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Accumulation and leaching of nitrate in soils in wheat-maize production in China

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ABSTRACT

Application rates of fertilizers in China often exceed crop requirements, resulting in high accumulation of nitrate (NO_3) in the soil. Nitrate that has accumulated in soils is highly prone to leaching, directly threatening the quality of groundwater. A study was conducted to assess the magnitude of NO_3 accumulation and leaching in China, to identify factors controlling NO_3 accumulation and leaching, and to develop strategies that can be used to minimize NO_3 leaching. Data were compiled from 212 studies conducted in China, amounting to 1077 observations of the NO_3 content of the 0–100 cm soil profile in wheat and maize fields after harvest. Leaching of NO_3 was significantly correlated with NO_3 accumulation in the soil. NO_3 leaching increased with 0.058 and 0.34 kg NO_3-N ha^{-1} per season for wheat and maize, respectively, for every 1 kg ha^{-1} increase in NO_3-N accumulation in 0–100 cm. This mainly related to lower precipitation during the wheat season and intensive rainfall in the maize season. Accumulation of NO_3 in maize systems was 50% lower than for wheat when fertilized at the same rate, due to differences in rainfall between seasons. Soil NO_3 accumulation was higher in heavy textured soils than in freely draining lighter textured soils, as most of NO_3 leached out of 0–100 cm soil in lighter textured soils. Compared to flood irrigation, sprinkler irrigation increased NO_3 accumulation by 17% and 152% for wheat and maize, respectively, due to lower irrigation and leaching rate. The level of nitrate accumulation in Chinese arable soils has become a significant hazard to drinking water, so good agricultural management is essential. Soil NO_3 accumulation and leaching in China can be reduced by source and process control, such as reducing fertilizer application, using slow or controlled release forms of fertilizers, and regulating irrigation.

1. Introduction

Nitrogen (N) fertilizers are used in crop production to obtain high yields. The global consumption of N fertilizer is approximately 109 million tons annually, one-third of which is used by China (Food and Agriculture Organization of United Nations (FAO, 2017). While increasing crop yield, overuse of fertilizers is problematic. Nitrogen fertilization in China, combined with other poor cropping practices, has led to low efficiencies of N utilization, typically ranging from 30 to 40% (Ju et al., 2009), but its much lower in regions where high N application rates are typical (Ju et al., 2003). In general, nitrate accumulates in soil when N fertilizer is oversupplied (Ju et al., 2004; Vitousek et al., 2009), especially in intensive cropping (double or triple cropping) regions (Zhou et al., 2016). Nitrate in soils can leach into groundwater following heavy rainfall or irrigation, contaminating drinking water (Ju et al., 2003; Liu, 2015). The Ministry of Water Resources of China (2016) analyzed the content of NO_3 in water from 2103 wells in 18 administrative regions in China, and found that 80% of the wells contained ≥ 30 mg L^{-1} NO_3-N, characterized as level V contamination (**GB14848-93**). The NO_3-N content of groundwater analyzed for the Bohai Rim Region averaged 11.9 mg L^{-1}, and 30% of monitored wells exceeded the World Health Organization (WHO) standard of 50 mg nitrate per L (11.3 mg L^{-1} NO_3-N) (Zhao and Liu, 2014). High NO_3 in groundwater poses a direct threat to human health (Tao and Xin, 2014; World Health Organization (WHO, 2011).

The risk of nitrate leaching to groundwater can be assessed from

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Table 1
List of leaching studies.

Timing of nitrate measurement	number of measurements	methods	references
once every 10 days during crop growth stage;	unknown	percolating pools, porous clay cup	Yi et al. (2004); Yi (2005)
after irrigation during crop growth stage;	2	lysimeter	Yin et al. (2010)
3-5 days after irrigation or rainfall during crop growth stage;	3-5	lysimeter	Ding et al. (2015); Ding et al. (2015); Fang et al. (2006);Yang et al. (2012); Yang et al. (2013)
		calculated	Liu et al. (2003); Li et al. (2012)

NO_3 accumulation in the soil (Salo and Turtola, 2006). As the concentration of NO_3 in groundwater responds slowly to changes in agricultural practices and is subject to weather events (Wick et al., 2012), soil residual NO_3 has been used as an alternative indicator for the risk of NO_3 leaching (Haene et al., 2014). Yadav (1997) determined that 68% of applied fertilizer N accumulated in the soil as NO_3, from which 20% entered the groundwater. Controlling groundwater NO_3 contamination is important for safe water supply (Chen et al., 2016; Kirchmann et al., 2002; Maeda et al., 2003; Zheng, 2015). In addition to the use of fertilizers and irrigation management, the use of manure and other N sources, crop type, soil properties such as soil texture, and rainfall affect soil NO_3 accumulation and leaching (de Ruijter et al., 2007; Li et al., 2016; Shang et al., 2012; Tosti et al., 2014). Many countries adopted water quality legislation to control NO_3 contamination, such as the implementation of the Nitrates Directive in the European Union (Oenema et al., 2011; Velthof et al., 2014). China has a unique challenge in feeding its large population with limited land resources and also needs similar strategies to reduce NO_3 leaching (Han et al., 2016; Bai et al., 2018).

The objectives of this study were to: i) determine the relationship between accumulation of NO_3 in agricultural soils in China and management, soil, and environmental factors; ii) quantify the relationship between accumulation and leaching of NO_3; and iii) explore mitigation opportunities to avoid accumulation of NO_3 in soils. The aim was to integrate data from reported studies at a regional scale in order to develop strategies to control soil NO_3 accumulation in China.

2. Materials and methods

2.1. Source of data

The data used in this study were extracted from the literature, between 1990 and 2016, that reported post-harvest soil NO_3 concentrations in wheat and maize fields in China. The following criteria were used in the literature search: a) field studies in which wheat or maize production systems, the geographical location, soil property, and agronomic practices involved were clearly described, and b) mean of NO_3 accumulation in the 0–100 cm soil layer, standard errors, and the number of replicates were reported or computable. Rice was not included in the literature search considering its low potential for accumulation of NO_3 in the soil (Tong et al., 2005). The search was conducted using the China Knowledge Resource Integrated Database, Google Scholar, and the Web of Science. Together, 212 published studies (34 in English) were identified, bringing in 1077 observations, including 441 for wheat and 636 for maize. Study areas included 13 of the 31 provinces in China, representing 81% of the wheat production and 61% of the maize production areas in 2016 (National Bureau of Statistics of China (NBSC, 2016).

2.2. Data collation and analysis

The following results were included in our database: the rate of N application (kg ha^{-1}), soil NO_3 accumulation in the 0–100 cm top layer (kg ha^{-1}), soil NO_3 content (mg kg^{-1}), NO_3 leaching per season (kg N ha^{-1}), study location (latitude and longitude), average annual rainfall (mm), the type of crops, and cropping practices, e.g. wheat-maize rotation, monoculture and intercropping. Exploration of the data was carried out using Get Data to extract numerical values from graphs, MetaWin software to analyze the effective size; and SPSS to do the significance test.

The influence of the following factors on soil NO_3 accumulation was analyzed: (1) geographical region (Northeast, North, and Northwest China), (2) crop type (wheat and maize), (3) soil texture, (4) fertilizer application (rate, method, and type of fertilizers used), (5) rainfall and irrigation (methods and rates), and (6) cropping systems (monoculture with one crop one year, intercropping with two crops within one season), and wheat-maize rotation within one year. Relationships between accumulation and leaching of NO_3 derived from the literature study are listed in Table 1. In these studies, soil NO_3 accumulation and leaching were measured simultaneously using percolating pools or lysimeter.

We analyzed the different influencing factors for the conventional range of N application rates based on the analysis of collected data and corrected with empirical application rate (wheat: 120–250 kg N ha^{-1}, maize: 170–280 kg N ha^{-1}) (Chen et al., 2011, 2014; Cui et al., 2010; Liang et al., 2016; Li et al., 2018), reflecting typical practice, and making any recommendations for mitigation strategies more meaningful. Since most of the data were from wheat-maize rotation studies, the analysis of irrigation management, rainfall and soil properties was conducted for the wheat-maize rotation system, and not for individual crops within the system. This was not the case for exploring the effects of fertilizer application method and fertilizer type, where all cropping systems were used, as data were not sufficient for the wheat-maize rotation.

To unify data and eliminate background interferences, gross and net accumulations of soil NO_3 were derived from Ding et al (2015), and calculated using the following equations:

$$C_{NO3} = ST*B*c/10 \quad (1)$$

$$NC_{NO3} = C_{NO3,\ treat} - C_{NO3,\ CK} \quad (2)$$

Where C_{NO3} (unit: kg N ha^{-1}) is the gross NO_3-N accumulation; ST (unit: cm) is soil thickness; B (unit: g cm^{-3}) is soil bulk density, which was derived from the publications of the experiments; c (unit: mg kg^{-1}) is the soil NO_3-N concentration; 10 is a factor to transform units; NC_{NO3} (unit: kg N ha^{-1}) is the net NO_3-N accumulation; $C_{NO3,treat}$ (unit: kg N ha^{-1}) is NO_3-N accumulation in crop fields that received fertilizers; and $C_{NO3,CK}$ (unit: kg N ha^{-1}) is NO_3-N accumulation in crop fields that did not receive fertilizer application.

Mean NO_3-N accumulation for different treatments were compared by Duncan's test in one-way ANOVA using SPSS Statistics 20. Differences were considered significant when P was < 0.05.

Results obtained from the referred studies were standardized by calculating their effect size. Effective size was defined as the natural logarithm of a response to fertilization (lnR, unit: 1) (Hou et al., 2015). The standardization was performed to facilitate pooling of quantitative statistical information and conducting robust comparisons of variables from different studies. The log transformation allowed variances of dependent variables to be stabilized for pairwise comparisons. The lnR was calculated as follows: