Field Crops Research 318 (2024) 109572

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Integrated farming optimization ensures high-yield crop production with decreased nitrogen leaching and improved soil fertility: The findings from a 12-year experimental study

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ARTICLE INFO

Keywords:
Sustainable intensification
Grain production
Nonpoint source pollution
Nitrogen leaching
Nitrogen use efficiency

ABSTRACT

Context or problem: Sustainable farming practices, including precision fertilization, water-saving irrigation and recycling of organic materials, have been implemented worldwide in recent decades to achieve high crop yields and minimize nonpoint source pollution. However, the comprehensive impacts of these agricultural practices have seldom been systematically evaluated in field production. As agricultural intensification started in the 1980s, most previous studies focused on a single practice in the context of low land productivity.
Objective or research question: The objective of this research is to investigate and evaluate how holistic farming practices affect both crop production and environmental quality.
Methods: We reported findings from a 12-year experiment (2008–2020) in the highly intensive North China Plain (NCP) farming region, and conventional and optimized farming measures were compared. Three field treatments with annual double cropping (winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.)) were chosen in the study, i.e., control without nitrogen (N) application (CK), farmers' conventional practices (CON), and optimized practices (OPT), were chosen for this study.
Results: Compared with the CON treatment, OPT reduced N fertilizer input by 41.4 % and irrigation water by 27.1 % but produced similar grain yields; OPT increased the N recovery efficiency (RE_N) and N utilization efficiency (NUT_2E) by 90.4 % and 53.0 %, respectively; these values were much greater than the increases in RE_N (+56.1 %) and NUT_2E (+25.5 %) when soil N change was not considered. Similarly, compared with those in the CON treatment, the soil N stock (0–60 cm) in the OPT treatment increased by 8.4 %, and the N loss via leaching, ammonia volatilization and $N_2O + NO + N_2$ decreased by 47.1 %, 11.4 % and 28.6 %, respectively.
Conclusions: Our study revealed that the integration of optimized practices of organic material recycling, precision fertilization and water-saving irrigation substantially reduced N losses, mainly through decreased N leaching, but maintained fertilizer N in the root-zone soil layer, which is important for a sustainable and high-yield crop production.
Implications or significances: The dissemination of these optimized practices to other regions in China and beyond will be highly important for achieving the dual goals of food security and environmental protection.

1. Introduction

Conventional intensive agriculture has achieved high-yield crop production and has also placed considerable negative pressure on natural resource utilization and water eutrophication, air pollution and soil degradation in China and worldwide (Beltran-Peña et al., 2020; Bolinder

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https://doi.org/10.1016/j.fcr.2024.109572
Received 1 May 2024; Received in revised form 22 August 2024; Accepted 3 September 2024
Available online 10 September 2024

et al., 2020; Ju and Zhang., 2017). The nitrogen (N) fertilizer use efficiency has decreased as agricultural intensification has progressed (Gu et al., 2017; Lassaletta et al., 2014b) during the past several decades, resulting in high-level waste and loss of fertilizer resources and soil degradation, through acidification and decreased fertility (Carlson et al., 2017; Gu et al., 2015a; Guo et al., 2010). Sustainable intensification was initiated worldwide and employed as an alternative approach beginning in the 1980s (Cassman, 1999; Ruttan, 1991; Trenbath et al., 1990) to sustain high-yield crop production while reducing the associated adverse environmental impacts (Garnett et al., 2013; Huang et al., 2018). In China, sustainable intensification practices such as optimizing and reducing fertilization and irrigation inputs have been implemented since the 2000s (Zhang et al., 2021).

Irrigation and fertilization are two important farming practices for crop production in uplands (Ren et al., 2022; Yin et al., 2021). On the North China Plain (NCP), one of the most intensive agricultural regions in China, fertilization inputs have been much excessive (up to 600 kg N ha^{-1} yr^{-1}), and flood irrigation has ranged from 150 to 490 mm yr^{-1} for annual double cropping systems of winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) since the 1980s (Fang et al., 2010). These practices have resulted in low N use efficiencies (NUEs) and high N losses via N leaching (10.6 %–18.2 %) and ammonia volatilization (10.0 %–17.6 %), and these two main pathways of N loss account for 10.1 %–56.9 % and 29.4 %–95.9 %, respectively (Adalibieke et al., 2021; Cui et al., 2013; Ma et al., 2021), of the total field reactive N (Nr) loss during the maize and wheat seasons. Since the 1990s, water-saving irrigation and precision fertilization have been employed in northern China to save groundwater resources and prevent nonpoint source pollution in the region (Zhang et al., 2017). However, most of the previous studies monitored N losses within a short duration (1–3 years; Wang et al., 2019), and few studies monitored the major pathways of N loss (N leaching and ammonia volatilization) simultaneously (Gai, 2019; Zhang et al., 2018). The recycling of organic materials was also introduced in the 1990s to improve long-term land productivity in the region (Bolinder et al., 2020; Chen et al., 2011; Yin et al., 2018). Straw incorporation increases crop yield, reduces N leaching and limits the downward movement of N in the soil (Meng et al., 2021), but the long-term effects need to be systematically evaluated. These studies highlighted that additional long-term studies are necessary to examine how these optimized farming practices holistically affect N loss, the soil N pool and crop production.

Precise quantification of NUE is highly necessary for evaluating the applicability of optimized farming practices at regional, national and global scales. The NUE indicators are usually defined as the partial factor productivity of N (PFP, in kilograms of grain per kilogram of N fertilizer applied) or the N recovery efficiency (RE_N, the difference in grain N harvested between farmland with and without fertilization divided by the N fertilizer rate; Cassman et al., 2002). In China, the national PFP increased from 27 kg grain kg^{-1} N_{fert} in 1995 to 38 kg grain kg^{-1} N_{fert} in 2015 (Liu et al., 2020), and the RE_N decreased from 51 % in 1984 to 35 % in 2003 and then increased steadily to 40 % in 2020 (Ministry of Agriculture and Rural Affairs, PRC 2020). These NUEs are mostly quantified by assuming that the soil N stock did not change during the experimental period (Quan et al., 2021). This approach is applicable for short-term experiments; however, in long-term fertilization experiments, the soil N stock may substantially change and thereby affect the accuracy of estimated N efficiencies (Ladha et al., 2005).

Many previous studies have focused on the effects of individual farming practices (such as the N rate, fertilizer type, straw incorporation and irrigation) on crop production and the environmental impacts (Adalibieke et al., 2021; Cui et al., 2013; Ma et al., 2021; Zhang et al., 2017). However, given that actual crop production is typically influenced by multiple management practices together, exploring the interactive effects of these farming variables in a more integrated manner is highly valuable (Rillig et al., 2019). Therefore, in 2008, a field experimental study on the NCP where agricultural intensification dominated was conducted to investigate and evaluate how holistic farming practices together affect crop production and environmental quality. We aimed to validate the first hypothesis, i.e., optimized farming measures will ensure high-yield production in the long-term within the context of intensive conventional farming. The second hypothesis stated that N losses are proportionally reduced as excessive N fertilization decreases. The N efficiency and soil fertility were also evaluated during the 12-year experimental period to explore how good agricultural practices work together. Our findings will help in seeking effective and robust farming measures in cereal crop production for green agricultural development.

2. Methods

2.1. Study area and experimental design

We established the field experiment in October 2008 at the Huantai Experimental Station of China Agricultural University, Shandong Province (36°51'50"–37°06'00"N, 117°50'00"–118°10'40"E), which is located on the NCP. The region has a typical temperate monsoon climate, and the annual mean precipitation and air temperature are 543 mm and 12.5°C, respectively (Zhang et al., 2019). The soil parent materials are mainly Yellow River alluvial deposits, which have developed into loamy soils classified as calcaric fluvisols (Liang et al., 2013), with a bulk density (BD) of 1.5 g cm^{-3}, pH (water: soil=2.5:1) of 7.7, soil organic matter content of 18.8 g kg^{-1}, and total nitrogen (TN) content of 0.41 g kg^{-1} (0–20 cm). The soil consists of 14.0 % clay (<0.002 mm), 12.5 % silt (0.002–0.02 mm), and 73.5 % sand (0.02–2 mm) (Shi et al., 2014). The cropping regime in the region consists of annual double-cropping of winter wheat from October to May of the following year and summer maize from June to September.

Three field treatments (4 replicate plots per treatment, for a total of 12 plots, 450 m^2 per plot) were chosen from the long-term field experiment: 1) CK: no N fertilizer input. Both wheat and maize straws were incorporated, and flood irrigation (100 mm per irrigation event) was applied, with no tillage before wheat sowing. 2) CON: Local farmers' conventional practices (300 kg chemical fertilizer N ha^{-1} $season^{-1}$ both for the winter wheat and summer maize seasons); only wheat straw was incorporated (maize straw was removed due to the high cost of manual and equipment). Similar to local farmer operations, crops were flooded with 100 mm of groundwater (well depth > 80 m) per irrigation event, and irrigated 3–5 times during the wheat season and 1–2 times during the maize season according to soil moisture and crop growth. The irrigation water was delivered via plastic hoses, and flow meters were used to measure the water quantity. Rotary tillage was implemented (~15 cm) before wheat sowing each autumn. 3) OPT: N fertilizer input was determined by soil inorganic N testing and formulated fertilization (STFF): for both the wheat and maize seasons, a crop N demand of 180 kg N ha^{-1} per season was set for a target crop yield of 7.5 t ha^{-1}. The soil N supply, mainly nitrate N, was analyzed at the beginning of each season (Cui et al., 2008). The organic and chemical N fertilizer inputs, i.e., the difference between crop N demand (180 kg N ha^{-1} $season^{-1}$) and the soil N supply, changed across the years due to variations in soil properties and crop production. For the 12-year experimental period, the average seasonal N fertilizer inputs for OPT were 161 (wheat season) and 191 N ha^{-1} $season^{-1}$ (maize season), in which approximately 1/3 of the N fertilizer was from organic fertilizer (composted broiler manure; Table S1) and the other 2/3 was from chemical fertilizer. Both wheat and maize straw were incorporated, and water-saving irrigation was adopted with 75 mm per event on the same date as CON. The soil was deeply plowed (25–30 cm) before the wheat sowing in each autumn.

For the CON and OPT treatments, the ratio of basal N fertilizer to topdressing N fertilizer for the winter wheat and summer maize seasons was 1:1. The wheat was sown in early October, and the maize was interplanted within the wheat field at the end of May before the wheat harvest by manual sowing. For the OPT treatment, 2/3 of the basal N fertilizer input was organic fertilizer for both the winter wheat and summer maize seasons, and the remaining 1/3 of the basal N fertilizer was urea. The top-dressing N fertilizer used was urea, which was applied at the shooting stage. Other inputs of N, such as atmospheric N deposition, N from irrigation water, abiotic N fixation, seed N, and incorporated straw N, also occurred during the experimental period. The detailed quantification of N input is presented in Appendix 1.1.

For both the CK and CON treatments, from 2008 to 2014, phosphorus (P) and potassium (K) fertilizers were applied only during the wheat season at rates of 120 kg P_2O_5 ha^{-1} (triple superphosphate) and 100 kg K_2O ha^{-1} (potassium sulfate), respectively, during the maize season. In addition to the same amount of P and K input from chemical fertilizer as that in the CK and CON treatments, 24–77 kg P_2O_5 ha^{-1} and 79–196 kg K_2O ha^{-1} in the wheat season and 60–65 kg P_2O_5 ha^{-1} and 153–178 kg K_2O ha^{-1} in the maize season were from organic fertilizer input. From 2015–2020, the P fertilization inputs in the CK and CON treatments were changed to 140 kg P_2O_5 ha^{-1} (wheat season) and 100 kg P_2O_5 ha^{-1} (maize season), respectively; for the OPT treatment, in addition to the same amount of chemical P input as that in the CK and CON treatments, 49–64 and 53–68 kg P_2O_5 ha^{-1} additional organic fertilizer were applied during the wheat and maize seasons, respectively. The K fertilization rates for the wheat season and summer season were the same, i.e., 60 kg K_2O ha^{-1} from chemical fertilizer for the CK, CON and OPT treatments, and in the OPT treatment, organic fertilizer additionally supplied 125–183 kg K_2O ha^{-1}. All these P and K fertilizers were applied as basal fertilizers. Pesticides and herbicides were sprayed to control disease and weeds. The detailed farming information is listed in Table S1.

2.2. Measurement of N losses

N leaching and NH_3 volatilization were monitored from 2017 to 2020, and N_2O emissions were monitored from 2011 to 2016. The actual monitored average annual/seasonal values were considered the average for the 12-year experimental period. For N leaching, field N leachate was collected after each irrigation and rainfall event and every 10 days if there was no irrigation or rainfall; ceramic suction cups were used to collect leachate and determine the TN content; and the leachate volume was quantified via water tensiometers (Fan et al., 2014; Moreno et al., 1996). NH_3 volatilization was measured daily via the continuous airflow enclosure method within the 1st week after fertilization and once every two days in the 2nd week (Kissel et al., 1977). For N_2O emission, the closed chamber method was adopted (Hutchinson and Mosier, 1981; Yan et al., 2015): gas fluxes (N_2O) were collected every day for 10 days after fertilization and irrigation/heavy rainfall, twice a week during the nonfertilization/irrigation/precipitation period from March to November, and once a week from December 15 to March 15 (nongrowing season). The detailed farming practices, as well as the measurements and calculations of N leaching, NH_3 volatilization and $N_2O + NO + N_2$ emissions, are listed in Appendixes 1.2.

2.3. Auxiliary measurements

Daily precipitation and temperature data were obtained from an AR5 automated meteorological station (Xinyuanshijie Technology Co. Ltd., Beijing, China) located 100 m from the experimental plots. The irrigation water quantity during each event was recorded. For irrigation water and precipitation water, the TN content was analyzed via potassium persulfate digestion and ultraviolet spectrophotometry.

Crop yield was measured during the harvest stage from a 2.5×3 m area for wheat and a 3×3 m area for maize in each replicated plot. The quantity of N in the grains and straw was determined via a CN analyzer (Thermo Flash EA 1112 Flash 2000, USA).

The soil was sampled (at intervals of 20 cm for the 0–100 cm profile, 3 samples per plot) every year after crop harvest every year. Soil inorganic N (i.e., NH_4^+ and NO_3^-) was extracted from fresh soil with a 1 M KCl solution (soil: solution=1:5) and analyzed via a continuous flow analyzer (AA3, SEAL, Inc., Germany). The air-dried soil was ground and oven-dried to determine the TN content via a CN analyzer (Thermo Flash EA 1112 Flash 2000, USA).

The TN stock was calculated by the following equation:

$$\text{TN stock}\ (\text{kg N ha}^{-1}) = \sum_{i-1}^{5} \rho_i \times 0.2 \times 10000 \times c_i \quad (1)$$

where ρ_i is the soil bulk density of the i^{th} soil layer (g cm^{-3}); c_i is the TN content of the i^{th} soil layer (g kg^{-1}); and i=1, 2, 3, 4, and 5 represent the 0–20, 20–40, 40–60, 60–80, and 80–100 cm soil layers, respectively.

2.4. N use efficiency, N balance and the contributions of different sources of N input to N output

In the present study, four N use efficiency indicators were calculated: partial factor productivity (PFP, kg grain kg^{-1} N_{fert}), apparent N use efficiency (ANUE, %), recovery efficiency (RE_N, %) and N utilization efficiency (NUE, %). We considered two scenarios for the calculation of N efficiency, i.e., the change in the soil N stock was considered or not considered during the experimental period.

1) Scenario I: the change in the soil N stock was not considered.

The PFP (kg grain kg^{-1} N_{fert}) was defined as the ratio of crop yield per unit of N applied (Kuosmanen, 2014):

$$PFP = Y_g / N_{fert} \quad (2)$$

where Y_g is the grain yield (kg ha^{-1}) and N_{fert} is the N fertilizer rate (kg N ha^{-1}).

The ANUE (%) was defined as the ratio of grain N harvested per unit of N fertilizer applied (Congreves et al., 2021):

$$ANUE = \frac{N_g}{N_{fert}} \times 100\% \quad (3)$$

where N_g is the N quantity in the wheat or maize grain harvested (kg N ha^{-1}).

The RE_N (%) was defined as the difference in grain N harvested between plots with and without N fertilization divided by the N fertilizer rate (Thilakarathna et al., 2020):

$$RE_N = \frac{(N_g - N_0)}{Nfert} \times 100\% \quad (4)$$

where N_0 is the N quantity in wheat/maize grain of the CK treatment (kg N ha^{-1}).

For NUE, there are 2 types of indicators based on differential total N inputs, i.e., $NU_{T1}E$ and $NU_{T2}E$. $NU_{T1}E$ (%) was defined as the ratio of grain N harvested to N_{T1} input (Lassaletta et al., 2014a):

$$NU_{T1}E = \frac{N_g}{N_{T1}} \times 100\% \quad (5)$$

where N_{T1} includes chemical N fertilizer, manure N, nonsymbiotic N fixation and atmospheric deposition N.

$NU_{T2}E$ was defined as the ratio of grain N harvested to N_{T2} input (Quan et al., 2021):

$$NU_{T2}E = \frac{N_g}{N_{T2}} \times 100\% \quad (6)$$

where N_{T2} includes N_{T1}, straw incorporated N, irrigation N and seed N inputs.

2) Scenario II: the change in the soil N stock was considered.

As the soil N stock changed as the experiment proceeded, especially for the long-term experiment, we also calculated the N use indicators under scenario II considering the change in the soil N stock during the experimental period.

The calculation of PFP was changed to the following equation:

$$PFP = Y_g / (N_{fert} - N_{s-f}) \quad (7)$$

where $N_{s\text{-}f}$ is the change in the soil N stock due to N fertilizer input (kg N ha^{-1}) during the 12-year experimental period. We assumed that the proportion of the soil N stock change due to N fertilizer input to the total soil N stock change was equal to the proportion of N fertilizer input to the total N input; then, $N_{s\text{-}f}$ was calculated by the following equation:

$$N_{s-f} = N_s \times \frac{N_{fert}}{N_{T2}} \quad (8)$$

where N_s is the total change in the soil N stock (kg N ha^{-1}) within the 12-year experimental period.

The calculation of ANUE was changed to the following equation:

$$ANUE = \frac{N_g}{(N_{fert} - N_{S-f})} \times 100\% \quad (9)$$

The calculation of RE_N was changed to the following equation:

$$RE_N = \frac{N_g - N_0}{(N_{fert} - N_{S-f})} \times 100\% \quad (10)$$

The calculation of $NU_{T1}E$ was changed to the following equation:

$$NU_{T1}E = \frac{N_g}{(N_{T1} - N_{S1})} \times 100\% \quad (11)$$

where N_{S1} is the total change in the soil N stock (kg N ha^{-1}) due to N_{T1} within the 12-year experimental period. N_{S1} was calculated by the following equation:

$$N_{S1} = N_S - N_s \times \frac{N_{T2} - N_{T1}}{N_{T2}} \quad (12)$$

Similarly, the calculation of $NU_{T2}E$ was changed to the following equation:

$$NU_{T2}E = \frac{N_g}{(N_{T2} - Ns)} \times 100\% \quad (13)$$

The N surplus was calculated by the following equation:

$$N_{surplus} = \sum N_{input} - \sum N_{output} \quad (14)$$

where N_{input} includes chemical N fertilizer, manure N, nonsymbiotic N fixation, atmospheric N deposition, straw incorporated N, irrigation N and seed N. N_{output} includes grain N, straw removal N, nitrification and denitrification (N_2O + NO + N_2), N leaching and NH_3 volatilization. Unknown N loss was defined as the difference between the N surplus and changes in the soil TN stock. The detailed quantifications of N_{input} and N_{output} are listed in Appendixes 1.1 and 1.2.

We also quantified the contributions of different sources of N input to N output; for that purpose, we divided all N inputs into N fertilizer (F, including chemical N fertilizer and manure N) and non-N fertilizer (NF, including straw N and other N (atmospheric-deposited N, nonsymbiotic N fixation, irrigation N and seed N)). We assumed that the use efficiencies of F and NF were the same. The detailed calculation process was shown in Appendix 1.3.

2.5. Statistical analysis

All the data are presented as the mean ± standard error (n=4). SPSS 22.0 (SPSS, Inc., Chicago, IL, USA) was used to conduct all the statistical analyses. One-way analysis of variance (ANOVA) at a 0.05 level of probability followed by the least significant difference (LSD) test was used to test the significance of differences in crop yield; PFP, ANUE, RE_N, $NU_{T1}E$, and $NU_{T2}E$; N leaching; cumulative gas emission; etc., in the CK, OPT, and CON treatments. The graphs were prepared using Origin 2018 (Origin Lab Corporation, Northampton, MA, USA).

3. Results

3.1. Crop production

Over the 12-year experimental period, the grain yields of the CON and OPT treatments were not significantly different for either wheat or maize production (Fig. 1). The wheat grain yield was stable over the years, but the maize grain yield increased as the experiment progressed: the maize yields in the CON and OPT treatments increased from 7.2 ± 0.3 and 7.2 ± 0.2 Mg ha^{-1} in 2008 to 9.7 ± 0.2 and 10.3 ± 0.7 Mg ha^{-1}, respectively in 2020. In 2020, compared with those in CON and OPT, the wheat and maize yields in CK were 42.5 % and 45.7 % lower, respectively ($p < 0.05$). The lowest wheat and maize yields in CK were recorded in 2013 (6.6 ± 0.28 Mg ha^{-1}), which were 59.5 % and 56.2 % lower than those in CON and OPT, respectively ($p < 0.05$).

3.2. N balance and losses

The total N input during the 12-year experimental period was 9110 ± 10.7 kg N ha^{-1} in CON, whereas that in OPT was 6915 ± 9.4 kg N ha^{-1}, in which the fertilizer N input in CN was 7200 kg N ha^{-1} and that in OPT was 41.4 % lower (Table S2). In the total N input, CON received 635 kg N ha^{-1} from wheat straw, and OPT incorporated both wheat and maize straw into the cropland and 1555 kg straw N ha^{-1} was returned. Because of the much lower yields of wheat and maize straw and lower straw N contents than those of CON and OPT, CK incorporated only 448 kg N ha^{-1} during the 12-year experimental period (Fig. 2; Table S2). Other N inputs were the same for the 3 treatments, with deposition and irrigation water N inputs of 46.8 and 30.5–41.8 kg N ha^{-1} yr^{-1}, respectively (Fig. 2; Table S2).

During the 12-year experimental period, the N losses in CON were 308 ± 4.7 (N_2O + NO + N_2), 1105 ± 5.7 (N leaching) and 1873 ± 13.8 kg N ha^{-1} (NH_3 volatilization) (Table S2), accounting for 9.4 %, 33.6 % and 57.0 %, respectively, of the total N loss. The corresponding losses via N_2O + NO + N_2, N leaching and NH_3 volatilization and total N losses in OPT were 28.6 %, 47.1 %, 11.4 % and 25.0 % lower ($p < 0.05$) than those in CON. The season N losses (including leaching, NH_3 volatilization and N_2O + NO + N_2) in CON were 104 ±1.0 kg N ha^{-1} wheat $season^{-1}$ (Fig. S1a) and 170 ±0.5 kg N ha^{-1} maize $season^{-1}$ (Fig. S1b), approximately 14.2 % ±2.2 % and 48.5 % ±0.7 % higher ($p < 0.05$), respectively, than those in the OPT treatment. The total crop grain N harvested in CON was 2811 ± 22.8 kg N ha^{-1}, which was 5.0 % higher ($p < 0.05$) than that in OPT (Table S2). The N surpluses of CON (2004 ± 37 kg N ha^{-1}) and OPT (1773 ± 26 kg N ha^{-1}) treatments did not significantly differ during the 12-year experimental period (Table S2).

3.3. Soil N stock and changes

Compared with that in the initial soil in 2008, the soil TN stock in the 0–60 cm soil layer in 2020 increased by 16.1 % ±3.9 % (CON), 26.3 % ±7.9 % (OPT) and 12.9 % ±2.0 % (CK) (Fig. S2a-c). Similarly, the soil N stock in the 20–40 cm layer in OPT increased by 41.2 % ±11.1 %, whereas that in CON increased by only 12.6 ±7.1 %. In the 60–100 cm layer, changes in the soil N stock were negligible, i.e., −1.1 % ±5.5 % (CON), 1.7 % ±6.9 % (OPT) and −3.9 % ±3.4 % (CK). Compared to that in 2008, the soil N stock at the whole 0–100 cm depth increased by 972 ±285 (CON), 1671 ±594 (OPT) and 705 ±173 kg N ha^{-1} (CK) in 2020 (Table S2). The corresponding annual soil N sequestration rates for the 0–60 cm layer were 84.0 ±20.8 (CON), 137 ±42.2 (OPT) and 66.4 ±9.7 kg N ha^{-1} yr^{-1} (CK), and for the 0–100 cm layer, the values were 81.0 ±23.7 (CON), 139 ±49.5 (OPT) and 58.8 ±14.5 kg N ha^{-1} yr^{-1} (CK), respectively.

3.4. N use efficiencies

Under scenario I, the NUE indicators of OPT were significantly

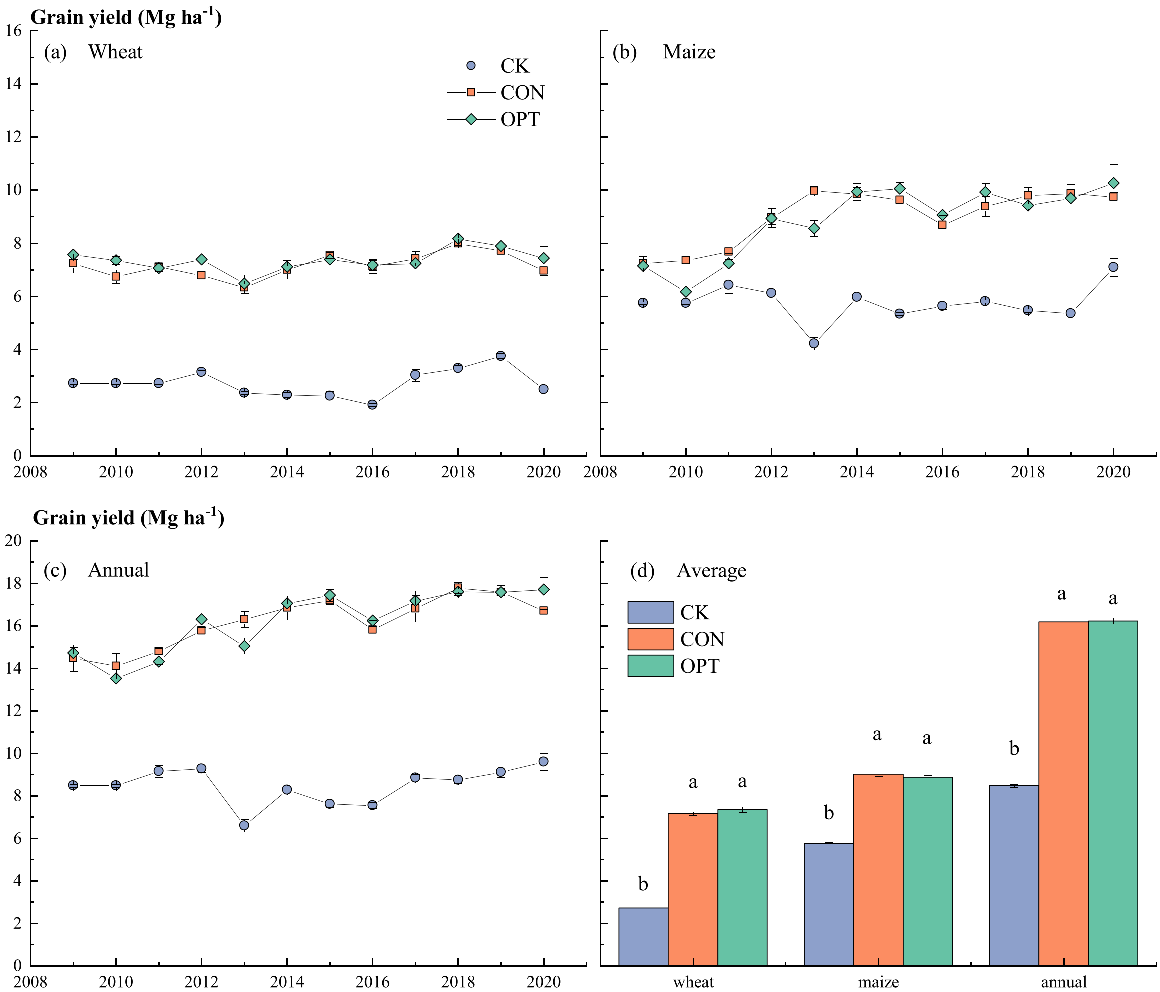

Fig. 1. Grain yield (Mg ha^{-1}) of seasonal wheat (a), seasonal maize (b), annual (wheat+ maize, c) and the 12-year average (d). The data shown are the means ± standard errors (n = 4). Different letters for the same crop indicate significant differences at $P < 0.05$ among the three treatments.

greater than those of CON ($p < 0.05$; Fig. 3). During the entire experimental period, the average PFP of OPT was 52.6 (wheat), 46.7 (maize) and 46.1 kg grain kg^{-1} N_{fert} (annual), which was significantly greater than that of CON (23.9 (wheat), 30.1 (maize), and 27.0 kg grain kg^{-1} N_{fert} (annual) (Fig. 3a)). The average ANUE of CON was 39.3 % (wheat), 38.8 % (maize) and 39.1 % (annual), respectively ($p < 0.05$), significantly lower than those of OPT, i.e., 82.5 % (wheat), 57.7 % (maize) and 63.4 % (annual) (Fig. 3b). Similarly, the $NU_{T1}E$ values in CON were 36.2 % (wheat), 34.6 % (maize) and 35.4 % (annual), all significantly lower than those of OPT (67.8 % (wheat), 48.4 % (maize) and 54.0 % (annual) (Fig. 3d)). The annual RE_N and $NU_{T2}E$ in CON were 21.8 % and 30.9 %, respectively, also significantly lower than those in OPT (34.0 % and 38.7 %, respectively) (Fig. 3c; Fig. S3a-b).

Under scenario II, which considered the change in the soil N stock, the annual NUE was recalculated (not for seasonal efficiencies, as the change in the seasonal soil N stock could not be separately defined). The annual PFP, ANUE, $NU_{T1}E$, RE_N and $NU_{T2}E$ of CON were 30.3 kg grain kg^{-1} N_{fert}, 43.8 %, 39.8 %, 24.5 % and 34.7 %, respectively, which were significantly lower than those of OPT, i.e., 63.2 kg grain kg^{-1} N_{fert}, 86.8 %, 73.9 %, 46.6 % and 53.0 %, respectively (Fig. 3 and Fig. S3c-d).

The fertilizer N input in OPT was 41.4 % lower than that in CON, and contribution of fertilizer N to crop grain N harvested and to N losses of OPT was lower by 8.5 % and 27.9 %, respectively, and the change in the soil N stock was 39.5 % (0–100 cm) greater than that in CON (Table S2, Fig. 4). Compared with that in CON, the straw N input in OPT was 145 % greater, and the straw N contribution to crop grain N harvested, N losses and soil N stock changes were 207 %, 143 % and 453 % greater, respectively (Fig. 4) (assuming that the use efficiencies of N fertilizer (F) and non-N fertilizer (NF) are the same).

4. Discussion

4.1. Maintaining long-term high crop yields and improving N efficiency in the intensively farmed regions

Our experimental results highlighted that the integrated adoption of optimized farming practices is a promising strategy for long-term and high crop production in China, where a population of 1.4 billion must be fed (Bolinder et al., 2020; Zhang et al., 2014). In our study, STFF and water-saving irrigation in the OPT treatment decreased the N fertilizer input by 41.4 % and the irrigation water input by 27.1 % (Table S1), decreased the total N leaching by 47.1 % (Table S2; Fig. S1), decreased the total N losses by 25 % (Table S2; Fig. S1), and the associated costs were also reduced, while the crop yield was similar to that in the CON treatment. These results were comparable to those of other similar studies that adopted optimum practices such as ISSM (integrated soil-crop system management; Chen et al., 2014; Cui et al., 2018) and SSNB (steady-state N balance; Yin et al., 2021), which reduced N fertilizer use by 11–28 % while increasing yields by 6–7 % and decreasing reactive N losses by 22.9 %–34.9 %, and the N leaching by 14.3 %–81.8 %. The PFP of wheat (52.6 kg grain kg^{-1} N_{fert}) and maize (46.7 kg grain kg^{-1} N_{fert}) under OPT was comparable to that of 45–72 kg grain

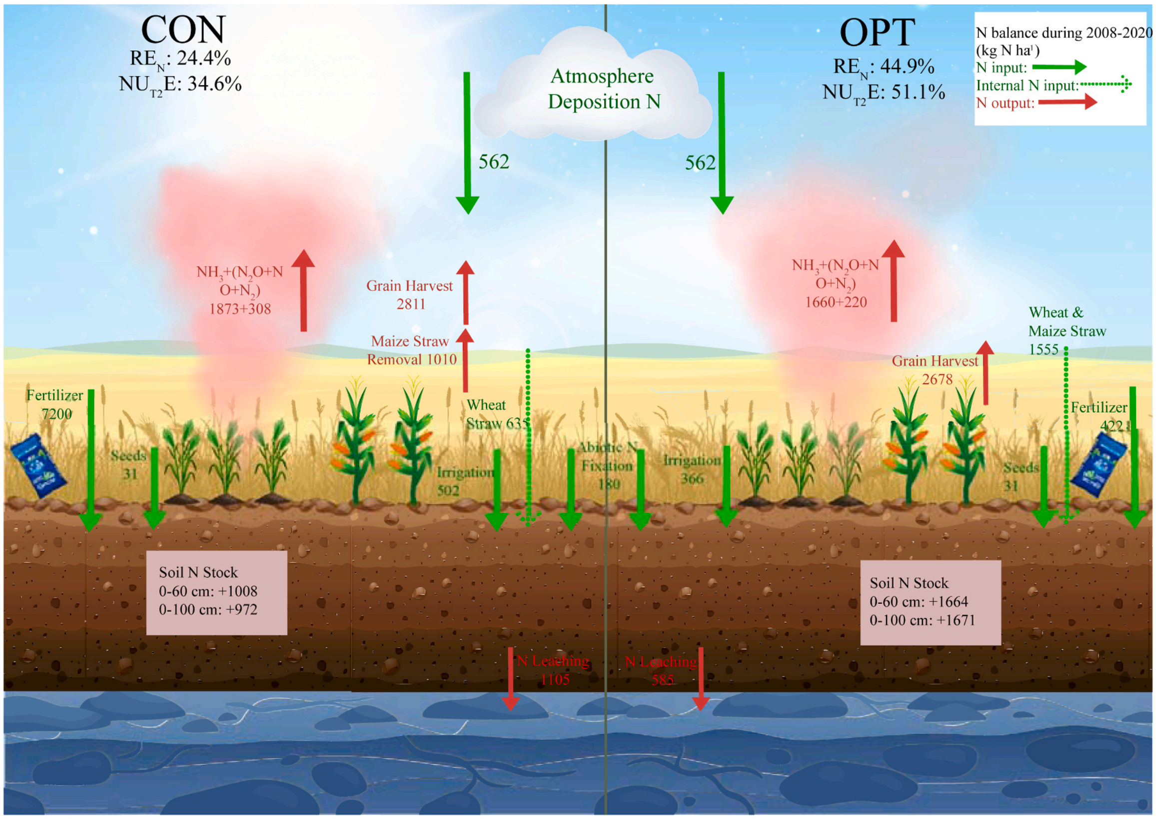

Fig. 2. N input, output, RE$_N$, NU$_{T2}$E (under Scenario II) and soil N stock changes in the experimental treatments from 2008 to 2020 (kg N ha^{-1}).

kg^{-1} N$_{fert}$ in North America and the EU (Ladha et al., 2005; López-Bellido et al., 2005); the ANUE in OPT of 82.5 % (wheat) and 57.7 % (maize) was also similar to or greater than that in the EU (approx. 60 %; Brentrup and Palliere, 2010). The NU$_{T1}$E, i.e., 67.9 % (wheat) and 48.4 % (maize), in OPT were also at similar levels in the EU and USA (Y/F=50 %–75 %; Lassaletta et al., 2014a).

In addition to the fertilizer optimization (reduction) performed in the above studies, our study also included integrated organic materials with chemical fertilization, water-saving irrigation and deep tillage. For organic material recycling (animal manure and straw), large amounts of macronutrients, such as P and K (129 kg P_2O_5 ha^{-1} yr^{-1} and 398 kg K_2O ha^{-1} yr^{-1}, Table S1), and micronutrients, such as Fe, Zn, Mg, Ca and others (Bai et al., 2015; Lal, 2013), are returned to farmland soil, increasing the assimilation of nitrate N by microorganisms (Cheng et al., 2017; Elrys et al., 2022; Hu et al., 2018; Xia et al., 2018). The physical, chemical and biological properties of the soil were also greatly improved (SOC content in OPT increased by 26.7 % in 0–20 cm soil layer compared to CON treatment, unpublished data). The unknown N losses in the CON treatment (1032 kg N ha^{-1}) were 10-fold greater than those in the OPT treatment (102 kg N ha^{-1}), and much of these unknown N losses might have leached below the 100 cm soil layer due to the high degree of water leaching (Table S2; Meng et al., 2021; Stone et al., 2014). The above analysis indicated that the integration of these appropriate intensive farming measures helped to effectively maintain the high crop yields after the experiment was established and maintained a high NUE. Our 12-year experimental results supported our first hypothesis, that high-yield production can be sustainably ensured by adopting appropriate farming measures via a holistic approach. This may provide beneficial experiences for many developing countries, where an increase in agronomic productivity is highly important (George, 2014; Lassaletta et al., 2023) and where sustainable agricultural intensification is needed (Bouwman et al., 2017).

Notably, in our study, NH_3 volatilization was reduced by only 11.4 % under OPT, much lower than the mitigation for N leaching (47.1 %), indicating that our second hypothesis was only partially supported. First, the soil in the study was alkaline, and NH_3 volatilization occurred easily. On the other hand, current farming measures do not effectively mitigate the NH_3 volatilization. Other techniques, such as urease inhibitors, might be deployed to further reduce gaseous N losses (Butterbach-Bahl et al., 2013; Xia et al., 2017a). Flood irrigation alone in our OPT treatment did not effectively save water resources, and N leaching could be further reduced by refining irrigation methods, such as drip irrigation or fertigation (Zhang et al., 2019, 2021). Because of concerns about food security in China, the annual wheat-maize double cropping system has been continuously implemented in the region since the 1990s (Zhang et al., 2017). However, this type of continuous and long-term cereal cropping might increase the incidence of diseases and pathogens (Jauri et al., 2018; Zhou et al., 2023), and rotation with noncereal crops may promote overall farming health and crop yield, which deserves further investigation in the studied region.

4.2. Soil N stock changes should be considered in the precise quantification of fertilizer N efficiency

We observed a rapid decrease in crop yield in the CK treatment as the N input decreased from 600 kg N ha^{-1} yr^{-1} pre-experiment to no N input at the initiation of the experiment; afterward, the crop yield gradually increased in the later experimental period (Fig. 1), which was different from the findings of other studies such as Cai et al. (2019) and Crystal-Ornelas et al. (2021). This occurred because in our study, although no fertilizer N was applied, both wheat and maize straw were incorporated in CK. Besides, high dry and wet N deposition in the studied region (Li, 2019; Liu et al., 2013), in addition to the straw N returned to the soil, did exhibit a remarkable effect on crop production and soil N stock under the long-term experimental context. The soil N stock also increased in CON and OPT treatments (Fig. S2), and the

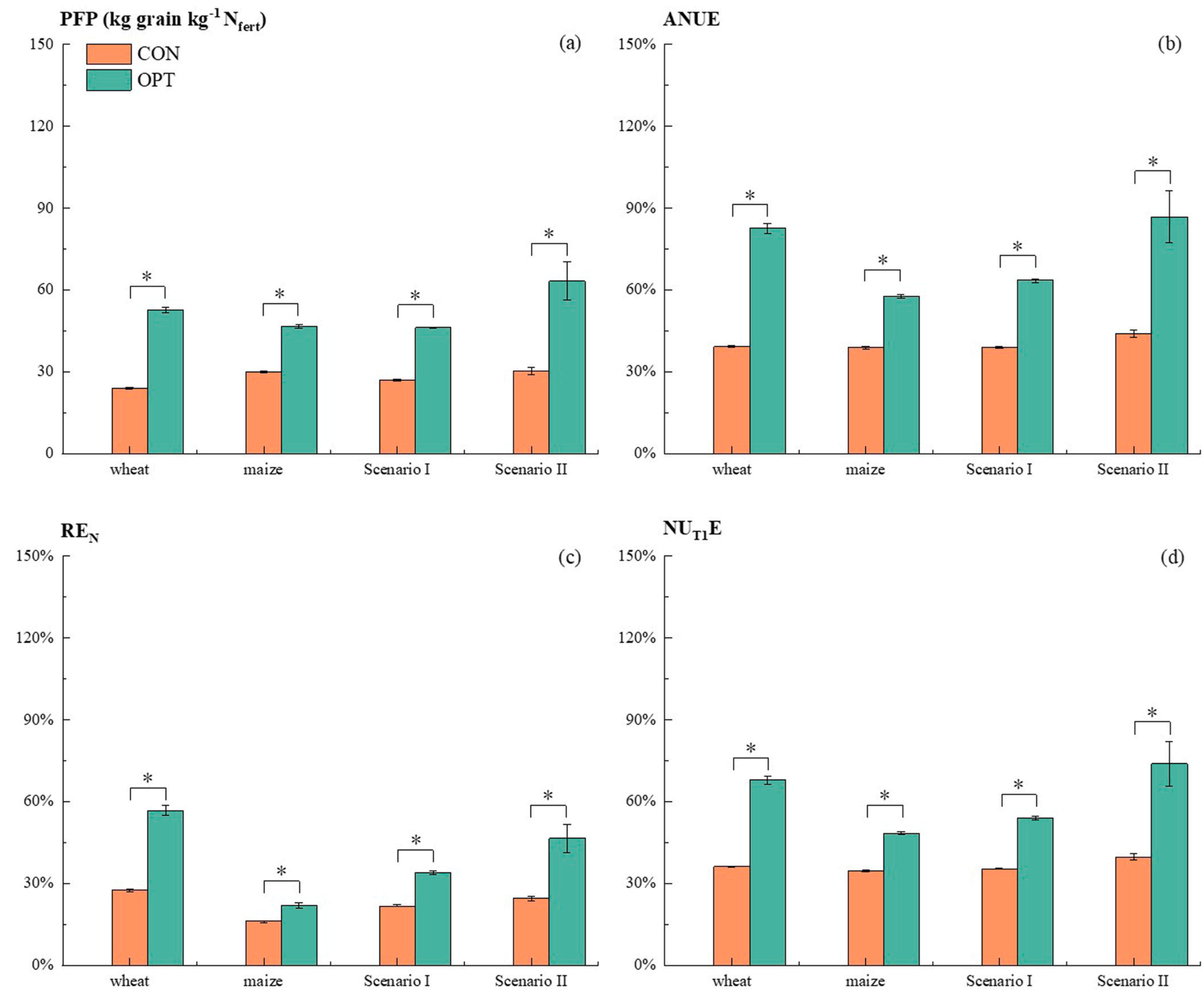

Fig. 3. The 12-year average partial factor productivity (PFP, a) for N fertilizer (kg grain kg^{-1} N$_{fert}$), apparent N use efficiency (ANUE, b), N recovery rate (RE$_N$,c) and nitrogen use efficiency (NU$_{T1}$E, d) of the three treatments. In Scenario I, the change in soil N stock was not considered; in Scenario II, the change in soil N stock was considered. The data shown are the mean ± standard error (n = 4). * indicate significant differences at $p < 0.05$ between CON and OPT treatments.

traditional N use efficiency calculation method underestimated the RE$_N$ and NU$_{T2}$E (Fig. S3a vs. Fig. S3c, Fig. S3b vs. Fig. S3d) under scenario I, in which the soil N stock change was not considered. If soil N stock changes were accounted for, the RE$_N$ and NU$_{T2}$E increased by 2.7 and 3.8 percentage points in CON, and by 12.6 and 14.3 percentage points in OPT, respectively.

We also calculated the soil N stock changes (0–100 cm), RE$_N$ and NU$_{T2}$E (under two scenarios) for the 4 stages of 2008–2012, 2008–2016, 2008–2018 and 2008–2020 (Fig. S4) to compare the impacts of the short-term (4-year and 8-year) and long-term (10-year and 12-year) experimental periods on the soil N stock, RE$_N$ and NU$_{T2}$E. There were large differences between RE$_N$ and NU$_{T2}$E in the 2008–2012 (4-year) and 2008–2020 stages (12-year) in CON (41.6 % vs. 24.5 % for RE$_N$, 82.6 % vs. 34.6 % for NU$_{T2}$E) and OPT (25.2 % vs. 46.6 % for RE$_N$, 40.6 % vs. 53.0 % for NU$_{T2}$E) treatments. This occurred because the excessive fertilizer N in CON remained within the soil in the short-term period but was lost by leaching or moved to the deeper layer (below 100 cm) by flooding irrigation in the long-term period (Meng et al., 2021; Poffenbarger et al., 2018), and these high N losses led to lower RE$_N$ and NU$_{T2}$E values. However, owing to the integration of optimized farming practices in OPT, the soil N stock changes increased gradually during the four short-term stages, and the RE$_N$ and NU$_{T2}$E thereby increased. These results confirmed that considering soil N stock changes is important for an accurate assessment of N use efficiency (Vonk et al., 2022; Quan et al., 2021).

4.3. N immobilization across the whole soil profile

We found that the soil N stock mostly increased at 0–60 cm (or more specifically, 20–40 cm) soil depth in OPT, and the increase of soil N stock below 60 cm was negligible (Fig. S2). Annual soil N increase (0–60 cm) was at 137 kg N ha^{-1} for OPT, much higher than those of CON and CK. These findings have seldom been reported, as soil N is not sensitive enough to be precisely examined within a 1- or 2- year experimental period (Quan et al., 2021; van Grinsven et al., 2022). Our analysis revealed that the contribution of straw N to the change in the soil N stock in the OPT treatment was 5.5 times greater than that in the CON treatment over the 12-year experimental period, whereas the straw N input was only 2.5-fold that in the CON treatment (Fig. 4a; Fig. 4f). If we considered the use efficiency of NF to be 10.0 % (mainly straw N; Fig. S5; Ding et al., 2016; Haynes, 1997), compared with the same use efficiency for fertilizer and non-N fertilizer (Fig. 4), the contribution of N

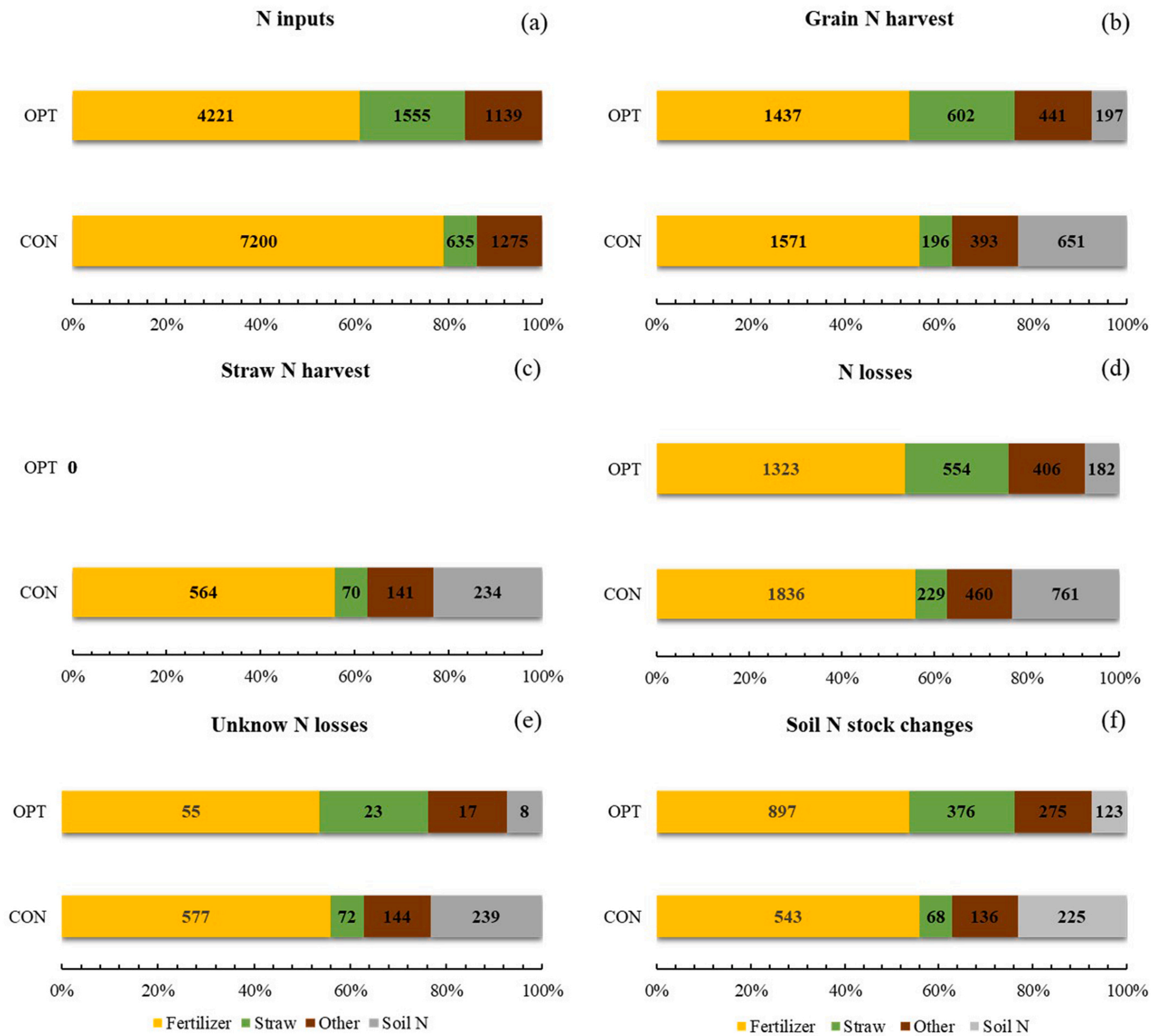

Fig. 4. Different sources of N input in the CON and OPT treatments (a); the contributions of different sources of N input to crop grain N harvested (b), to straw N harvested (c), to N losses (d), to unknown N losses (e), and to soil N stock changes (f) in the CON and OPT treatments during the 12-year experimental period.

fertilizer to all types of N output did not change, but the contribution of soil N increased. Therefore, the soil N contribution reflects the residual effect of fertilizer and non-N fertilizer (van Grinsven et al., 2022; Yan et al., 2014) and should be considered in the long-term field crop production.

Organic matter provides carbon to microorganisms and the input mineral N is efficiently assimilated into the soil organic N pool (Crystal-Ornelas et al., 2021; Elrys et al., 2022; Xia et al., 2017b). Deeper tillage (~25 cm) under OPT promoted the humification of organic materials in the 20–40 cm soil layer and prevented the decomposition of straw in the surface soil (Wu et al., 2022). In addition, water-saving irrigation in OPT also alleviated the downward N movement (especially chemical fertilizer N) into the deeper soil profile (> 100 cm) and more N was retained in the root zone layer (0–60 cm). These findings provide important insights that were difficult to obtain in short-term experiments; i.e., soil fertility or N stock are crucial factors for sustainable intensification (Foley et al., 2005, 2011; Yan et al., 2020), and the soil organic N can be easily decomposed and transformed to the inorganic N (NH_4^+-N and NO_3-N), which is highly available for subsequent crops (Cheng et al., 2017), but it can also have a high risk of leaching if irrigation is high (Gu et al., 2015b; Zhang et al., 2021).

We used the current experimental study data as the calculation basis to estimate the impacts of disseminating these optimized farming measures across the entire NCP. These techniques dissemination can directly save 3.8 million tons of fertilizer N and 22.0 billion m^3 of irrigation water, and approximately 1.1 million tons of fertilizer N can be sequestrated in soil N. In total, 4.9 million tons of fertilizer N saved is equivalent to 50 % of the fertilizer N input in the EU in 2020 (FAOSTAT, 2021), and 1.1 million tons of N losses were also avoided, equivalent to a similar amount of fertilizer N usage in the UK in 2020 (FAOSTAT, 2021). The dissemination of integrated optimum farming practices is highly important for other cereal production regions in China and other countries.

There are several limitations in our study. We measured the N losses for only 4–5 years rather than for the entire experimental period, which may introduce uncertainty. As the measured N losses during the monitoring period (Fig. S6) were stable, we are convinced that these measured N losses represent the actual N losses over the 12 years. In addition, the use of the N_2O/NO ratio and N_2/N_2O ratio may also lead to over- or underestimation of NO and N_2 emissions (Balaine et al., 2016; Butterbach-Bahl et al., 2013; Wang et al., 2013; Yan et al., 2013). The short distance between the no N fertilizer treatment (CK) and the N fertilization treatments might also overestimate the NH_3 volatilization (Pacholski et al., 2006) and the crop canopy uptake of volatilized NH_3 from the CK treatment (Table S3; Sommer et al., 1997; Yang, 2021). The targeted maize yield at the start of the experiment was set as 7.5 Mg ha^{-1} season^{-1} with the N demand of 180 kg N ha^{-1} season^{-1} (Cui et al., 2008), and the actual N fertilizer input was 191 kg N ha^{-1} in the maize season, which was also higher than the 161 kg N ha^{-1} season^{-1} N input in the wheat season (Table S1). This limited the further increase in wheat yield and should be refined in the future. Integration of organic with chemical fertilization, such as the operation in OPT, in the whole cereal cropping region, might be difficult. However, in the intensive animal production regions such as Shandong, Hebei and Henan, the disposal of animal waste has been a major challenge, as there is not always enough vegetable or fruit farmland near the animal farms. In this case, organic fertilization in cereal production can be a good alternative option for organic resource recycling and the promotion of green agriculture (Ashraf et al., 2023; Beillouin et al., 2023; Gross and Glaser, 2021).

5. Conclusions

Our study is based on the first comprehensive field experiment in which multiple optimized farming measures were integrated and examined in the typical intensive farming region of northern China. This study demonstrated that the integration of optimized farming practices may achieve sustainable high-yield cereal crop production and significantly mitigate N losses, especially N leaching. The potential yield decreased due to chemical fertilizer inputs reduction was avoided by organic material recycling, and N was effectively sequestered in the root-zone soil (0–60 cm) due to water-saving irrigation and increased carbon input. The NUEs under the optimized farming techniques were improved to the developed country level. Long-term field experiments are vital for the robust assessment of NUEs under substantial changes in the soil N stock. Urease inhibition, fertigation, rotation, and other appropriate technologies may also be included in the experimental studies to further optimize farming practices in China and beyond.

CRediT authorship contribution statement

Cong Xu: Writing – review & editing. **Xuan Yang:** Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation. **Roland Bol:** Writing – review & editing. **Longlong Xia:** Writing – review & editing. **Wenliang Wu:** Writing – review & editing. **Fanqiao Meng:** Writing – review & editing, Resources, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Ning Yuan:** Writing – review & editing, Formal analysis, Data curation. **Xiuchun Xu:** Writing – review & editing, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Acknowledgement

This study is supported by the National Key Research and Development Programs of China (2022YFD1900304 and 2023YFD1701701).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2024.109572.

References

Adalibieke, W., Zhan, X., Cui, X., Reis, S., Winiwarter, W., Zhou, F., 2021. Decoupling between ammonia emission and crop production in China due to policy interventions. Glob. Change Biol. 27, 5877–5888. https://doi.org/10.1111/gcb.15847.

Ashraf, M., Hu, C., Xu, X., Aziz, T., 2023. Long–term manure application increased soil organic carbon and nitrogen mineralization through accumulation of unprotected and physically protected carbon fractions. Pedosphere 33, 343–354. https://doi.org/10.1016/j.pedsph.2022.06.047.

Bai, Y., Wang, L., Lu, Y., Yang, L., Zhou, L., Ni, L., Cheng, M., 2015. Effects of long-term full straw return on yield and potassium response in wheat-maize rotation. J. Integr. Agric. 14, 2467–2476. https://doi.org/10.1016/S2095-3119(15)61216-3.

Balaine, N., Clough, T.J., Beare, M.H., Thomas, S.M., Meenken, E.D., 2016. Soil gas diffusivity controls N_2O and N_2 emissions and their ratio. Soil Sci. Soc. Am. J. 80, 529–540. https://doi.org/10.2136/sssaj2015.09.0350.

Beillouin, D., Corbeels, M., Demenois, J., Berre, D., Boyer, A., Fallot, A., Feder, F., Cardinael, R., 2023. A global meta-analysis of soil organic carbon in the Anthropocene. Nat. Commun. 14, 3700. https://doi.org/10.1038/s41467-023-39338-z.

Beltran-Peña, A., Rosa, L., D'Odorico, P., 2020. Global food self-sufficiency in the 21st century under sustainable intensification of agriculture. Environ. Res. Lett. 15, 095004 https://doi.org/10.1088/1748-9326/ab9388.

Bolinder, M.A., Crotty, F., Elsen, A., Frac, M., Kismányoky, T., Lipiec, J., Tits, M., Tóth, Z., Kätterer, T., 2020. The effect of crop residues, cover crops, manures and nitrogen fertilization on soil organic carbon changes in agroecosystems: a synthesis of reviews. Mitig. Adapt. Strateg. Glob. Change 25, 929–952. https://doi.org/10.1007/s11027-020-09916-3.

Bouwman, A.F., Beusen, A.H.W., Lassaletta, L., Van Apeldoorn, D.F., Van Grinsven, H.J.M., Zhang, J., Ittersum Van, M.K., 2017. Lessons from temporal and spatial patterns in global use of N and P fertilizer on cropland. Sci. Rep. 7, 40366 https://doi.org/10.1038/srep40366.

Brentrup, F., Palliere, C., 2010. Nitrogen use efficiency as an agro-environmental indicator. OECD Workshop. Agric. Environ. Indic. Lessons Learn. Future Dir. 23–26.

Butterbach-Bahl, K., Baggs, E.M., Dannenmann, M., Kiese, R., Zechmeister-Boltenstern, S., 2013. Nitrous oxide emissions from soils: how well do we understand the processes and their controls? Philos. Trans. R. Soc. B Biol. Sci. 368, 20130122. https://doi.org/10.1098/rstb.2013.0122.

Cai, A., Xu, M., Wang, B., Zhang, W., Liang, G., Hou, E., 2019. Manure acts as a better fertilizer for increasing crop yields than synthetic fertilizer does by improving soil fertility. Soil Tillage Res. 189, 168–175. https://doi.org/10.1016/j.still.2018.12.022.

Carlson, K.M., Gerber, J.S., Mueller, N.D., Herrero, M., MacDonald, G.K., Brauman, K.A., Havlik, P., O'Connell, C.S., Johnson, J.A., Saatchi, S., West, P.C., 2017. Greenhouse gas emissions intensity of global croplands. Nat. Clim. Change 7, 63. https://doi.org/10.1038/NCLIMATE3158.

Cassman, K.G., 1999. Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture. Proc. Natl. Acad. Sci. USA 96, 5952–5959. https://doi.org/10.1073/pnas.96.11.5952.

Cassman, K.G., Dobermann, A., Walters, D.T., 2002. Agroecosystems, nitrogen-use efficiency, and nitrogen management. AMBIO A J. Hum. Environ. 31, 132–140. https://doi.org/10.1579/0044-7447-31.2.132.

Chen, X., Cui, Z., Fan, M., Peter, V., 2014. Producing more grain with lower environmental costs. Nature 514, 486. https://doi.org/10.1038/nature13609.

Chen, X.P., Cui, Z.L., Vitousek, P.M., Cassman, K.G., Matson, P.A., Bai, J.S., Meng, Q.F., Hou, P., Yue, S.C., Römheld, V., Zhang, F.S., 2011. Integrated soil-crop system management for food security. Proc. Natl. Acad. Sci. USA 108, 6399–6404. https://doi.org/10.1073/pnas.1101419108.

Cheng, Y., Wang, J., Wang, J.Y., Chang, S.X., Wang, S., 2017. The quality and quantity of exogenous organic carbon input control microbial NO_3^- immobilization: a meta-analysis. Soil Biol. Biochem. 115, 357–363. https://doi.org/10.1016/j.soilbio.2017.09.006.

Congreves, K.A., Otchere, O., Ferland, D., Farzadfar, S., Williams, S., Arcand, M.M., 2021. Nitrogen use efficiency definitions of today and tomorrow. Front. Plant Sci. 12, 637108 https://doi.org/10.3389/fpls.2021.637108.

Crystal-Ornelas, R., Thapa, R., Tully, K.L., 2021. Soil organic carbon is affected by organic amendments, conservation tillage, and cover cropping in organic farming systems: a meta-analysis. Agric., Ecosyst. Environ. 312, 107356 https://doi.org/10.1016/j.agee.2021.107356.

Cui, Z., Chen, X., Zhang, F., 2013. Development of regional nitrogen rate guidelines for intensive cropping systems in China. Agron. J. 105, 1411–1416. https://doi.org/10.2134/agronj2012.0398.

Cui, Z., Chen, X., Miao, Y., Zhang, F., Sun, Q., Schroder, J., Zhang, H., Li, J., Shi, L., Xu, J., Ye, Y., Liu, C., Yang, Z., Zhang, Q., Huang, S., Bao, D., 2008. On-Farm evaluation of the improved soil N_{min}–based nitrogen management for summer maize in North China Plain. Agron. J. 100, 517–525. https://doi.org/10.2134/agronj2007.0194.

Cui, Z., Zhang, H., Chen, X., Zhang, C., Ma, W., Huang, C., 2018. Pursuing sustainable productivity with millions of smallholder farmers. Nature 555, 363. https://doi.org/10.1038/nature25785.

Ding, W.C., Li, S.T., Huang, S.M., 2016. Bioavailability and fate of nitrogen from ^{15}N-labeled corn straw as affected by nitrogen management and straw microbial inoculants (in Chinese). Sci. Agric. Sin. 49 (14), 2725–2736. https://doi.org/10.3864/j.issn.0578-1752.2016.14.007.

Elrys, A.S., Chen, Z., Wang, J., Uwiragiye, Y., Helmy, A.M., Desoky, E.M., Cheng, Y., Zhang, J., Cai, Z., Müller, C., 2022. Global patterns of soil gross immobilization of ammonium and nitrate in terrestrial ecosystems. Glob. Change Biol. gcb 16202. https://doi.org/10.1111/gcb.16202.

Fan, Z., Lin, S., Zhang, X., Jiang, Z., Yang, K., Jian, D., Chen, Y., Li, J., Chen, Q., Wang, J., 2014. Conventional flooding irrigation causes an overuse of nitrogen fertilizer and low nitrogen use efficiency in intensively used solar greenhouse vegetable production. Agric. Water Manag. 144, 11–19. https://doi.org/10.1016/j.agwat.2014.05.010.

Fang, Q.X., Ma, L., Green, T.R., Yu, Q., Wang, T.D., Ahuja, L.R., 2010. Water resources and water use efficiency in the North China Plain: current status and agronomic management options. Agric. Water Manag. 97, 1102–1116. https://doi.org/10.1016/j.agwat.2010.01.008.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Snyder, P.K., 2005. Global consequences of land use. Science 309 (5734), 570–574. https://doi.org/10.1126/science.1111772.

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Zaks, D.P.M., 2011. Solutions for a cultivated planet. Nature 478 (7369), 337–342. https://doi.org/10.1038/natur e10452.

Gai, X., 2019. Effects of Input of Different Organic Materials on Co-Transformation of Carbon and Nitrogen and Environment in Farmland in North China Plain. Chinese Academy of Agricultural Sciences, Beijing (in Chinese).

Garnett, T., Appleby, M.C., Balmford, A., Bateman, I.J., Benton, T.G., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., Herrero, M., Hoffmann, I., Smith, P., Thornton, P.K., Toulmin, C., Vermeulen, S.J., Godfray, H.C.J., 2013. Sustainable intensification in agriculture: premises and policies. Science 341, 33–34. https://doi.org/10.1126/science.1234485.

George, T., 2014. Why crop yields in developing countries have not kept pace with advances in agronomy. Glob. Food Secur. 3, 49–58. https://doi.org/10.1016/j.gfs.2013.10.002.

van Grinsven, H.J.M., Ebanyat, P., Glendining, M., Gu, B., Hijbeek, R., 2022. Establishing long-term nitrogen response of global cereals to assess sustainable fertilizer rates. Nat. Food 3, 122. https://doi.org/10.1038/s43016-021-00447-x.

Gross, A., Glaser, B., 2021. Meta–analysis on how manure application changes soil organic carbon storage. Sci. Rep. 11, 5516. https://doi.org/10.1038/s41598-021-82739-7.

Gu, B., Ju, X., Chang, J., Ge, Y., Vitousek, P.M., 2015a. Integrated reactive nitrogen budgets and future trends in China. Proc. Natl. Acad. Sci. USA 112, 8792–8797. https://doi.org/10.1073/pnas.1510211112.

Gu, B., Ju, X., Chang, S.X., Ge, Y., Chang, J., 2017. Nitrogen use efficiencies in Chinese agricultural systems and implications for food security and environmental protection. Reg. Environ. Change 17, 1217–1227. https://doi.org/10.1007/s10113-016-1101-5.

Gu, L., Liu, T., Zhao, J., Dong, S., Liu, P., Zhang, J., Zhao, B., 2015b. Nitrate leaching of winter wheat grown in lysimeters as affected by fertilizers and irrigation on the North China Plain. J. Integr. Agric. 14, 374–388. https://doi.org/10.1016/S2095-3119(14)60747-4.

Guo, J.H., Liu, X.J., Zhang, Y., Shen, J.L., Han, W.X., Zhang, W.F., Christie, P., Goulding, K.W.T., Vitousek, P.M., Zhang, F.S., 2010. Significant acidification in major Chinese croplands. Science 327, 1008–1010. https://doi.org/10.1126/science.1182570.

Haynes, R.J., 1997. Fate and recovery of ^{15}N derived from grass/clover residues when incorporated into a soil and cropped with spring or winter wheat for two succeeding seasons. Biol. Fertil. Soils 25, 130–135. https://doi.org/10.1007/s003740050292.

Hu, C.S., Zhang, Y.M., Qin, S.P., Wang, Y.Y., Li, X.X., Dong, W.X., 2018. Nitrogen processes and related environmental effects on agro-ecosystem in the North China Plain. Chin. J. Eco. Agric. 26 (10), 1501–1514. https://doi.org/10.13930/j.cnki.cjea.180633.

Huang, T., Yang, H., Huang, C., Ju, X., 2018. Effects of nitrogen management and straw return on soil organic carbon sequestration and aggregate-associated carbon. Eur. J. Soil Sci. 69, 913–923. https://doi.org/10.1111/ejss.12700.

Hutchinson, G.L., Mosier, A.R., 1981. Improved Soil cover method for field measurement of nitrous oxide fluxes. Soil Sci. Soc. Am. J. 45, 311–316. https://doi.org/10.2136/sssaj1981.03615995004500020017x.

Jauri, P.V., Altier, N., Pérez, C.A., Kinkel, L., 2018. Cropping history effects on pathogen suppressive and signaling dynamics in streptomyces communities. Phytobiomes J. 2, 14–23. https://doi.org/10.1094/PBIOMES-05-17-0024-R.

Ju, X., Zhang, C., 2017. Nitrogen cycling and environmental impacts in upland agricultural soils in North China: a review. J. Integr. Agric. 16, 2848–2862. https://doi.org/10.1016/S2095-3119(17)61743-X.

Kissel, D.E., Brewer, H.L., Arkin, G.F., 1977. Design and test of a field sampler for ammonia volatilization. Soil Sci. Soc. Am. J. 41, 1133–1138. https://doi.org/10.2136/sssaj1977.03615995004100060024x.

Kuosmanen, N., 2014. Estimating stocks and flows of nitrogen: application of dynamic nutrient balance to European agriculture. Ecol. Econ. 108, 68–78. https://doi.org/10.1016/j.ecolecon.2014.10.008.

Ladha, J.K., Pathak, H.J., Krupnik, T., Six, J., van Kessel, C., 2005. Efficiency of fertilizer nitrogen in cereal production: retrospects and prospects. Adv. Agron. 85–156. https://doi.org/10.1016/S0065-2113(05)87003-8.

Lal, R., 2013. Food security in a changing climate. Ecohydrology & hydrobiology. Ecohydrol. Harmon. Soc. needs biosphere Potential 13, 8–21. https://doi.org/10.1016/j.ecohyd.2013.03.006.

Lassaletta, L., Billen, G., Grizzetti, B., Garnier, J., Leach, A.M., Galloway, J.N., 2014b. Food and feed trade as a driver in the global nitrogen cycle: 50-year trends. Biogeochemistry 118, 225–241. https://doi.org/10.1007/s10533-013-9923-4.

Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J., Garnier, J., 2014a. 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. Environ. Res. Lett. 9, 105011 https://doi.org/10.1088/1748-9326/9/10/105011.

Lassaletta, L., Einarsson, R., Quemada, M., 2023. Nitrogen use efficiency of tomorrow. Nat. Food 4, 281–282. https://doi.org/10.1038/s43016-023-00740-x.

Li, Q., 2019. Atmospheric Nitrogen and Phosphorus Deposition in North China. China Agricultural University, Beijing (in Chinese).

Liang, L., Wu, W., Lal, R., Guo, Y., 2013. Structural change and carbon emission of rural household energy consumption in Huantai, northern China. Renew. Sustain. Energy Rev. 28, 767–776. https://doi.org/10.1016/j.rser.2013.07.041.

Liu, Y., Heuvelink, G.B.M., Bai, Z., He, P., Xu, X., Ma, J., Masiliūnas, D., 2020. Space-time statistical analysis and modelling of nitrogen use efficiency indicators at provincial scale in China. Eur. J. Agron. 115, 126032 https://doi.org/10.1016/j.eja.2020.126032.

Liu, X., Zhang, Y., Han, W., Tang, A., Shen, J., Cui, Z., Vitousek, P., Erisman, J.W., Goulding, K., Christie, P., Fangmeier, A., Zhang, F., 2013. Enhanced nitrogen deposition over China. Nature 494, 459–462. https://doi.org/10.1038/nature11917.

López-Bellido, L., López-Bellido, R.J., Redondo, R., 2005. Nitrogen efficiency in wheat under rainfed Mediterranean conditions as affected by split nitrogen application. Field Crops Res. 94, 86–97. https://doi.org/10.1016/j.fcr.2004.11.004.

Ma, R., Zou, J., Han, Z., Yu, K., Wu, S., Li, Z., Liu, S., Niu, S., Horwath, W.R., Zhu-Barker, X., 2021. Global soil-derived ammonia emissions from agricultural nitrogen fertilizer application: a refinement based on regional and crop-specific emission factors. Glob. Change Biol. 27, 855–867. https://doi.org/10.1111/gcb.15437.

Meng, X., Guo, Z., Yang, X., Su, W., Li, Z., Wu, X., Ahmad, I., Cai, T., Han, Q., 2021. Straw incorporation helps inhibit nitrogen leaching in maize season to increase yield and efficiency in the Loess Plateau of China. Soil Tillage Res. 211, 105006 https://doi.org/10.1016/j.still.2021.105006.

Moreno, F., Cayuela, J.A., Fernández, J.E., Fernández-Boy, E., Murillo, J.M., Cabrera, F., 1996. Water balance and nitrate leaching in an irrigated maize crop in SW Spain. Agric. Water Manag. 32, 71–83. https://doi.org/10.1016/S0378-3774(96)01256-5.

Pacholski, A., Cai, G., Nieder, R., Roelcke, M., 2006. Calibration of a simple method for determining ammonia volatilization in the field-comparative measurements in Henan Province, China. Nutr. Cycl. Agroecosystems 74, 259–273. https://doi.org/10.1007/s10705-006-9003-4.

Poffenbarger, H.J., Sawyer, J.E., Barker, D.W., Olk, D.C., Six, J., Castellano, M.J., 2018. Legacy effects of long-term nitrogen fertilizer application on the fate of nitrogen fertilizer inputs in continuous maize. Agric., Ecosyst. Environ. 265, 544–555. https://doi.org/10.1016/j.agee.2018.07.005.

Quan, Z., Zhang, X., Fang, Y., Davidson, E.A., 2021. Different quantification approaches for nitrogen use efficiency lead to divergent estimates with varying advantages. Nat. Food 2, 241. https://doi.org/10.1038/s43016-021-00263-3.

Ren, K., Xu, M., Li, R., Zheng, L., Liu, S., Reis, S., Wang, H., 2022. Optimizing nitrogen fertilizer use for more grain and less pollution. J. Clean. Prod. 360, 132180 https://doi.org/10.1016/j.jclepro.2022.132180.

Rillig, M.C., Ryo, M., Lehmann, A., Aguilar-Trigueros, C.A., Buchert, S., Wulf, A., Iwasaki, A., Roy, J., Yang, G., 2019. The role of multiple global change factors in driving soil functions and microbial biodiversity. Science 366, 886–890. https://doi.org/10.1126/science.aay2832.

Ruttan, V., 1991. Sustainable Growth in Agricultural Production – Poetry, Policy and Science. In: Vosti, S.A., Reardon, T., Vonurff, W. (Eds.), Agricultural Sustainability, Growth, and Poverty Alleviation: Issues and Policies. Presented at the International Conf on Agricultural Sustainability, Growth, And Poverty Alleviation: Issues And Policies. Deutsche Stiftung Internationale Entwicklung, Feldafing, pp. 13–28.

Shi, Y.F., Wu, W.L., Meng, F.Q., Zheng, L., Wang, D.P., Ye, H., Ding, G.W., 2014. Nitrous oxide and methane fluxes during the maize season under optimized management in intensive farming systems of the North China Plain. Pedosphere 24, 487–497. https://doi.org/10.1016/S1002-0160(14)60035-7.

Sommer, S.G., Friis, E., Bach, A., Schjerring, J.K., 1997. Ammonia volatilization from pig slurry applied with trail hoses or broadspread to winter wheat: effects of crop developmental stage, microclimate, and leaf ammonia absorption. J. Environ. Qual. 26, 1153–1160. https://doi.org/10.2134/jeq1997.00472425002600040030x.

Stone, M.M., DeForest, J.L., Plante, A.F., 2014. Changes in extracellular enzyme activity and microbial community structure with soil depth at the Luquillo Critical Zone Observatory. Soil Biol. Biochem. 75, 237–247. https://doi.org/10.1016/j.soilbio.2014.04.017.

Thilakarathna, S.K., Hernandez-Ramirez, G., Puurveen, D., Kryzanowski, L., Lohstraeter, G., Powers, L., Quan, N., Tenuta, M., 2020. Nitrous oxide emissions and nitrogen use efficiency in wheat: Nitrogen fertilization timing and formulation, soil nitrogen, and weather effects. Soil Sci. Soc. Am. J. 84, 1910–1927. https://doi.org/10.1002/saj2.20145.

Trenbath, B.R., Conway, G.R., Craig, I.A., 1990. Threats to sustainability in intensified agricultural systems: analysis and implications for management. Agroecol. Res. Ecol. basis Sustain. Agric. 337–365.

Vonk, W.J., Hijbeek, R., Glendining, M.J., Powlson, D.S., Bhogal, A., Merbach, I., Silva, J. V., Poffenbarger, H.J., Dhillon, J., Sieling, K., 2022. The legacy effect of synthetic N fertiliser. Eur. J. Soil Sci. 73, e13238 https://doi.org/10.1111/ejss.13238.

Wang, R., Feng, Q., Liao, T., Zheng, X., Butterbach-Bahl, K., Zhang, W., Jin, C., 2013. Effects of nitrate concentration on the denitrification potential of a calcic cambisol and its fractions of N_2, N_2O and NO. Plant Soil 363, 175–189. https://doi.org/10.1007/s11104-012-1264-x.

Wang, S., Luo, S., Yue, S., Shen, Y., Li, S., 2019. Residual effects of fertilizer N response to split N applications in semiarid farmland. Nutr. Cycl. Agroecosystems 114, 99–110. https://doi.org/10.1007/s10705-019-09995-y.

Wu, G., Ling, J., Zhao, D., Xu, Y., Liu, Z., Wen, Y., 2022. Deep–injected straw incorporation improves subsoil fertility and crop productivity in a wheat-maize rotation system in the North China Plain. Field Crops Res. 286, 108612 https://doi.org/10.1016/j.fcr.2022.108612.

Xia, L., Lam, S.K., Chen, D., Wang, J., Tang, Q., Yan, X., 2017a. Can knowledge-based N management produce more staple grain with lower greenhouse gas emission and reactive nitrogen pollution? A meta–analysis. Glob. Change Biol. 23, 1917–1925. https://doi.org/10.1111/gcb.13455.

Xia, L., Lam, S.K., Wolf, B., Kiese, R., Chen, D., Butterbach-Bahl, K., 2018. Trade-offs between soil carbon sequestration and reactive nitrogen losses under straw return in global agroecosystems. Glob. Change Biol. 24, 5919–5932. https://doi.org/10.1111/gcb.14466.

Xia, L., Lam, S.K., Yan, X., Chen, D., 2017b. How does recycling of livestock manure in agroecosystems affect crop productivity, reactive nitrogen losses, and soil carbon balance? Environ. Sci. Technol. 51, 7450–7457. https://doi.org/10.1021/acs.est.6b06470.

Yan, M., Pan, G., Lavallee, J.M., Conant, R.T., 2020. Rethinking sources of nitrogen to cereal crops. Glob. Change Biol. 26, 191–199. https://doi.org/10.1111/gcb.14908.

Yan, X., Ti, C., Vitousek, P., Chen, D., Leip, A., Cai, Z., Zhu, Z., 2014. Fertilizer nitrogen recovery efficiencies in crop production systems of China with and without consideration of the residual effect of nitrogen. Environ. Res. Lett. 9, 095002 https://doi.org/10.1088/1748-9326/9/9/095002.

Yan, G., Yao, Z., Zheng, X., Liu, C., 2015. Characteristics of annual nitrous and nitric oxide emissions from major cereal crops in the North China Plain under alternative fertilizer management. Agric., Ecosyst. Environ. 207, 67–78. https://doi.org/10.1016/j.agee.2015.03.030.

Yan, G., Zheng, X., Cui, F., Yao, Z., Zhou, Z., Deng, J., Xu, Y., 2013. Two–year simultaneous records of N_2O and NO fluxes from a farmed cropland in the northern China plain with a reduced nitrogen addition rate by one–third. Agric., Ecosyst. Environ. 178, 39–50. https://doi.org/10.1016/j.agee.2013.06.016.

Yang, T., 2021. Response of Soil Ammonia Volatilization and Canopy Ammonia Exchange to Conservation Tillage in Spring Maize Field of Guanzhong Region. Northwest A & F University, Shaanxi (in Chinese).

Yin, H., Zhao, W., Li, T., Cheng, X., Liu, Q., 2018. Balancing straw returning and chemical fertilizers in China: role of straw nutrient resources. Renew. Sustain. Energy Rev. 81, 2695–2702. https://doi.org/10.1016/j.rser.2017.06.076.

Yin, Y., Zhao, R., Yang, Y., Meng, Q., Ying, H., Cassman, K.G., Cong, W., Tian, X., He, K., Wang, Y., Cui, Z., Chen, X., Zhang, F., 2021. A steady-state N balance approach for sustainable smallholder farming. Proc. Natl. Acad. Sci. USA 118, e2106576118. https://doi.org/10.1073/pnas.2106576118.

Zhang, X., Bol, R., Rahn, C., Xiao, G., Meng, F., Wu, W., 2017. Agricultural sustainable intensification improved nitrogen use efficiency and maintained high crop yield during 1980–2014 in Northern China. Sci. Total Environ. 596 61–68. https://doi.org/10.1016/j.scitotenv.2017.04.064.

Zhang, T., Liu, H., Luo, J., Wang, H., Zhai, L., Geng, Y., Zhang, Y., Li, J., Lei, Q., Bashir, M.A., Wu, S., Lindsey, S., 2018. Long-term manure application increased greenhouse gas emissions but had no effect on ammonia volatilization in a Northern China upland field. Sci. Total Environ. 633, 230–239. https://doi.org/10.1016/j.scitotenv.2018.03.069.

Zhang, X., Meng, F., Li, H., Wang, L., Wu, S., Xiao, G., Wu, W., 2019. Optimized fertigation maintains high yield and mitigates N_2O and NO emissions in an intensified wheat-maize cropping system. Agric. Water Manag. 211, 26–36. https://doi.org/10.1016/j.agwat.2018.09.045.

Zhang, P., Wei, T., Jia, Z., Han, Q., Ren, X., 2014. Soil aggregate and crop yield changes with different rates of straw incorporation in semiarid areas of northwest China. Geoderma 230–231 41–49. https://doi.org/10.1016/j.geoderma.2014.04.007.

Zhang, X., Xiao, G., Bol, R., Wang, L., Zhuge, Y., Wu, W., Hu, L., Meng, F., 2021. Influences of irrigation and fertilization on soil N cycle and losses from wheat-maize cropping system in northern China. Environ. Pollut. 278, 116852 https://doi.org/10.1016/j.envpol.2021.116852.

Zhou, Y., Yang, Z., Liu, J., Li, X., Wang, X., Dai, C., Zhang, T., Carrión, V.íctorJ., Wei, Z., Cao, F., 2023. Crop rotation and native microbiome inoculation restore soil capacity to suppress a root disease. Nat. Commun. 14, 8126. https://doi.org/10.1038/s41467-023-43926-4.