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Winter wheat grain yield and summer nitrate leaching: Long-term effects of nitrogen and phosphorus rates on the Loess Plateau of China

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ABSTRACT

Excessive N application in agriculture may lead to nitrogen losses in the environment, particularly nitrate leaching, which is a growing concern worldwide. However, only limited information is available about nitrate leaching during summer fallow in dryland areas, especially after the long-term application of N or P fertilizer. In 2004, we initiated a nine-year field experiment with five N and five P rates in the Loess plateau of China to investigate the nitrate leaching from top soil and its accumulation in deep soil. The objective was to determine suitable N and P rates for maintaining high grain yields and reducing nitrate leaching. The results showed that the winter wheat grain yield and N uptake were affected by the N and P rates, but they showed no response to N fertilizer in dry years. The nitrate leaching occurred mainly from the top 40 cm soil, and it was affected by the N and P rates, as well as the summer precipitation intensity. In the wet summer of 2011, the nitrate leaching increased from 14.6 to 250 kg N ha^{-1} as the N rate increased from 0 to 320 kg N ha^{-1}, and only the P rate of 100 kg P_2O_5 ha^{-1} significantly decreased the nitrate leaching compared with the other P rates. In the normal summer of 2012, the nitrate leaching occurred only at 240 and 320 kg N ha^{-1}, and no leahcing occurred in the dry summer of 2013. The nitrate leached from top soil was found to be accumulated in deep 40–300 cm soil, and the amount of deep soil accumulated nitrate was clearly higher than that leached from the top soil. The accumulation increased as the N rate increase, i.e., 37.7–387 kg N ha^{-1} in 2011, and 53.9–193 kg N ha^{-1} in 2012 when the N rate increased from 0 to 320 kg N ha^{-1}, whereas it decreased from 196 to 134 kg N ha^{-1} in 2011, and from 134 to 55.9 kg N ha^{-1} in 2012 as the P rate increased from 100 to 200 kg P_2O_5 ha^{-1}, but no accumulation was observed in deep soil in 2013. The downward movement of nitrate lagged behind that of the soil water, and 1 mm rainfall could cause a 1.6–3.6 mm downward movement of nitrate in the soil profile in summer. In conclusion, the application of less than 160 kg N ha^{-1} and around 100 kg P_2O_5 ha^{-1} could reduce nitrate leaching from top soil and decrease its accumulation in deep soil, while still maintaining a relatively high grain yield and N uptake in the dryland area of the Loess Plateau.

1. Introduction

Synthetic nitrogen (N) fertilizer has played a vital role in enhancing food production and meeting half of the food demands for the world's population (Zhang et al., 2013). However, the long-term application of N fertilizer or its overuse beyond the needs of crops has been reported to lead to large amounts of residual nitrate in soil. In the North China Plain, 221–620 kg N ha^{-1} of residual nitrate was detected in the 0–100 cm soil layer at N rates of 200–300 kg N ha^{-1} after two wheat-maize rotations (Fang et al., 2006). Further studies found that the nitrate peaks moved down to 140 cm after 15 years of annual application with 180 kg N ha^{-1} or 16 cropping cycles with an annual N application of 320 kg N ha^{-1} (Benbi et al., 1991; Fan et al., 2003), which indicated that the residual nitrate in soil was likely to leach into deeper layers over time.

The gradually leaching of residual nitrate into the layers below the root zone is a major N loss pathway in cropping systems (Liu et al., 2003; Cui et al., 2014; Li et al., 2016), and the leached nitrate is also the main agricultural pollutant of groundwater (Groffman

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et al., 2002; Wakida and Lerner, 2005). Thus, the environmental impact of nitrate leaching has attracted increasing attention. In northern Italy, where the annual rainfall was 822 mm, nitrate leaching from the 150 cm soil layer ranged from 14 to 321 kg N ha^{-1} yr^{-1} at N rates around 209–801 kg N ha^{-1} yr^{-1} (Perego et al., 2012). In southern China, nitrate leaching was 1.88–15.7 kg N ha^{-1} in the top 60 cm soil layer when the N fertilizer rate was increased from 0 to 360 kg N ha^{-1}, where the rainfall was the major factor related to leaching (Liang et al., 2011). However, in dryland areas with low annual total rainfall, nitrate leaching is generally acknowledged to be negligible and unlikely (Li et al., 1993). Corbeels et al. (1999) noted that on the Sais plateau in Morocco with the long-term average rainfall of 526 mm, nitrate leaching only reached beyond 60 cm depth after heavy rainfall of 93 mm, and out of the 90 cm layer in the following year after precipitation of 84 mm, where the amount of leaching was very low.

The two main conditions that control nitrate leaching are an adequate soil nitrate content and the generation of sufficient subsurface drainage water by rainfall or irrigation. In northwest China, a five-year drainage lysimeter experiment showed that the annual nitrate leaching from the top 90 cm soil layer were 2.5, 10.1, and 15.8 kg N ha^{-1} y^{-1}, when the soil nitrate were annually 36.6, 178, and 212 kg N ha^{-1} y^{-1}, respectively (Yang et al., 2015). In drylands of Canada, 123 kg N ha^{-1} nitrate was found to be leached out of the 0–240 cm layer of fallow soil by precipitation of 274 mm from mid-May to the end of September (Campbell et al., 1984). In northwest China, the fallow period after the winter wheat harvest is the summer season when the rainfall is most intense, with approximately 60–70% of the annual total, and thus residual nitrate in the soil is inevitably leached by the concentrated precipitation. Another lysimeter experiment found that nitrate was leached out of the 100 cm soil depth after harvesting winter wheat when the annual water input (rainfall combined with irrigation) was 349 mm (Lu et al., 1996). Additionally, several studies reported that balanced application of N with phosphorus (P) significantly reduced soil residual nitrate as much as 39% compared with only N fertilzier application (Fan et al., 2003; Wen et al., 2016; Zhou et al., 2016), which decreased nitrate leaching inevitably. However, previous studies demonstrate that nitrate leaching occurred at certain soil depths and it was enhanced by increased precipitation in dryland areas, where the amount of nitrate leached increased as the N rate increased and decreased as the P rate increased. It is not known how the nitrate level changes in the vertical soil profile as nitrate moves downward by leaching and accumulates in various soil layers, and how this might be affected by the N and P application rates and precipitation during the summer fallow. In addition, it would be useful to determine whether there is a suitable fertilizer rate that could ensure improved crop growth, grain yields, and crop N uptake, but without increasing nitrate leaching under different levels of summer fallow precipitation in dryland areas. Information about these issues is still lacking for the dryland areas of the Loess Plateau.

In the present study, based on a nine-year stationary fertilization field experiment (initiated in 2004) with winter wheat grown at different N and P rates in the dryland area of the Loess plateau, we analyzed the grain yield, crop N uptake at harvest, as well as the soil water and nitrate in the 0–300 cm soil profile before and after the summer fallow season during the last three years (2010–2013). The objectives of this study were: (1) to monitor the residual nitrate leaching and its accumulation occurred in which soil layers, as well as the effects of different N and P application rates and variation in precipitation over the years; (2) to ascertain the characteristics of soil nitrate and water movement during summer fallow; (3) to identify suitable N and/or P rates to ensure improved crop growth, grain yields, and N uptake, but without significantly increasing nitrate leaching in dryland farming areas.

2. Materials and methods

2.1. Study site description

The field experiment was initiated in October 2004 at the Research Station of Northwest Agriculture & Forestry University (34°18′N, 108°05′E, altitude = ca 520 m), which is located in Yangling, Shaanxi, China (a typical rainfed area). The area has a semi-humid and prone to drought climate, with an annual average air temperature of 12.9 °C, mean precipitation of 581 mm during 1957–2013 (54.2% in the summer between July and September), and potential evaporation of 1400 mm. Fig. 1 shows the distribution of precipitation during the last three experimental years (2010–2013) and the average during 1957–2013 at the experimental site. The soil at this site is calcareous Eum-Orthic Anthrosol (Udic Haplustalf according to the USDA system), with a loamy texture and 1.24–1.62 g cm^{-3} bulk density in top 0–40 cm soil, and other initial main properties of the top soil is shown in Table 1. Winter wheat-summer fallow is the major local cropping system, and winter wheat is usually sown in early October and harvested in late May or early June of the following year, then the period from harvest to next sowing of winter wheat is the summer fallow.

2.2. Experimental design and treatments

The field experiment had a randomized complete block design with five different N and five P fertilizer rates, and four replicates. The area of each plot was 40 m^2 (4 × 10 m), where buffer zones of 1 m separated plots and zones of 2 m separated blocks. Winter wheat (*Triticum aestivum* L.), which is the major local food crop, was used as the test crop grown in a winter wheat-summer fallow system at five N fertilizer rates of 0, 80, 160, 240, and 320 kg N ha^{-1} with 100 kg P_2O_5 ha^{-1}, and five P fertilizer rates of 0, 50, 100, 150, and 200 kg P_2O_5 ha^{-1} with 160 kg N ha^{-1}. The N fertilizer was applied in the form of urea (N 46%) and the P fertilizer was triple superphosphate (P_2O_5 46%). In each year, all of the fertilizer was applied by hand broadcasting evenly over the soil surface in each plot as a basal fertilizer at sowing, which was then plowed immediately into the top 20 cm soil layer using a rotavator. A widely used local winter wheat cultivar "Xiaoyan 22" was sown on October 16, 17, and 12 during 2011, 2012, and 2013, respectively, at a seeding rate of 135 kg ha^{-1}, with a row space width of 20 cm and a sowing depth of 5 cm. The wheat was harvested on June 4 in 2011, June 7 in 2012, and May 27 in 2013. One week after the harvest, the experimental field was ploughed to the depth of 30–40 cm using a plough machine for the first time, and it was then tilled to 10–15 cm for the second time using a rotavator at two weeks before seeding. Supplemental irrigation was not provided during the winter wheat growing season, and thus water from natural precipitation was the only water resource available for winter wheat growth. In addition, the other cropping management practices employed were consistent with those used by local farmers. Herbicides and insecticides were used to prevent weeds and pests.

2.3. Sample collection and analysis

2.3.1. Plant sampling and analysis

At winter wheat maturity during the last three consecutive years (2011–2013), approximately 100 wheat plants were randomly sampled from each plot for analysis. The plants were manually pulled from each plot and the roots were immediately cut off at the stem base (the root–stem connection point). The aboveground plant parts from the same plots were mixed to form a single sample and then separated into stems (including leaves), glumes, and grains to determine the crop N uptake. Air-dried samples were