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Research paper

Optimising nitrogen fertilisation: A key to improving nitrogen-use efficiency and minimising nitrate leaching losses in an intensive wheat/maize rotation (2008–2014)

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ABSTRACT

Optimising nitrogen (N) fertilisation is critically important for obtaining high crop yields with low environmental costs. A seven-year field experiment was conducted to evaluate the effects of the rate of N application on crop yield, N-use efficiency (NUE), nitrate residue (NR), and nitrate leaching in an intensive wheat/maize rotation system on the Loess Plateau of China. Five treatments were tested: a control (no N fertilisation) and conventional, low, moderate, and high rates of N fertilisation. Nitrates were leached mainly after heavy rains and with flood irrigation and varied notably between years. Annual nitrate-leaching loss (ANLL) averaged 3.4–17.3 kg N ha^{-1} y^{-1} at N rates of 165–495 kg N ha^{-1}. Crop yields increased quadratically and NUE decreased linearly with increasing rates of N application. NR and ANLL increased exponentially. Compared with conventional management, moderate N fertilisation increased NUE and decreased NR and ANLL by 46 and 34%, respectively, without any significant decrease in crop yield. High yields can thus be achieved at a moderate N rate and an economically optimal N rate with less ANLL and acceptable soil NR. We recommend N-application rates of 150–170 and 180–200 kg N ha^{-1} for wheat and maize, respectively, for obtaining high crop yields with low environmental risks.

1. Introduction

Nitrogen (N) is an essential nutrient for plant growth and plays a crucial role in sustainable agriculture (Tilman et al., 2002; Zhang et al., 2015a). The invention of the Haber–Bosch process in the early twentieth century greatly facilitated the industrial production of synthetic N fertilisers and has helped to feed about half of the global population during the last century (Erisman et al., 2008). Agriculture in China is currently feeding 22% of the world's population with only 7% of the world's arable land (Lu et al., 2015). This achievement is closely associated with the great intensification of agricultural production, characterised by large inputs of nutrients on a limited land area (Zhang et al., 2011). The total consumption of synthetic N fertilisers in China has increased from 9.3 million t in 1980–24.0 million t in 2012, but this 158% increase in N-fertiliser use has increased total grain production by only about 70% (from 320.6 million to 546.5 million t) (Li et al., 2016). The large input of N fertilisers in agriculture has greatly surpassed the crop demands, which has both decreased N-use efficiency (NUE) (Tilman et al., 2002; Zhang et al., 2008) and caused serious environmental problems such as soil acidification (Guo et al., 2010), emissions of greenhouse gases (Zhang et al., 2013; Nayak et al., 2015), eutrophication of surface water (Le et al., 2010), contamination of groundwater (Zhang et al., 1996; Gu et al., 2013), and nutrient imbalances (Vitousek et al., 2009).

The rotation of winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) is a common cropping system in central and northern China, where about 25% of the country's food is produced (Zhang et al., 2015b). Over-fertilisation, however, is very common in this intensive rotation system (Zhu and Chen, 2002; Zhao et al., 2006). Ju et al. (2009) reported that the typical rates of N application for wheat (n = 121) and maize (n = 148) in the North China Plain were about 325 and 263 kg N ha^{-1}, respectively, much

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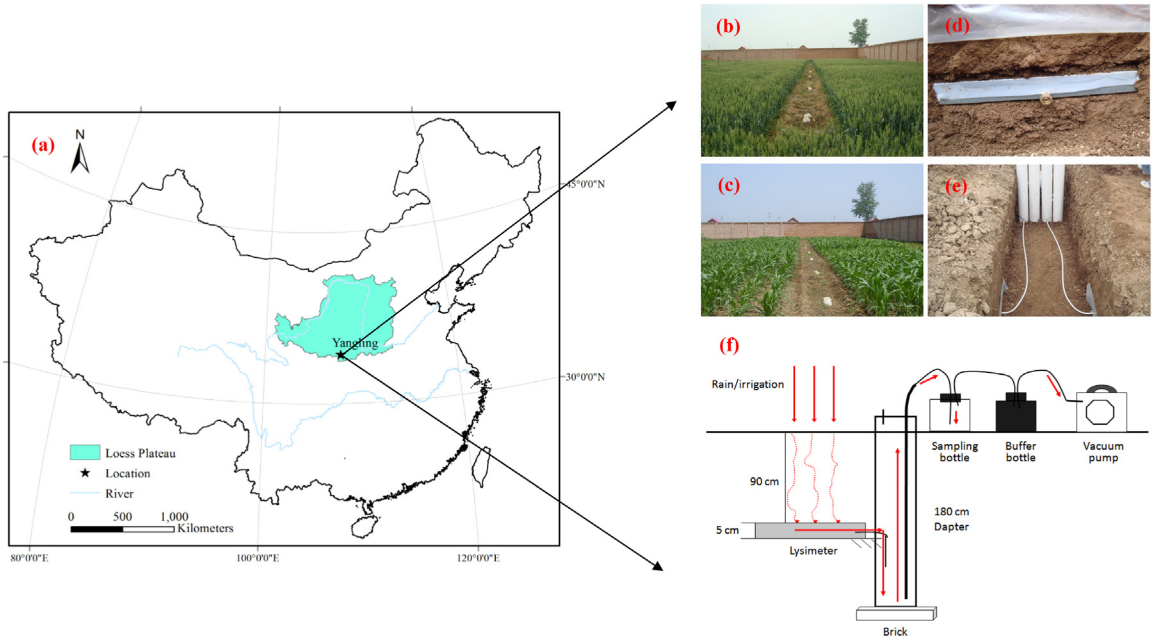

Fig. 1. Study area (a) and photographs of the setup for collecting leachates (b–f).

higher than the optimal N rates (120–180 kg N ha^{-1}) demonstrated by field experiments (Cui et al., 2008a,b; Ju et al., 2009). Excessive N fertilisation may not have a large impact on crop yield (Cui et al., 2010, 2013) but can notably decrease NUE (Tilman et al., 2002; Zhang et al., 2008). Zhang et al. (2015a) reported that average NUE (the fraction of N input harvested as product) across crops in China has decreased sharply from 60 to 70% in the 1960s to 20–30% in the 2010s, lower than the 60–70% in the USA during the same period. Excessive N application has also contributed to the accumulation of large amounts of nitrate in the soil. Total nitrate accumulations in the 0–4 m soil layer in Chinese semi-humid croplands determined from 7000 observations for 1994–2015 were as high as 453 ± 39 and 749 ± 75 kg N ha^{-1} in wheat and maize fields, respectively (Zhou et al., 2016). These residual nitrates are prone to leaching to deeper soil layers due to their high mobility, following continuously downward water fluxes over years of precipitation or from heavy rains and irrigation (Yang et al., 2015; Zhou et al., 2016).

Nitrate leaching and the subsequent contamination of the groundwater have become worldwide problems (Jun et al., 2005; Kaushal et al., 2011; Perego et al., 2012). Nitrate leaching in northern China has been ignored for decades due to the scarcity of precipitation. The annual precipitation in this area, though, is highly concentrated in four months (June to September), accounting for about 70% of the annual rainfall, which can facilitate the rapid transport of surface nitrate deeper into the soil profile (Fan et al., 2010). The groundwater in some intensive cropping areas in China has thus been seriously contaminated with high nitrate concentrations (Zhang et al., 1996; Ju et al., 2006). A survey conducted in Beijing, Tianjin, Hebei, Shandong, and Shaanxi Provinces found that as many as 45% of 600 groundwater samples exceeded the WHO standard for drinking water (NO_3^--N ≤10 mg L^{-1}) (Ju et al., 2006), and Zhao et al. (2007) reported that 34.1% of 1139 groundwater samples in northern China exceeded the WHO standard. The higher concentrations of nitrate in groundwater are closely associated with the intensification of agricultural production due to the increasing application of inorganic N fertilisers (Gu et al., 2013; Ju et al., 2006, 2009).

The Guanzhong Plain is an important area of cereal production in Shaanxi Province. It covers an area of 34 000 km^2 (nearly 20% of the area of the province) and supplies more than 50% of the total grain produced in the province (Liu et al., 2013). Winter wheat/summer maize rotation is generally practiced in the area because of the favourable conditions for their growth (abundant light energy & temperature). Local farmers usually apply N fertilisers at rates exceeding the needs of the crops in this rotation (Tong et al., 2004; Zhang et al., 2015b), because of a lack of knowledge, ineffective services for soil testing (Lu et al., 2015), fear of lower yields, and ignorance of the harsh consequences to the environment. Long-term field experiments are therefore needed to comprehensively evaluate the adverse effects of excessive N fertilisation on crop yield, NUE, and the environment and to determine an optimal rate of N application to solve the problem. We consequently conducted a seven-year stationary field experiment with wheat/maize rotation to: (1) study the long-term effects of varying N fertilisation on crop yield and NUE, (2) quantify the responses of the annual loss of nitrate due to leaching, nitrate leaching factor, and nitrate residue (NR) under different rates of N fertilisation, and (3) determine an optimal rate of N application for maximising crop yield with a high NUE at a low environmental cost.

2. Materials and methods

2.1. Site description

This seven-year field experiment was conducted in a field at the Chinese National Soil Fertility and Fertilizer Efficiency Monitoring Base of Loessial Soil (34°04′N, 108°02′E; 534 m a.s.l.) from October 2007–2014 in Yangling, Shaanxi Province, China (Fig. 1). This region is on the south-central edge of the Loess Plateau, a typical rainfed area, where the mean annual precipitation is 600 mm, with 60–70% falling during July to September. The mean annual soil evaporation and air temperature are 993 mm and 13 °C, respectively. The soil at the study site is classified as a calcareous Eum-Orthic Anthrosol (Udic Haplustalf in the USDA system). The main physical and chemical properties of the 0–100 cm soil layers are shown in Table 1.

2.2. Experimental design

We tested five treatments for both the wheat and maize cropping seasons (Table 2): control (CK, no N fertilisation), conventional