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Improving crop yields, nitrogen use efficiencies, and profits by using mixtures of coated controlled-released and uncoated urea in a wheat-maize system

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ABSTRACT

The economic benefits of using controlled-release urea (CRU) on wheat and maize depend on costs and grain yields. Delays in the release of nitrogen (N) from CRUs can limit the availability of early season N and crop growth. Because of its high cost, the use of CRUs for wheat and maize production by commercial growers is very limited. We investigated the effects of a mixture of CRU and uncoated urea (N ratios 7:3, respectively) on crop yields, economic benefits, N budgets, and soil fertility in a wheat-maize rotation system over an 8-year period in Shandong Province, China. Annually, the mixture was applied at 270 kg N ha^{-1} (Mix 1), 540 kg N ha^{-1} (Mix 2), and 810 kg N ha^{-1} (Mix 3). Uncoated urea treatments were simultaneously applied at 540 kg N ha^{-1} (Urea 2) and 810 kg N ha^{-1} (Urea 3). The N release characteristics of these mixtures under field condition were synchronized with N requirements of the wheat and maize crops during their entire growth periods. Applying the mixture increased grain yields of wheat and maize by 8.2–11.9% and 6.8-9.8%, respectively, compared with treatments of monotypic, uncoated urea. Mean N use efficiencies were increased by 35.7–37.6% and 13.2–14.3% for wheat and maize, respectively, and annual net profits increased 15.4–21.8%, compared with uncoated urea treatments at the same rates of N application. Considering the N budget, apparent N losses were increased with higher N application rates, and applying the mixture significantly reduced N losses compared with monotypic urea. Regardless of application rate, the mixed urea treatments reduced the leaching of N in the soil profile by augmenting NO_3^--N and NH_4^+-N contents at the 0–40 cm soil depth and reduced the leaching of NO_3^--N into deeper soil layers. The pH of the surface soil was also lowered and exchangeable Ca^{2+} and Mg^{2+} were reduced by the long-term application of monotypic urea. In conclusion, applying the mixture of CRU and uncoated urea is recommended for sustainable increases in crops yields, maintaining soil fertility, reduction of N leaching, and increased net profits.

1. Introduction

Wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) are among the most important food crops and are commonly used in crop rotation systems worldwide (Duan et al., 2014). An example is the rotation of winter wheat with summer maize, which is the main rotation system used in the North China Plain, where it occurs on more than 14 million ha (Editing Committee of the China Agriculture Yearbook, 2013). This area accounts for more than 50% of the annual wheat production and about 33% of the annual maize production in China (Wang et al., 2012). Over the last two decades, excessive quantities of nitrogen (N) fertilizer have been used in the

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North China Plain attempting to increase productivity in wheat-maize rotation systems (Liu et al., 2003). The extra N applied to achieve the maximum yield inevitably has caused land, water, and air quality deterioration through leaching and runoff; eutrophication; and gaseous emissions (Vitousek et al., 2009; Dawson and Hilton, 2011). The environmental effects of reactive N in China have been evident (Zhu and Chen, 2002), but the trend of increasing application of N has yet to be reversed. Hence, there is a need to reduce the losses of reactive N and to improve the N use efficiencies (NUEs) in agricultural systems (Galloway et al., 2008; Chien et al., 2009).

Effective N management can improve NUEs, and involves selecting a combination of application rate, source, timing, and placement of fertilizers that improve N availability as crop demand increases (Cui et al., 2010; Nash et al., 2013a). One of the best management practices for uncoated urea is to apply the fertilizers at different times to coincide with different growth stages of crops. Generally, the resulting extra (and unnecessary) fertilizer is expensive, labor-intensive, and operationally difficult to add (Patil et al., 2010). Alternatively, controlled-release urea (CRU) was designed to release nutrients into the soil solution at rates which closely match the N demands of crops, which maximizes NUEs and reduces N losses (Shaviv, 2001).

Many studies have found that applying CRUs significantly increased NUEs and yields of crops (Geng et al., 2016; Haderlein et al., 2001). According to Yang et al. (2011) and Nash et al. (2013b) CRUs have increased wheat and maize grain yields through prolonged releases of soil N and thus met the N requirements for these crops over extended periods. Moreover, rates of N application and numbers of applications often can be reduced during a growing season, which also saves labor costs. However, the manufacturing costs for sulfur- or resin-coated urea are at least 2–4 times those of conventional mineral N fertilizers (Shaviv, 2001), and despite being proposed, a government policy to subsidize fertilizer costs has yet to be materialized. Hence, the present cost-to-benefit ratio prevents the wide use of CRU fertilizers for general cereal production, but this is not the case with non-agricultural markets or high-value crops. A better management strategy is therefore needed for employing CRUs in crop production systems.

Reincorporating crop debris into the fields helps to sustain soil productivity (Singh et al., 2004) and is therefore highly recommended for China and elsewhere. However, retention of additional crop debris also results in undesirable side effects, such as short-term N immobilization and rapid moisture loss (Kong, 2014). According to Shaukat et al. (2011), increased retention of crop debris led to a higher soil C/N ratio, which lowered the decomposition rate and caused a net immobilization of N. Alijani et al. (2013) recommended the application of inorganic N to amend the C/N ratio to a level more conducive to microbial activity. Compared with uncoated urea, yield losses have resulted from using CRUs that were attributable to delayed release of N from fertilizer granules. This limited the early season N availability and crop growth, such as in maize with its high N demand (Grant et al., 2012). Hence, the N fertilizer used in the present study was a mixture of CRU and uncoated urea with an N ratio of 7:3, respectively. We hypothesized that the uncoated urea in the mix would amend the soil to the appropriate range of C/N ratios and supply the N required early in the growing season, while the CRU would delay N release until later in the season.

According to Grant et al. (2012), N from nitrate was not adsorbed onto the soil particles but was free in the soil solution. This reduced the time that inorganic N remained in the soil before crop uptake, which lowered the N losses while increasing NUEs (Grant et al., 2012). Many studies have shown that residual levels of soil nitrates have increased sharply when N fertilizer application rates greatly exceeding the crop requirements. This resulted in a "saturation point", beyond which adding more fertilizer led to reduced fertilizer use efficiency, and the corresponding crop yields did not increase (Barton and Colmer, 2006). Jia et al. (2014) noted that rates of N leaching from winter wheat crops were lower than from summer maize in a rotation system involving winter wheat and summer maize in the North China Plain. Therefore, the present study attempted to investigate the N leaching from fields of summer maize under different N fertilizer treatments.

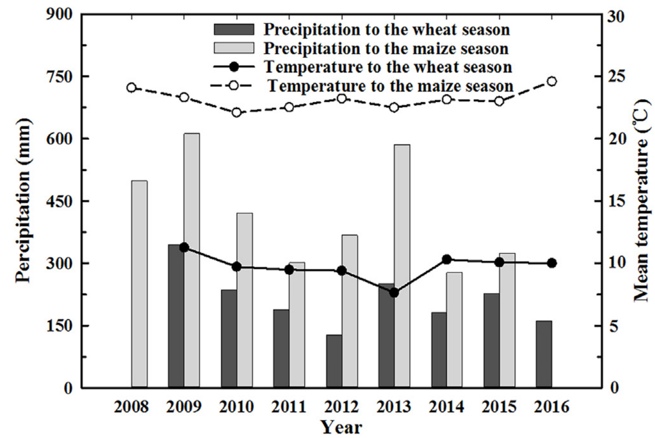

Fig. 1. Mean soil temperature (10 cm depth) and total precipitation in each growing season for wheat and maize (2008–2016).

Long-term fertilization experiments can help identify important soil fertility problems (Chinnadurai et al., 2014). Several long-term field experiments have been performed to determine changes in the sustainability of crop production and the physical, chemical, and biological properties of soils (Hati et al., 2008; Manna et al., 2005; Chu et al., 2007). However, all these studies focused on the effects of uncoated urea, organic fertilizer, or combining mineral and farmyard manures on crop yields (Yang et al., 2006). Few reports have addressed the long-term effects of mixing CRU and urea on crop yields and on soil chemistry. Hence, the primary objectives of the present study were (i) To evaluate the effectiveness of using mixtures of CRU and urea on crop yields; (ii) To concurrently perform an economic analysis; (iii) To examine the effects of long-term application of CRU mixed with urea on the soil fertility and N budget in a wheat-maize rotation system. The results will provide a basis for fertilizer innovation, which involves sustainable, highly efficient fertilizers and application techniques.

2. Materials and methods

2.1. Study site and materials

The experiment was conducted from June 2008 to June 2016 in Huantai County, Shandong Province, China (117°59′21″ E, 36°57′75″ N) with mean air temperatures and precipitation recorded by an automatic meteorological station near the experimental plots (Fig. 1). The crops grown in rotation included wheat (T. *aestivum* 'Jimai 22′) and maize (Z. *mays* 'Zhengdan 958′), which are widely planted cultivars in the North China Plain. The soil type of experimental site was classified as Carbonatic Ochri-Aquic Cambosols according to the Chinese Soil Taxonomy (CRGCST, 2001). At the experimental site just before planting in June 2008, the top soil layer (0–20 cm) had a pH of 8.35, 1:2.5 soil to water ratio, 0.81 g kg^{-1} total N content, 18.26 g kg^{-1} organic matter content, 5.0 mg kg^{-1} NO_3^--N content, 4.1 mg kg^{-1} NH_4^+-N content, 9.2 mg kg^{-1} in available phosphorus, 112.5 mg kg^{-1} in available potassium, and 26.4 cmol kg^{-1} in cation exchange capacity. The soil