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Combined Applications of Nitrogen and Phosphorus Fertilizers with Manure Increase Maize Yield and Nutrient Uptake *via* Stimulating Root Growth in a Long-Term Experiment

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ABSTRACT

Imbalanced application of nitrogen (N) and phosphorus (P) fertilizers can result in reduced crop yield, low nutrient use efficiency, and high loss of nutrients and soil nitrate nitrogen (NO_3^--N) accumulation decreases when N is applied with P and/or manure; however, the effect of applications of N with P and/or manure on root growth and distribution in the soil profile is not fully understood. The aim of this study was to investigate the combined effects of different N and P fertilizer application rates with or without manure on maize (*Zea mays* L.) yield, N uptake, root growth, apparent N surplus, Olsen-P concentration, and mineral N (N_{min}) accumulation in a fluvo-aquic calcareous soil from a long-term (28-year) experiment. The experiment comprised twelve combinations of chemical N and P fertilizers, either with or without chicken manure, as treatments in four replicates. The yield of maize grain was 82% higher, the N uptake 100% higher, and the N_{min} accumulation 39% lower in the treatments with combined N and P in comparison to N fertilizer only. The maize root length density in the 30–60 cm layer was three times greater in the treatments with N and P fertilizers than with N fertilizer only. Manure addition increased maize yield by 50% and N uptake by 43%, and reduced N_{min} (mostly NO_3^--N) accumulation in the soil by 46%. The long-term application of manure and P fertilizer resulted in significant increases in soil Olsen-P concentration when no N fertilizer was applied. Manure application reduced the apparent N surplus for all treatments. These results suggest that combined N and P fertilizer applications could enhance maize grain yield and nutrient uptake *via* stimulating root growth, leading to reduced accumulation of potentially leachable NO_3^--N in soil, and manure application was a practical way to improve degraded soils in China and the rest of the world.

Key Words: apparent N surplus, degraded soils, chemical fertilizers, nitrate nitrogen, root length density, soil mineral N, soil Olson-P

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INTRODUCTION

Nitrogen (N) fertilizer application is usually required for maximizing crop yields. However, less than half of the fertilizer N applied in China is taken up by crops; the rest is largely lost to the environment as gas emissions (NH_3, NO, N_2O and N_2) or in leached forms (NH_4^+ and NO_3^-) (Liu *et al.*, 2013). For example, the average nitrate nitrogen (NO_3^--N) concentrations in the 0–400 cm soil profile have been measured to be 1 230 and 459 kg NO_3^--N ha^{-1} in vegetable fields and winter wheat-summer maize rotation fields, respectively (Fan *et al.* 2010). This accumulated mineral N is readily leached from soils, potentially contaminating surface and groundwater bodies (Zhang *et al.*, 2013a, b). The pollution of surface and groundwater resulting from the over-application and subsequent leaching of fertilizer N has become a worldwide concern (Ju *et al.*, 2009; Good and Beatty, 2011). In a study of 600 groundwater samples from a typical agricultural region in China by Zhang *et al.* (1996), 45 samples exceeded the European Union (EU) Nitrates Directive (Directive 91/676/EEC) limit of 11.3 mg NO_3^--N L^{-1} for drinking water (Council of European Communities, 1980).

Root length density plays an important role in de-

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termining the ability of a plant to acquire nutrients, especially under conditions of limited nutrient availability (Ryser and Lambers, 1995). Root proliferation is important for plant in capturing N from organic sources, in interspecific competition, and in competition with microbes (Hodge, 2004), although the correlations between N captured from simple N sources, such as NO_3^--N, and root length densities are often weak (Fitter *et al.*, 2002). However, in some cases strong relationships are found, as demonstrated by Sapkota *et al.* (2012), who showed that the rate of soil N depletion is highly correlated with the size of the rooting system of fodder radish. To maximize N capture, an effectively competing root system must rapidly unregulate inflow and then increase root growth (Robinson *et al.*, 1999).

In addition to chemical fertilizers, manure is an important source of nutrients for agricultural production in China. Application of manure helps maintain the soil nutrient balance, improves soil structure and moisture-holding capacity, and is more beneficial for environmental protection compared with the application of chemical fertilizers alone (Reganold, 1995; Conacher and Conacher, 1998).

Previous studies have shown that soil NO_3^--N accumulation decreases when N is applied in combination with phosphorus (P) and/or manure (Tong *et al.*, 1997; Hao *et al.*, 2005), but whether this effect is due to enhanced nutrient uptake *via* stimulating root growth and distribution in the soil profile is not well known. We hypothesize that N and P combined with manure stimulates root growth and distribution in the soil, resulting in increased nutrient uptake and crop yield and consequently decreased NO_3^--N accumulation in soil. The main goal of this study was to determine how different combinations of N and P either with or without manure affect root growth and distribution in the soil profile, crop yield, and accumulation of potentially leachable NO_3^--N in the upper 100 cm of a fluvo-aquic calcareous soil in a long-term experiment.

MATERIALS AND METHODS

Long-term experiment

A long-term experiment was initiated in 1984 under a maize cropping system at the Changping Experimental Station of China Agricultural University in Beijing, China (40° N, 116° E). The experiment was a split-plot factorial design comprising 12 different combinations of N and/or P with or without chicken manure (M) as treatments in 4 replications. Application rates of N and P were as follows: zero N (N0), 135 kg N ha^{-1} year^{-1} (N1), and 270 kg N ha^{-1} year^{-1} (N2); zero P (P0) and 67.5 kg P_2O_5 ha^{-1} year^{-1} (P1). In 2009, because of urban expansion in Beijing, an intact soil monolith (2 m × 1 m × 1 m, length × width × depth) from each one of the 48 plots in the long-term experiment was moved into a concrete-lined facility in the Shangzhuang Experimental Station of China Agricultural University (5 km away from the Changping Experimental Station with similar soil and climatic condition) by truck and crane without disturbing the soil profile structure. The experiment continued on the newly established plots.

The soil type of the experimental field was a calcareous alluvial fluvo-aquic soil with a silty loam texture. The initial soil properties before the initiation of the long-term experiment were: pH (H_2O), 8.2; total N, 0.71 g kg^{-1}; Olsen-P, 6.1 mg kg^{-1}; NH_4OAc-extractable K, 114 mg kg^{-1} (at a sufficient level in the given calcareous soil); organic matter, 13.1 g kg^{-1} (Guo *et al.*, 1998). The soil properties in the treatment of N0 plus P0 at the beginning of 2011 were: pH (H_2O), 8.2; total N, 0.71 g kg^{-1}; Olsen-P, 2.6 mg kg^{-1}; NH_4OAc-extractable K, 101.3 mg kg^{-1} (at a sufficient level in the given calcareous soil); organic matter, 10.3 g kg^{-1}. Mean annual temperature and rainfall at the study site were 13 °C and 699 mm, respectively.

A maize (*Zea mays* L.) hybrid, ZD958, was used in the long-term experiment. The hybrid ZD958 was developed by the Henan Academy of Agricultural Science, Henan Province, China, in 1996. Maize was sown on May 12, 2011 and April 27, 2012. The plots were over-seeded with hand and seedlings were thinned to 20 plants in each plot. The plot size was 2 m × 1 m and the distances between rows and plants were 45 and 30 cm, respectively (Zhang *et al.*, 2012). Guard rows were planted on each side of the plots. Flooding irrigation was used to maintain the soil water content above 75% of field capacity (Zhang *et al.*, 2012). Grain yields were determined by harvesting the whole area of each plot on September 27, 2011 and September 15, 2012.

Nitrogen fertilizer was applied as urea, 60% of which was applied as base fertilizer and the rest was top-dressed at jointing stage (42 d after sowing). A single application of P fertilizer was applied as triple superphosphate ($Ca(H_2PO_4)_2 \cdot H_2O$) and mixed into the top 15 cm of the soil before sowing. No K fertilizer was applied because the amount of extractable K in the soil was deemed sufficient for optimal maize growth based on soil analysis and there were no observed symptoms of K deficiency.

Manure was applied at a rate of 7 500 kg ha^{-1} year^{-1} (equivalent to 1.5 kg plot^{-1} year^{-1}). After digestion with H_2SO_4-H_2O_2, the manure was analyzed for N using the Kjeldahl method (Nelson and Som-