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Agricultural sustainable intensification improved nitrogen use efficiency and maintained high crop yield during 1980–2014 in Northern China

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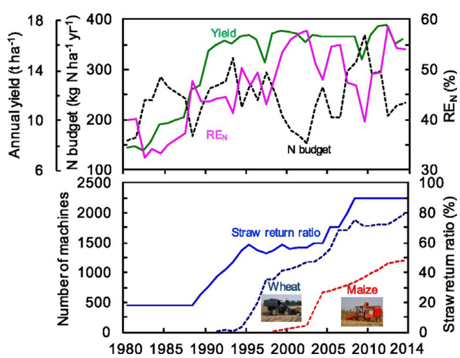
HIGHLIGHTS

- From 1980 to 2014 reactive N losses decreased by 21.5% in northern China.
- From 1980 to 2014 annual N recovery increased from 39.8% to 54.1% at a stable yield.
- Partial factor productivity may reach up to 45 kg grain kg^{-1} N_{fert} by 2030.
- Straw return and optimized fertilization enhanced soil N stock & reduced N losses.

GRAPHICAL ABSTRACT



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ABSTRACT

Global population increase will require rapid increase of food production from existing agricultural land by 2050, which will inevitably mean the increase of agricultural productivity. Due to agricultural sustainable intensification since the 1990s, crop production in Huantai County of northern China has risen to 15 t ha^{-1} yr^{-1} for the annual wheat–maize rotation system. We examined the temporal dynamics of nitrogen (N) budget, N losses, and N use efficiency (NUE) during the 35 years (1980–2014) in Huantai. The results revealed that atmospheric N deposition increased 220% while reactive N losses decreased by 21.5% from 1980s to 2010s. During 1980–2002, annual N partial factor productivity (PFP_N), apparent NUE and N recovery efficiency (RE_N) increased from 20.3 to 40.7 kg grain kg^{-1} N_{fert}, from 36.5% to 71.0%, and from 32.4% to 57.7%, respectively; meanwhile, reactive N losses intensity, land use intensity and N use intensity decreased by 69.8%, 53.4%, 50.0%, respectively, but without further significant changes after 2002. Overall increases in NUE and decreases in N losses were largely due to the introduction of optimized fertilization practice, mechanization and increased incorporation of crop straw in Huantai. Straw incorporation was also significant in soil N stock accrual and fertility improvement. By 2030, northern China may reach the lowest end of PFP_N values in developed countries (>45 kg grain kg^{-1} N_{fert}). These agricultural sustainable intensification practices will be critical in maintaining high grain yields and associated decreases in environmental pollution, although water use efficiency in the region still needs to be improved.

1. Introduction

Worldwide, agriculture is facing unpredicted challenges and risks, made more complicated due to the additional environmental need

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for higher nitrogen (N) use efficiency (NUE) in agriculture. Global population is likely to reach 7.9–10.5 billion by 2050 and this will require a rapid increase of global food demand from exiting agricultural land (Tilman et al., 2011; Bouwman et al., 2013; Ray et al., 2013), the area of which is unlikely to further increase due to current multiple pressures on available land and labor (Pretty and Bharucha, 2014). During the second half of the twentieth century, the Green Revolution has been the prime driver of increased per capita food production globally (Tilman et al., 2011). However, agriculture is also placing unpredictable requirements and demands on natural resource, which could hinder or obstruct environmental protection (Chen et al., 2014; Collins et al., 2016). The N loss from agriculture has increased significantly in comparison to losses from industrial and residential land within recent decades (Reungsang et al., 2007). In some of the most intensive agricultural production systems, over 50% of the fertilizer N applied is lost to the environment (López-Bellido et al., 2005; Ju et al., 2009). Such large losses of N from agriculture pose serious potential 'downstream' pressures on aquatic environment (Chien et al., 2009), air quality (Xu et al., 2016) and may also contribute to regional and global greenhouse gas emissions (Maris et al., 2015; Loick et al., 2016).

Sustainable intensification is defined as a process or production system in which crop yields are increased without adverse environmental impacts and without additional land use (Garnett et al., 2013). It has been implemented across different parts of the world, in various local environmental, economic and social contexts. For example, industrialized countries with intensive agriculture (e.g., North America, Australia, and most European countries) have improved the NUE with increasing yields contributed by the sustainable intensification since the 1980s (Ray et al., 2013; Lassaletta et al., 2014a). In contrast, developing countries, such as China, India, Pakistan, and Indonesia have generally experienced overall declines in NUE without benefit in terms of yields by increasing N fertilization since 1980 (Lassaletta et al., 2014a). In parallel, these developing countries have also continued to increase their nutrient inputs to cropland (Dobermann and Cassman, 2005). For China, the current agricultural NUE is generally low with high reactive N losses, leading to both unnecessary wastage of natural resources and enhanced dramatic environmental problems (Cui et al., 2014). The North China Plain (NCP) is one of the most important agricultural regions in China, and produced 67% and 28% of nation's wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) in 2014, respectively (NBSC, 2015). Overall crop yields in this region increased by a factor of 2.8 during 1980–2008, but the application of mineral fertilizers also increased by a factor of 5.1 (Chen et al., 2011). Studies on wheat and maize production in northern China revealed that the proportion of N losses from applied fertilizers via nitrate (NO_3^-) leaching, ammonium (NH_3) ammonification, nitrification/denitrification were in the ranges of 12.1–21.3%, 11.0–24.7% and 0.9–10.9%, respectively (Zhang et al., 2008; Ju et al., 2009; Butterbach-Bahl et al., 2011).

One critical important issue to address on further improving crop production is the pattern of agriculture productivity and N utilization and loss during the past three decades of agricultural sustainable intensification at a regional scale in northern China. We hypothesized that the process of agricultural sustainable intensification in some developed regions of northern China improved NUE and reduced N losses. Huantai County, a typical farming region in northern China, was chosen to test this hypothesis. Huantai was the first county in northern China to achieve an average grain yield of 15 t ha^{-1} after 1990 (Liao et al., 2015). We quantified changes in NUE and reactive N losses of nitrous oxide (N_2O), nitric oxide (NO), nitrogen gas (N_2), NH_3 and NO_3^- during the period 1980–2014. Factors driving the changes in NUE and losses were analyzed. The study aimed to provide scientific insights and support for the development of sustainable agriculture in China and other countries.

2. Materials and methods

2.1. Study area

Huantai is located in Shandong Province, northern China (36°51′50″–37°06′00″N, 117°50′00″–118°10′40″E) (Bai et al., 2011). The farmed area in Huantai is 510 km^2. The region has a typical continental monsoon climate, with annual average temperature of 12.5 °C and an annual frost-free season of about 198 days (Chen et al., 2010; Liao et al., 2015). Annual precipitation is 543 mm with most rainfall during June–August, and soil parent materials are mainly mountain diluvium and Yellow River alluvial deposits, which developed into loam soils classified as Calcaric Fluvisols with pH (H_2O) 8.29, soil organic carbon content of 10 g kg^{-1} and total N content of 1.1 g kg^{-1} (Chen et al., 2010; Yan et al., 2013). An annual double crop rotation of winter wheat (*T. aestivum* L.) and summer maize (*Z. mays* L.) form the main cropping in the county.

2.2. Data collection

Data of land use, grain yield, mineral fertilizer rate, irrigation and crop straw incorporation were collected from the annual Huantai Agricultural Yearbook for the period 1980–2014. This study focused on winter wheat and summer maize as these two crops have always occupied >80% of total cropland area in Huantai. A more detailed description of N inputs (fertilizer, incorporated/return, deposition, irrigation and seeds) and N outputs (crop removal, NO_3^- leaching and gaseous emission) is provided in Supporting Information (SI). It should be particularly mentioned that from 1980s to 2010s, organic manure was only used on vegetable and fruits in Huantai, thus total N inputs do not include the N from organic fertilizers.

2.3. Establishing models of N content of crop straw and grain and reactive N losses

Data collection and model establishment are listed in the SI. The fitted equations were as follow:

N content (Y, g kg^{-1}) of straw or grain for wheat and maize (SI Fig. S1):

$$\text{wheat straw}: Y = -0.57{x_1}^2 + 2.25x_1 + 4.48 \quad (1)$$

$$\text{wheat grain}: Y = -1.34{x_1}^2 + 4.99x_1 + 16.33 \quad (2)$$

$$\text{maize straw}: Y = -0.70{x_1}^2 + 2.49x_1 + 4.95 \quad (3)$$

$$\text{maize grain}: Y = -0.59{x_1}^2 + 2.30x_1 + 12.57 \quad (4)$$

where x_1 = fertilizer N applied (×100 kg N ha^{-1}).

Similar to N content, we also carried out a mini meta-analysis for the regression relationship of reactive N losses (volatilization, leaching, nitrification/denitrification) with N rate or N surplus based on studies in northern China (SI Fig. S2). The derived fitted equations were as follow:

NH_3 volatilization (Y, kg N ha^{-1}) with N application rate:

$$\text{wheat}: Y = 0.11x_2 - 2.63 \quad (5)$$

$$\text{maize}: Y = 0.16x_2 - 8.10 \quad (6)$$

where x_2 = fertilizer N applied (kg N ha^{-1}).

N_2O emission (Y, kg N ha^{-1}) with N surplus:

$$\text{wheat}: Y = 0.55e^{0.0048x_3} \quad (7)$$

$$\text{maize}: Y = 1.57e^{0.0076x_3} \quad (8)$$

where x_3 = N surplus = (fertilizer N applied − N removal via crop straw and grain) (kg N ha^{-1}). The emission factors for NO and N_2