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A green eco-environment for sustainable development: framework and action

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Abstract Following its 40-year reform and 'Open Door' policy, China has recently proposed a new approach to green development and rural revitalization—the idea of Agriculture Green Development (AGD), with the key feature of creating a green eco-environment. In this mini-review we introduce the definition, theory, framework and major components of a green eco-environment as a key part of the AGD. We define a green eco-environment as including four key elements or measures: (1) a green eco-environmental indicator system; (2) environmental monitoring and warning networks; (3) emission standards and environmental thresholds for key pollutants; (4) emission controls and pollution remediation technologies. We have used Quzhou County (a typical county in the center of the North China Plain) as an example to show how detailed air, water and soil monitoring networks, as well as improved farmer practices and pollution control measures (especially ammonia emission mitigation and PM$_{2.5}$ pollution reduction), can begin to create a green eco-environment in China and that AGD is possible. We conclude by stressing the need to improve the framework and practice for a green eco-environment, especially the importance of linking proposals and practices for a green eco-environment with the United Nations high priority Sustainable Development Goals.

Keywords monitoring networks, environmental thresholds, ammonia emission mitigation, green ecological environment, Quzhou County

1 Introduction

Producing enough food and fiber (often based on large chemical inputs) is the prime task of agriculture. Maintaining air, water and soil quality and biodiversity is the aim of environmental protection, which requires minimal if any pollutant emissions. The two are often in conflict. To overcome this conflict, scientists have proposed the concept of sustainable agriculture or the sustainable intensification of agriculture[1]. China's situation is little different from developed countries. China has produced and consumed the largest amounts of chemical fertilizers, pesticides and plastic film and irrigated the largest areas of cropland worldwide since the 1990s[2,3]. As a consequence, environmental problems such as air pollution[4,5] resulting in enhanced N deposition[6], soil acidification[7] and water pollution[8] have been widely reported due to the overuse of N fertilizer and other chemical inputs over the same time period. Considering such serious conflict between intensive agricultural development and ecological environment protection, we believe that China needs a new concept/framework to solve these problems and balance agricultural development and environmental sustainability.

With the release of global sustainability indexes, in particular the United Nations Sustainable Development Goals, Agriculture Green Development (AGD) has been introduced by the 19th National Congress of the Communist Party of China in 2017 as 'a national strategy of sustainable development; pursuing green development'. AGD emphasizes the need for developing both a more sustainable agriculture and a more green eco-environment and food industry. The establishment and maintenance of a green eco-environment are key issues in AGD practice. In this mini-review, we define the concept, framework, practice and actions needed to create a green eco-environment through interdisciplinary research. In general, AGD has a close relationship with the sustainable

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development of agricultural systems[9]. The difference is that AGD emphasizes both environment (green) and production (development) while sustainable development pays more attention to environmental protection. To demonstrate what has already been achieved in precursors to AGD, and therefore that AGD is achievable, we report some of the research and development carried out in Quzhou County by China Agricultural University (CAU)[10,11].

2   Framework for a green eco-environment

A green eco-environment must run through the whole agricultural production chain, which includes 'green' plant breeding, 'green' farming, 'green' processing and 'green' consumption. It can be understood as integrating eco-environmental protection with agricultural production. From the perspective of environmental components, a green eco-environment can be defined as a combination of excellent air quality, healthy soil, clean water, high biodiversity and a beautiful rural landscape. To realize these five proposed goals, here we develop a conceptual model for high environmental quality of the water-soil-air system in agricultural production (Fig. 1). This will promote the transformation of traditional agriculture and change environmental damage to environment-friendly green agriculture, achieving good eco-environmental service function and agricultural sustainable development in today's China and other developing countries worldwide.

To achieve a green eco-environment, we define the following four actions required: (1) develop a green eco-environmental indicator system; (2) establish monitoring and warning networks; (3) set emission standards and environmental thresholds for key pollutants; (4) develop new emission control measures and pollution remediation technologies. Measures (1–3), in turn, provide feedback to optimize measure (4). For the implementation of each measure, we provide an introduction and key points below.

2.1   Green indicator system—a core factor in achieving a green eco-environment

A green agricultural system that is able to confront the challenges of the human demand for food and yet be environmentally friendly requires an indicator system that comprises the defining elements of a green eco-environment. Such a system can guide relevant work on environmental monitoring and assessment, the establishment of environmental thresholds, and pollution remediation. In selecting indictors, it should consider agricultural
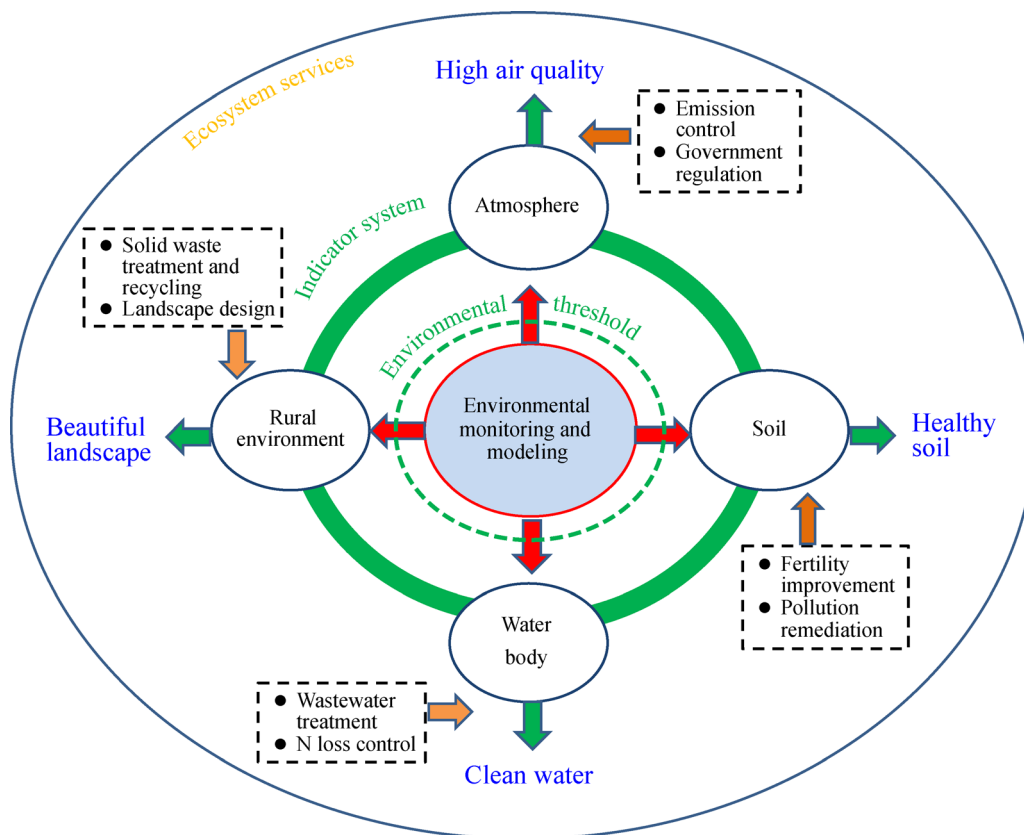

Fig. 1   The conceptual model of a green eco-environment with five ultimate goals: clean air, clean water, healthy soil, high biodiversity, and a beautiful landscape.

scales and existing and/or foreseeable environmental risks. At the farm level, a major task is to identify indicators that signal performance or specific management problems, or which identify undesirable environmental changes and the actions that are needed to rectify them. The focus must be on changing practices at the farm scale in a way likely to improve overall farm 'health'[12].

There is still much debate about whether to use location-specific or universal indicators. Some argue that the important indicators of sustainability are location specific and vary between eco-regions. For example, on hillsides, soil erosion has a major impact on sustainability, but in flat lowlands it is insignificant and may not be a useful indicator; soil organic matter content as a universal indicator might be more useful. In Quzhou County, according to our previous environmental assessments, agricultural ammonia emissions, cropland nitrogen surpluses, PM$_{2.5}$ (fine particulates smaller than 2.5 μm) concentrations, the extent of livestock production and nitrate leaching are proposed as the most useful indicators for evaluating green agriculture at the county scale[13,14]. Additionally, diversity conservation can be achieved by afforestation, diversified crop planting, integrated cropping system and animal production system.

2.2 Establishing monitoring and warning networks

Establishing a comprehensive network for monitoring agriculture is crucial to evaluating the state of the environment and the effectiveness of environmental protection measures. Such a network will use a combination of monitoring, modeling and remote sensing for integrated measurements of key pollutants in water, air and soil, with the aim of (1) not only evaluating the current status of the environment but also forecasting trends in both the short- and long-term, and (2) identifying pollution sources and their relative contributions. As an example, in order to mitigate air pollution, the Chinese government introduced a nationwide air quality monitoring network in 2013 that includes hourly measurements of major atmospheric pollutants (PM$_{2.5}$, PM$_{10}$, SO$_2$, NO$_2$, CO and O$_3$) at 1499 sites in 366 cities and counties. In addition, existing national monitoring programs to quantify surface ammonia concentrations include the Chinese Nationwide Nitrogen Deposition Monitoring Network (NNDMN, monthly data) established in 2010[13–15], Ammonia Monitoring Network in China (AMoN-China)[16], the Ammonia Monitoring Network in the US (AMoN-US) as well as the European Monitoring and Evaluation Programme (EMEP)[17].

2.3 Setting environmental thresholds for key pollutants

Emission standards for each pollutant need to be established, based on national or international environmental standards. However, establishing environmental thresholds such as cropland N inputs must balance two aspects: on one hand, avoiding adverse impacts of elevated reactive nitrogen emissions to water, air and soils, and on the other hand, feeding the population in an adequate way. Based on the Planetary Boundaries (PBs) framework, environmental limits have been widely studied at regional and national scales[18,19]. The concept of PBs is fairly recent[20] and is defined as a set of nine physical and biological limits for the Earth and introduced as planet-wide environmental boundaries or 'tipping points'. For example, the widely accepted environmental threshold for nitrate concentration in drink water or groundwater is 50 ppm or 11.3 mg·L^{-1} N. The concept is that, beyond PBs humanity is at risk, while values below the PBs are considered to be a 'safe operating space'.

2.4 Developing new emission control and pollution remediation approaches

It is essential that advanced technologies and management strategies are developed that not only increase nutrient use efficiency and reduce the environmental impact per unit of food produced, but also remediate polluted environments. At present, options for reducing the environmental footprint of food production include dietary changes toward healthier, more plant-based diets, improvements in technologies and management practices, and reductions in food loss and waste[21]. For example, options for cropping include '4R Nutrient Stewardship' (Right fertilizer products, rate, place and time), optimal farming practices (irrigation, residue retention, amendments), and enhanced efficiency fertilizers (fertilizers with urease inhibitors, nitrification inhibitors or controlled release coatings) that reduce methane, nitrous oxide and ammonia emissions[22–24], and for livestock production include the manipulation of animal diets[25], the trapping of particulate emissions and the installation of methane capturing systems. These could all reduce air and water pollution, increase manure-nitrogen recycling rates and improve sanitation[8].

As for polluted environments, remediation strategies for pesticides in soil, for example, that have been intensively researched and widely used can be divided into two categories: microorganism/plant-based technologies and abiotic methods such as physical or chemical remediation[26]. Physical remediation methods aim to isolate or remove pesticides from soil by, e.g., soil washing and electrokinetic soil flushing. These treatments have been proved to be effective at removing 2,4-D and oxyfluorfen from soil[27,28]. However, because of the high costs and possible damage to soil quality caused by the treatment equipment, this method is not suitable for the remediation of non-point source contaminated farmland soils. Bioremediation, especially microbial remediation, is a promising solution for the removal of pesticide residues in arable

land due to it being much cheaper, having a shorter processing cycle potentially causing no environmental damage[29].

No single measure is sufficient to maintain all pollutants within all PBs (i.e., the boundaries of the green eco-environment) at the same time. A combination of effective measures is needed to fully alleviate the projected increase in environmental pressures.

3 Practice and action for a green eco-environment in Quzhou County

3.1 Establishment of environmental monitoring network

Taking Quzhou County (at the center of North China Plain) as an example, we have established environmental monitoring networks for air, water and soil quality. There are two air quality monitoring networks in Quzhou County. The first is organized by the Bureau of Environmental Protection of Quzhou County and comprises 12 sites (one at each of ten villages and towns and two sites in the county center) and covers six typical air pollutants: $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO and O_3. The second network is run by CAU and includes complete N wet and dry deposition as well as $PM_{2.5}$ and its chemical components, with one site at Quzhou Experimental Station with daily, weekly and/or monthly sampling frequency[13,30] and an NH_3 monitoring network based on passive ALPHA samplers (10 sites with weekly sampling frequency) initiated in August 2018 (Fig. 2). Regular surface water quality monitoring at 20 sites, with monthly sampling, began in November 2018 along the Zhizhang and Fuyang rivers (Fig. 2). The pH, EC, ammonium N, total N, total P as well as COD in water samples are measured. CAU has also carried out a county-scale soil quality monitoring campaign (1 km × 1 km resolution for mineral N including nitrate and ammonium N in 5 soil layers (0–20, 20–40, 40–60, 60–80, 80–100 cm) in March 2018[31]. These air, water and soil monitoring networks provide basic information on the current air, water and soil quality/pollution status, which are important for determining whether county-level pollution control measures (e.g., NH_3 emission mitigation action) are effective.

3.2 Dynamics of NH_3 and air quality indices based on monitoring network

To make an assessment of air quality in Quzhou County, we reviewed the concentrations of six major air pollutants from 2014 to 2017 measured at one site in the county center, which belongs to the air quality monitoring network under the Ministry of Ecology and Environment of China.

As shown in Fig. 3, during 2014–2017, the annual average concentrations of SO_2, $PM_{2.5}$, PM_{10}, and CO
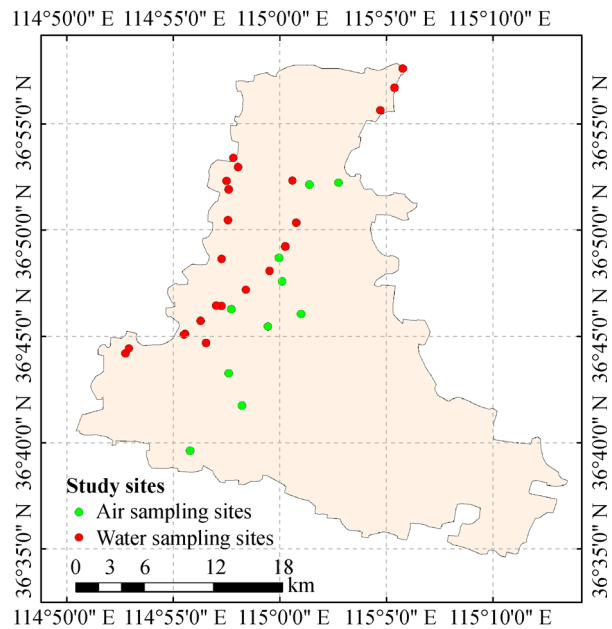

Fig. 2 Spatial distribution of surface water and ammonia sampling sites in Quzhou County.

decreased but to different extents (Fig. 3). In 2017, the annual concentrations of SO_2, $PM_{2.5}$, PM_{10}, and CO were 46.0, 72.8, 124.3, and 1.5 $mg·m^{-3}$, respectively, which were equivalent to respective reductions of 8%, 25%, 37%, and 29% when compared to corresponding concentrations in 2014. In contrast, annual concentrations of NO_2 and O_3 both showed slight increases in 2017, the NO_2 concentrations were slightly higher than the Grade II limit (40 $μg·m^{-3}$) of the National Ambient Air Quality Standard (NAAQS, GB3095-2012), and the annual $PM_{2.5}$ concentrations in 2017 were still twice the Grade II limit (35 $μg·m^{-3}$). Based on statistical analyses on polluted days, the three most important air pollutants were $PM_{2.5}$ (196 d), O_3 (79 d) and PM_{10} (58 d). Therefore, emission controls that synergistically reduce concentrations of NO_2, SO_2 and NH_3 are urgently needed because of their multiple impacts on $PM_{2.5}$ and O_3 concentrations.

3.3 Action to improve crop productivity while reducing NH_3 emissions

3.3.1 Demonstration field experiments

As reported in previous papers[13,14], NH_3 pollution was one of the most serious environmental issues in Quzhou County. To determine the most effective NH_3 emission control strategies, several field trials were laid out in Quzhou County to optimize the potential for N reduction and the efficacy of the novel urease inhibitor Limus® (Fig. 4). Optimized N application (N_{opt}) on its own reduced
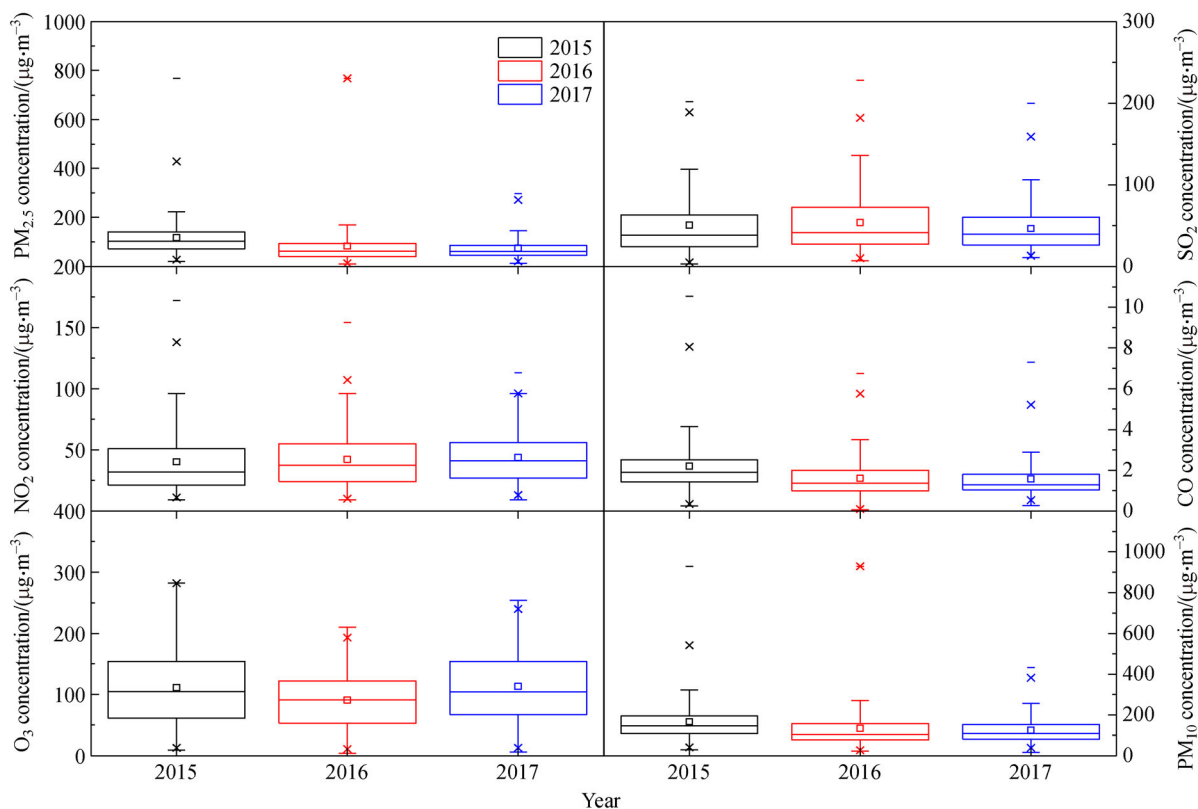
Fig. 3 Box plots of daily concentrations of $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and O_3 during 2015–2017 in Quzhou County. Data from open assessed air quality monitoring network under the Ministry of Ecology and Environment of China[32].

NH_3 loss and improved nitrogen use efficiency (NUE, to be defined as the percentage of net crop N uptake in N treatment (relative to Control or Zero N treatment) to total fertilizer N input) but led to lower grain yields compared to conventional N applications (N_{con}). Urease inhibitors were designed to inhibit soil urease activity and retard urea hydrolysis to allow time for surface-applied urea to move into the soil, slowly releasing mineral N to meet crop growth needs, minimizing NH_3 volatilization and improving N use efficiency[10,33]. Using Limus ($N_{opt/L}$) resulted in a 30% improvement in NUE and 70% reduction in NH_3 emissions compared to use of urea alone (N_{opt}); grain yield also increased and was comparable with high N treatments. Yield-scaled NH_3 emissions (defined as NH_3 emission per unit crop yield) are effective at showing the environmental cost of crop production[34]. Limus amendment reduced yield-scaled NH_3 emissions by 75%.

3.3.2   Demonstration on farmers' fields

The efficacy of a urease inhibitor in a field experiment may not be replicated at the larger scale in farmers' fields due to soil heterogeneity, climate or poor farming management. To test if this was the case, a demonstration field trial was established with area of 2 ha in Quzhou County (latitude 36°51′ N, longitude 115°1′ E), and the efficiency of the urease inhibitor was evaluated under local farmer practice. Applying fertilizer with Limus® reduced NH_3 emissions by 50% and 60%, respectively, while yield increased by 4% and 11%, respectively, in wheat and maize production, compared to normal urea use on local farms (unpublished data).

3.3.3   Demonstration at the county level

In 2009, CAU launched the innovative model of Science and Technology Backyards (STBs) to support farmers on their farms, and STBs were first practiced in Quzhou County[11]. One of the main tasks for STBs, together with applying national soil testing and fertilizer recommendations, was to increase crop production and nutrient use efficiency while reducing N losses to the environment (including NH_3 loss) by optimizing N inputs in crop production. As shown in Fig. 5, STBs plus national soil testing and fertilizer recommendations have led to a 20% yield increase and a 10% decrease in N fertilizer use. In addition, through a series of air pollution control measures and the positive impact of STBs, annual concentrations of $PM_{2.5}$ have declined significantly (by 50% or more) in Quzhou County, Handan city over the last ten years[35]. This shows that high yield and high nutrient use efficiency can be achieved at the same time as lower environmental emissions and improved air quality at a county level.
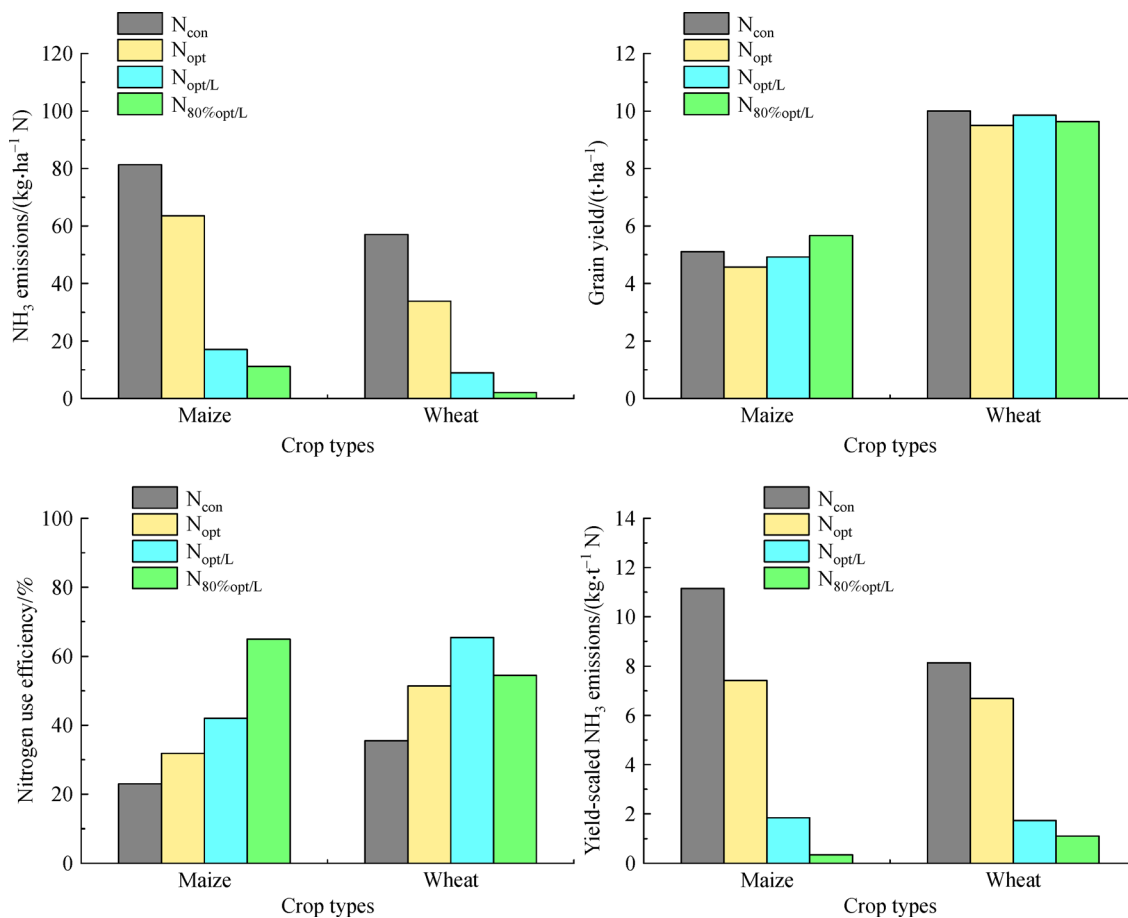
Fig. 4   Field trials with the urease inhibitor Limus® (L) in Quzhou County. N_{con}, N_{opt}, $N_{opt/L}$, $N_{80\%opt/L}$ denote conventional N, optimized N, optimized N with Limus, 80% of opitmized N with Limus treatments in maize and wheat field experiments, respectively (data from Li et al.[10,24]).

4   Conclusions and outlooks

In this paper, we systematically propose the definition, framework and main components of a green eco-environment as part of Agriculture Green Development. It consists of four key measures: (1) a green eco-environmental indicator system; (2) environmental monitoring and warning networks; (3) emission standards and environmental thresholds for key pollutants; (4) emission control approaches and pollution remediation technologies. We took Quzhou County as an example and discussed its environmental monitoring networks, county-level action for a green eco-environment (e.g., agricultural NH$_3$ mitigation). We have shown successful results to date of: (1) significant NH$_3$ emission reductions (up to 50%–60%) with a small yield increase (4%–11%) by using a urease inhibitor on farmers' croplands; (2) a substantial air quality improvement (50% decrease in PM$_{2.5}$ concentrations in the last decade) by using an optimized N application rate (−10% of traditional farmer practice) at the same time as an increased grain yield (+20%) and NUE (+30%). However, as a novel and developing concept/framework,
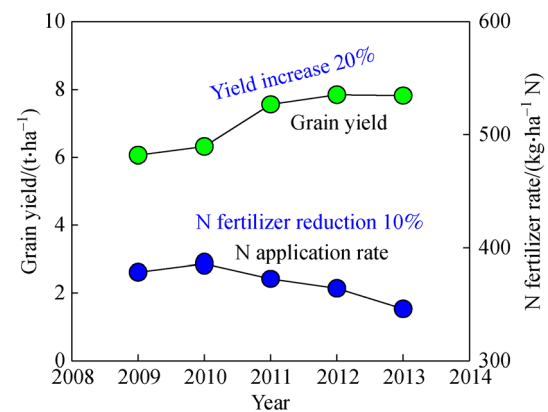

Fig. 5   Trends in grain production and N fertilizer inputs in Quzhou County.

the theory and practice of a green eco-environment (including green rural environment and ecosystem services) needs further research and improvement, especially linking it to the United Nations high priority Sustainable Development Goals.

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