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Improving nitrogen use efficiency with minimal environmental risks using an active canopy sensor in a wheat-maize cropping system

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ABSTRACT

Nitrogen (N) management needs to be significantly improved to address the triple challenge of global food security, environmental pollution and climate change. In addition to being site-specific, dynamic in-season management is needed to respond to temporal variability in soil N supply and crop N demand. Active canopy sensor-based precision N management (CS-PNM) aims to match N supply with crop N demand in both space and time. Studies that systematically compare this strategy with other N management strategies are limited, especially in intensively farmed regions of developing countries. The objective of this study was to compare CS-PNM strategy in terms of agronomic and environmental impacts in comparison with farmer's N practice, regional optimum N management, modified Green Window-based N Management and soil test-based in-season root zone N management for an intensive winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) rotation system in North China Plain. A field experiment was conducted from 2008 to 2012 in Quzhou, Hebei Province of China to evaluate these systems. The CS-PNM strategy was consistently better for both crops than the other tested strategies. In comparison with farmer's practice and regional optimum N management, the CS-PNM strategy reduced N fertilizer applications by 62% and 36%, increased N use efficiencies by 68–123% and 20–61%, decreased apparent total N losses by 81% and 57%, and lowered intensities of total N_2O emission, greenhouse gas emission and reactive N losses by 54–68% and 20–42%, respectively. Here we demonstrate that relative to current N management strategies, the CS-PNM strategy has significant potential to improve N use efficiencies and mitigate environmental degradation for sustainable intensification of agriculture in developing countries.

1. Introduction

There is little doubt that synthetic N fertilizer contributes significantly to global food security. However, large N fertilizer input rates and low NUEs have made it "too much of a good thing", resulting in enhanced losses of reactive N to the environment (Sutton et al., 2011; Erisman et al., 2013; Zhang et al., 2013, 2015). Reactive N is very mobile and has caused a series of environmental problems, affecting human health, ecosystem services, climate change, biodiversity and sustainable development (Diaz and Rosenberg, 2008; Galloway et al., 2008; Ravishankara et al., 2009; Fowler et al., 2013; Zhang et al., 2015). The influence has already exceeded many thresholds of human and ecosystem health and the safe operating limit (Rockström et al., 2009; Erisman et al., 2013). This calls for a new paradigm of

Abbreviations: AE, agronomic efficiency; CS-PNM, active canopy sensor-based precision nitrogen management strategy; FNP, farmer's nitrogen practice; GHG, greenhouse gas; INSEY, in-season estimates of potential yield; IRNM, soil test-based in-season root zone nitrogen management; MGWNM, modified Green Window-based nitrogen management; N, nitrogen; NDVI, normalized difference vegetation index; NUEs, nitrogen use efficiencies; PFP, partial factor productivity; PNU, plant nitrogen uptake; RE, recovery efficiency; RONM, regional optimum nitrogen management

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sustainable intensification in agriculture to simultaneously increase both production and environmental sustainability (Tilman et al., 2011; Garnett et al., 2013; Zhao et al., 2013). This paradigm is especially important for large developing countries like China (West et al., 2014; Zhang et al., 2015).

With the world's largest population, China is facing one of the greatest challenges of this century to continue to increase annual cereal production and ensure food security with shrinking cropland and limited resources, while maintaining or improving soil fertility, and protecting the environment. China is now the world's largest producer, consumer, and importer of chemical fertilizers, accounting for over 30% of the world's N fertilizer consumption (Zhang et al., 2013). However, mismanagement of N fertilizer is common in China (Miao et al., 2011; Norse and Ju, 2015) and recovery efficiency (RE) of N has been declining steadily from 37% in 1960 to 29% in 2007 (Conant et al., 2013). On the other hand, per capita N footprint in China has increased 68% from 19 kg N yr^{-1} in 1980 to 32 kg N yr^{-1} in 2008 (Gu et al., 2013). Nitrogen fertilizer related GHG emissions account for about 7% of total GHG emissions in China and have exceeded soil carbon gain related to N fertilizer use by 700% (Zhang et al., 2013). It has also contributed to the widespread surface and groundwater pollution (Norse and Ju, 2015; Strokal et al., 2016).

A key strategy to mitigate the environmental impacts of agricultural N is to improve NUEs (Huang and Tang, 2010; Snyder and Fixen, 2012; Cui et al., 2014). Increasing current RE of N in China from about 30% to 50% would reduce synthetic N fertilizer use by 40% each year (about 6.6 Tg) and GHG emissions by 39% (equivalent to 60 Tg CO_2 yr^{-1}) (Huang and Tang, 2010).

A first step to improve N management in China is to develop a regional optimum N rate for the whole region (e.g. a county or a township) based on multi-site-year N response experiments that avoid significant over- or under-application problems (Cui et al., 2013a). The RONM strategy is a good starting point and does not mandate any soil or plant testing. However, it is still general in nature and does not account for site-specific or year-specific N requirements (Cui et al., 2013a). It will unavoidably lead to over- or under-applications in different fields or different parts of a large field, resulting in sub-optimal NUE or crop yield. In-season site-specific precision N management strategies that consider synchronization of N supply and crop N demand in space and time have potential to further improve NUE relative to the RONM strategy.

The Ramp Calibration Strips approach was proposed by Raun et al. (2008) as a simple in-season N management strategy in Oklahoma, USA. This strategy applies continuously changing or stepped rates of pre-plant N fertilizers in a band or strip across a portion of a farmer's field on top of a farmer's normal fertilization rate. The suitable N application rate can be determined by identifying the lowest N rate that is not visually different from the highest N rate. This information can help the farmers refine top-dressing or side-dressing N rates based on the growing conditions encountered up until the time of calibration ramp interpretation. Yue et al. (2015) proposed a modified version of Ramp Calibration Strips and termed it Green Window Approach for small scale farming in China. In this approach, a basal N application of 30 kg N ha^{-1} was supplemented with two split-applications of stepped increasing N rates in small plots placed in a compact layout near the border of a farmer's field. The small plots can be visually examined to determine optimal N rates as with Ramp Calibration Strips. However, Green Window Approach is mainly for determining the suitable N application rate for the next planting season, assuming that variability in optimal N rate is small from year to year. This assumption may not be true (Mamo et al., 2003; Miao et al., 2006). A modified Green Window Approach strategy is needed that is more suitable for guiding in-season N management.

An in-season root-zone N management system based on soil N test has been developed for the intensive winter wheat-summer maize rotation system in the North China Plain (Cui et al., 2008a,b). In this strategy, the total amount of N fertilizer is sub-divided into 2–3 applications during the growing season, while the optimal N rate for each application is based on soil nitrate-N tests in the root zone and a target N value in root soil layer for the corresponding growth period of the crop. Soil nitrate-N is then analyzed by nitrate-N-test strips and a reflectometer in the field. This strategy was evaluated for winter wheat and summer maize in different farmers' fields of North China Plain and the results indicated that it significantly improved NUE, reduced environmental contamination, and increased net economic gains compared with traditional farmer's N practices (Cui et al., 2008a,b). However, it may not be practical to apply this soil test-based management strategy to large areas for in-season site-specific N management due to labor, time, and cost limitations (Li et al., 2009; Miao et al., 2011).

Active canopy reflectance sensors can be used for real-time non-destructive diagnosis of crop N status, without the need for plant or soil testing. Based on the diagnosis results, side- or top-dressing N rates can be adjusted to better match crop N demands in space and time. Raun et al. (2002) developed an active canopy reflectance sensor-based N fertilization strategy, which increased NUE by more than 15% when compared to traditional practices in Oklahoma, USA. This CS-PNM strategy was further developed for winter wheat in an intensive agricultural region of North China Plain, and increased RE of N by 369% from 13% with typical FNP to 61% with the CS-PNM strategy (Li et al., 2009). Although the CS-PNM strategies generally increased NUEs significantly, studies evaluating their environmental impacts have been limited (Roberts et al., 2011).

Currently, no study has been reported to evaluate all these N management strategies together to determine their potential for improving NUE and reducing environmental pollution. Therefore, the objective of this study was to compare the CS-PNM strategy in terms of agronomic and environmental impacts with FNP, RONM, MGWNM and IRNM strategies for the intensive winter wheat-summer maize cropping system.

2. Materials and methods

2.1. Study site

A field experiment was conducted from October 2008 to June 2012 at the Quzhou Experimental Station of China Agricultural University (QZ, 115.0°E, 36.5°N, 37 m above sea level), located in Quzhou County, Hebei Province. The soil was a Fluvisol according to the Second National Soil Survey or a Fluvent as per the United States Department of Agriculture soil taxonomic system. The texture of the topsoil was silt loam. Two years prior to the commencement of this study, winter wheat and summer maize were planted from October in 2006 to September in 2008, and no fertilizers were applied to the soils, to reduce residual soil nutrient levels in preparation for the subsequent experiments. The soil test parameters for the 0-0.3 m soil layer before planting in 2008 included soil pH (8.5), total N (0.23 g kg^{-1}), Olsen-P (6.15 mg kg^{-1}), exchangeable-K (96.8 mg kg^{-1}), and organic matter content (7.36 g kg^{-1}).

2.2. Experimental design

A winter wheat and summer maize rotation system, the most important agricultural production system in this region, was used for this study on the same plots over the four year period. Winter wheat was generally planted in early October using a seeder with a row spacing of 0.15 m and a seeding rate of 300 kg ha^{-1} and harvested in early June of the following year. After winter wheat harvest, summer maize was planted immediately with a row spacing of 0.6 m and a plant density of 6.5–7 plants m^{-2} and harvested in early October each year. The most commonly adopted cultivars in the region, Liangxing 99 for winter wheat and Zhengdan 958 for summer maize were used. A randomized complete block design with four replicates and six different N