Field Crops Research 197 (2016) 52–62

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Combining controlled-release urea and normal urea to improve the nitrogen use efficiency and yield under wheat-maize double cropping system

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ARTICLE INFO

Article history:
Received 1 May 2016
Received in revised form 2 August 2016
Accepted 3 August 2016
Available online 9 August 2016

Keywords:
Controlled-release urea
Wheat-maize rotation system
Nitrogen release
Nitrogen uptake
Nitrogen use efficiencies

ABSTRACT

Controlled-release urea (CRU) has been shown to improve nitrogen use efficiencies (NUEs) and yields in wheat and maize crops, although high cost has limited its use. From October 2013 to September 2015, the effects of a fertilizer mixture (polymer coating of sulfur-coated urea, polymer coated urea, and normal urea with N ratios of 3: 3: 4, respectively, during the wheat growing season, and 3.5: 3.5: 3, respectively, during the maize season) on crop yields and nutrients uptake were investigated in a field using a wheat (*Triticum aestivum* L.) and maize *(Zea mays* L.*)* rotation system. Crop residues were returned into the field at the end of the growing season. Before planting each crop, the fertilizer mixture was applied once as basal dressing at two application rates of 225 kg N ha^{-1} (CRU1) and 150 kg N ha^{-1} (CRU2). Meanwhile, the equivalent rates of normal urea (BBF1 and BBF2) used as twice-split fertilization, 60% at pre-plant and 40% at jointing stage of wheat or V12 (twelve leaf collar) stage of maize as the control. The results suggested that blended applications of CRU and normal urea fulfilled the wheat and maize plants demand for nitrogen during the entire growth periods with crop residues were returned into the field. The yields in the CRU1 treatment were increased by 7.9–10.3% for wheat and 9.1–21.0% for maize, compared with normal urea treatment at the same nitrogen application rates. The NUEs in the mixture treatments were increased by 33.7–56.4% for wheat and 16.7–48.5% for maize, respectively, and the average annual net profit was also increased by 14.5–19.9%, compared with normal urea treatments at the same nitrogen application rates. Although the treatment of CRU2 supplied one-third less N, its yield was similar with that of urea at 225 kg N ha^{-1}. However, the BBF2 treatment supplied one-third less N, the yields were significantly decreased by 6.1–11.1% for wheat and 7.2–9.4% for maize than that the urea at 225 kg N ha^{-1}. In addition, the mixture treatments significantly increased the quality and quantity of tillering of wheat. Furthermore, the NO_3^--N and NH_4^+-N concentration in soil were enhanced especially during the later crops stages, and leaching of soil nitrogen was reduced by using the fertilizer mixture. These results demonstrate that combining CRU and normal urea improved crop yields and NUEs while decreasing costs of fertilizer and the labors required for fertilizer application.

1. Introduction

Nitrogen (N) is one of the most important nutrients for plant growth and the nutrient generally applied in the largest amount (Grant et al., 2012). Increasing applications of N fertilizer have been an effective way of improving crop yields (Abbasi et al., 2013). However, improper fertilization techniques including excessive N fertilization have resulted in low N use efficiencies (NUEs) (Cassman et al., 2002). Nitrogen fertilization of arable lands in excess of crop needs may negatively affect groundwater, surface water, and the atmosphere through leaching, runoff, and volatilization of N (Drecht et al., 2003; Galloway et al., 2008). Additionally, low NUEs leads to lower economic returns to growers from their fertilizer investments.

Rotation of winter wheat with summer maize (two crops harvested in a year) is an important agricultural production system in the North China Plain, which provides more than 50% of the food production in China (China Agricultural Yearbook, 2013). Traditionally in the North China Plain, a large proportion of N has been applied too early when the capacity of plants uptake is small,

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http://dx.doi.org/10.1016/j.fcr.2016.08.004
0378-4290/

although the majority of crops N uptake occurs later in the growing season when the crops grow more rapidly (Liu et al., 2003). In addition, excessive use of N fertilizer is very common in this wheat-maize cropping system, especially in the higher-yielding regions (Zhao et al., 2006). Supplying N greatly exceeding the abilities and requirements of crops that use it will lead to considerable N waste and low NUEs (Zhu and Chen, 2002). Ju and Christie (2011) found that leaching of NO_3^--N increased with increased application rates of N fertilizers. In a wheat-maize rotation system, N leaching mainly occurs during the maize season (Jia et al., 2014). In China, the NUEs for the wheat-maize crop rotation system can be as low as 26–31%, and a large amount of applied N (~180 kg ha^{-1} yr^{-1}) is lost to the environment (Miao et al., 2011). Thus, it is necessary to optimize N fertilizer use both to meet crop requirements and to reduce N losses.

Effective N management has involved selecting an application source, rate, placement, and timing that ensures an adequate amount of N is available as required by the crop to maximize crop yields and NUEs and to minimize the negative effects of N on the environment (Malhi et al., 2001). Torbert et al. (2001) and Otteson et al. (2007) have found that split N applications can increase grain yields and NUEs, but the costs of the additional applications can make split N applications economically unprofitable. Recently, controlled-release urea (CRU), which was designed to release N into the soil solution at a rate that more closely matches nutrient uptake by the crops, has been extensively used in China (Song et al., 2014). By using CRU, the yields of wheat and maize have increased by 12.8–14.3% and 5.5–8.1%, respectively, over treatments with normal urea (Sun et al., 2010). Zhao et al. (2013) and Li et al. (2010) also found that wheat and maize yields were increased by using CRU compared normal urea. Other studies have found that CRU not only improved the NUEs (Kondo et al., 2005) but also decreased NO_3^--N leaching (Zvomuya et al., 2003; Shoji et al., 2001). Moreover, a one-time application of CRU can be more labors and time-saving than the more conventional N fertilizers, which need split (hence multiple) fertilizations (Geng et al., 2015a). However, CRU has been considered too expensive for use in cereal crops, especially in developing countries (Shaviv, 2001). However a better management strategy for CRU (mixed use of CRU and normal urea) has led to the possible feasibility of their use in many grain and oilseed cropping systems (Noellsch et al., 2009). Farmaha and Sims (2013) reported that using a fertilizer mixture that is at least partly CRU can increase protein contents of wheat grains and provide economic benefit to producers compared to fertilizers without CRU.

Considerable research has focused on the effects of CRU on yields and soil environmental pollution, but the synchronized relationships between nutrient release rate of CRU and nutrient requirements of wheat and maize have been rarely addressed. Hence, the cumulative release rate of CRU in water and soil, the change of soil N content, and the dynamics changes of N uptake by wheat and maize plants were investigated in the present study. The objectives of this study were: to determine if it is possible to synchronize the nutrient release patterns from CRU with wheat and maize N uptake needs and to investigate the effects of CRU application on crop yields and NUEs in a crop rotation system involving wheat and maize. The results can demonstrate new fertilizer techniques permitting more sustainable and high efficient application of fertilizers.

2. Material and methods

2.1. Experimental materials

The experiment was conducted during two consecutive wheat-maize rotation cycles (October 2013–September 2015) at the New Fertilizer Experiment Station (36°09′15″ N, 117°09′02″ E), Shandong Agriculture University, (northeast) China. The test soil was classified as Typic-Hapli-Udic Argosols according to the Chinese Soil Taxonomy (CRGCST, 2001) and as Typic Hapludalf according to USDA "Soil Taxonomy" (Soil Survey Staff, 1999). The soil texture was sandy loam with 56.97% sand, 31.05% silt, and 11.98% clay (Miller and Miller, 1987). Before planting at the study site in 2013, main properties for the top soil layer (0–20 cm) were: pH 7.28, soil to water ratio 1: 2.5; organic matter content 11.4 g kg^{-1}; total soil N 0.78 g kg^{-1}; NO_3^--N 10.7 mg kg^{-1}, NH_4^+-N 7.8 mg kg^{-1}; available phosphorus 39.2 mg kg^{-1}; and available potassium 75.7 mg kg^{-1}. The North China Plain typically has a temperate and monsoon climate and is very suitable for winter wheat and summer maize cultivation (Fig. 1). The wheat cultivar used in this study was 'Jimai 22′, and the maize cultivar was 'Zhengdan 958′; both cultivars are widely cultivated in the North China Plain. Conventional fertilizers used were urea as an N fertilizer (46% N), calcium superphosphate for phosphorus (16% P_2O_5) and potassium chloride for potassium (60% K_2O). The polymer coating of sulfur-coated urea (PSCU, 35% N, the release longevity was 3 months) and polymer coated urea (PCU, 43% N, the release longevity was 3 months) were used as CRU for crops, and these CRU components were made by the National Engineering Research Center for Slow/Controlled-Release Fertilizers of Shandong Agriculture University, Shandong, China.

2.2. Experimental design and field management

The experimental design consisted of three replications of five N fertilizer treatments: Control (without N fertilizer); CRU1 (fertilizer mixture with an N rate of 225 kg ha^{-1}); CRU2 (fertilizer mixture with an N rate of 150 kg ha^{-1}); BBF1 (urea with an N rate of 225 kg ha^{-1}); BBF2 (urea with an N rate of 150 kg ha^{-1}). The N fertilizer used in the CRU1 and CRU2 treatments were a mixture of PSCU, PCU, and normal urea with N ratios of 3: 3: 4, respectively, during the wheat growing season, and 3.5: 3.5: 3, respectively, during the maize season. The CRU was applied as basal fertilizer once before planting wheat or maize. However, the urea was applied twice: once before planting the wheat or maize seeds (60% of the total) and again at the jointing stage of wheat or V12 of maize when it was broadcast by hand (40% of the total). Phosphate and potassium fertilizers in all treatments were applied once as basic fertilizer at 150 kg ha^{-1} (P_2O_5) and 75 kg ha^{-1} (K_2O) during the wheat growing season and at 75 (P_2O_5) and 150 (K_2O) kg ha^{-1} in the maize season. The depth of basal fertilizer application to the soil was 10–15 cm, whereas the topdressing urea was broadcast to the soil surface just before irrigation. Before beginning the experiment, maize was cultivated for one year without any fertilization to help balance the soil fertility. Following harvest of the wheat or maize each year, the remaining crop residues was mechanically crushed, then tilled into the soil.

The field experiment was a completely randomized block design with three replications. The size of each plot was 4 m × 4 m. All the 15 plots had 80 mm thickness cement board buried to 100 cm depth to prevent the mixture of fertilizer and water among plots. Each year, the wheat seeds (1000-grain weight was 41 g) were sown in alternating narrow and wide rows at 150 kg ha^{-1} of seed with an average of 25 cm between wide rows and 15 cm between narrow rows. The fertilizer was applied in the middle of wide rows. The wheat was sown in 20 rows per plot: the middle 10 rows were used to measure yield, and 5 rows on each side were for collecting soil and plant samples. Maize seeds were sown in 7 rows per plot with 60 cm between rows and a density of 83,000 plants ha^{-1}. Here, 3 rows in the middle were reserved to measure yields, and 2 rows on each side were for collecting soil and plant samples. Diseases, pests, and weeds were well controlled by managers as needed.