fertilizer levels differ among the treatments of long-term experiments. To solve this problem, we conducted pot tests by growing wheat in soils from different fertilization treatments of a long-term field experiment, and investigated how soil productivity had been affected by 18 years of organic and chemical fertilizer application under a winter wheat-summer maize cropping system on the North China Plain. Our expectation was that the results would help in selecting optimal fertilization management practices for soil productivity improvement and the sustainable use of agricultural soils.

MATERIALS AND METHODS

Study area

This study was conducted at the Fengqiu State Key Agro-Ecological Experimental Station, a region typical of the North China Plain (Gong *et al.*, 2009), in Fengqiu County, Henan Province, China (35°00′ N, 114°24′ E), with a winter wheat-summer maize rotation, which is the main cropping system of the North China Plain. The 30-year mean annual temperature is 13.9 °C, and the lowest and highest mean monthly temperatures are −1.0 °C in January and 27.2 °C in July, respectively. The mean annual precipitation is 615 mm, two-thirds of which falls between June and September.

Long-term field experiment

A long-term experiment was established in 1989 in a field of the study site. The field had been under a winter wheat-summer maize rotation for many years and, to achieve homogenous conditions, was not fertilized for three years before the start of the experiment in September 1989. The fertility of the soil, an Aquic Inceptisol (USDA Soil Taxonomy), was low: the 0–20 cm soil layer contained 4.42 g kg^{-1} organic C, 0.45 g kg^{-1} total N, 0.50 g kg^{-1} total P, 18.6 g kg^{-1} total K, 9.51 mg kg^{-1} inorganic N, 1.9 mg kg^{-1} available P (Olsen-P), and 78.8 mg kg^{-1} available K.

The long-term field experiment included seven fertilization treatments with a winter wheat-summer maize rotation: 1) a balanced application of N, P, and K chemical fertilizers (150 kg N ha^{-1} + 32.7 kg P ha^{-1} + 124.5 kg K ha^{-1} for wheat and 150 kg N ha^{-1} + 26.2 kg P ha^{-1} + 124.5 kg K ha^{-1} for maize) (NPK); 2) application of organic fertilizer (equivalent to 150 kg N ha^{-1}) with additional chemical fertilizers applied to make the total P and K input equal to that of the NPK treatment) (OM); 3) application of half the amounts of the chemical fertilizers applied in the NPK treatment and half the amounts of the organic and chemical fertilizers applied in the OM treatment (1/2OMN); 4) application of N and P chemical fertilizers (150 kg N ha^{-1} + 32.7 kg P ha^{-1} for wheat and 150 kg N ha^{-1} + 26.2 kg P ha^{-1} for maize) (NP); 5) application of P and K chemical fertilizers (32.7 kg P ha^{-1} + 124.5 kg K ha^{-1} for wheat and 26.2 kg P ha^{-1} + 124.5 kg K ha^{-1} for maize) (PK); 6) application of N and K chemical fertilizers (150 kg N ha^{-1} + 124.5 kg K ha^{-1} for both wheat and maize) (NK); and 7) unfertilized control (CK). Each treatment had four replicates and the 28 plots each of 9.5 m × 5 m were arranged in a randomized block design (Gong *et al.*, 2009). The above-ground biomass in each plot was removed, except the crop stubble after harvest of each crop.

The N, P, and K chemical fertilizers used are urea, calcium superphosphate, and potassium sulfate, respectively. Urea, totaling 150 kg N ha^{-1}, is applied in two splits: for maize, two-fifths (60 kg N ha^{-1}) as basal fertilizer and the remaining three-fifths (90 kg N ha^{-1}) as supplemental fertilizer; for wheat, three-fifths (90 kg N ha^{-1}) as basal fertilizer and the remaining two-fifths (60 kg N ha^{-1}) as supplemental fertilizer. All P, K, and organic fertilizers were applied as basal fertilizers. The organic fertilizer was made from wheat straw, oil rapeseed cake, and cottonseed cake after composting. All basal fertilizers were evenly spread onto the soil sur-