Title

Long-term balanced organic and synthetic nitrogen fertilization can realize sustainable crop production

Journal

Agricultural Systems, 233

ISSN

0308-521X

Authors

Zhang, Chong
Zhang, Xin
Rees, Robert M
et al.

Publication Date

2026-03-01

DOI

10.1016/j.agsy.2026.104653

Peer reviewed

Agricultural Systems 233 (2026) 104653

Contents lists available at ScienceDirect

Agricultural Systems

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

Long-term balanced organic and synthetic nitrogen fertilization can realize sustainable crop production

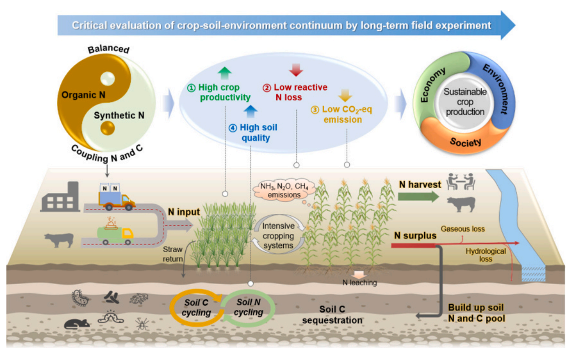
Chong Zhang [a], Xin Zhang [b], Robert M. Rees [c], Wim de Vries [d], Luis Lassaletta [e], Jagdish K. Ladha [f], Xiaotang Ju [a,*]

[a] School of Tropical Agriculture and Forestry, Hainan University, Haikou 570228, China
[b] Appalachian Laboratory, University of Maryland Center for Environmental Science, Frostburg, MD 21532, USA
[c] Scotland's Rural College, Edinburgh, Scotland EH9 3JG, UK
[d] Wageningen University and Research, Environmental Systems Analysis Group, P.O. Box 47, Wageningen 6700AA, the Netherlands
[e] CEIGRAM/Department of Agricultural Production, ETSIAAB, Universidad Politécnica de Madrid, Madrid 28040, Spain
[f] Department of Plant Sciences, University of California, Davis, California 95616, USA

HIGHLIGHTS

- We evaluated the sustainability of crop production using a long-term field trial.
- Crop yield, soil C and N stock change, N losses and GHG balance were quantified.
- Balanced organic and synthetic N fertilization realized sustainable crop production.
- High N surplus did not cause high N losses but increased soil organic N stock.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Leonard Rusinamhodzi

Keywords:
Sustainable crop production
Manure recycling
Crop yield
Nitrogen surplus
Greenhouse gas emissions
Long-term field experiment

ABSTRACT

CONTEXT: Manure recycling to cropland reduces synthetic fertilizer use and nitrogen (N) waste while increasing soil carbon (C) sequestration, which is important for sustainable crop production. However, few studies have systematically integrated long-term N budgets with changes of soil C and N stocks and the greenhouse gas (GHG) balance.
OBJECTIVE: We aim to quantify the long-term responses of crop productivity, changes of soil C and N stock, reactive N losses and the GHG balance to various C and N management practices, thus providing evidence for sustainable crop production.
METHODS: We used a 15-year wheat-maize double cropping system in the North China Plain. The experiment included eight fertilization treatments with contrasting C and N management practices. Crop productivity, N losses, changes of soil C and N stock; and the GHG balance were evaluated.
RESULTS AND CONCLUSIONS: Compared with conventional fertilization with excess synthetic N, long-term balanced organic and synthetic N fertilization (in which N rates were determined using an N balance

* Corresponding author.
E-mail address: juxt@cau.edu.cn (X. Ju).

https://doi.org/10.1016/j.agsy.2026.104653
Received 25 July 2025; Received in revised form 16 January 2026; Accepted 23 January 2026
Available online 28 January 2026

approach and target N yield, and the rates of synthetic N equal to the difference between above N rate and mineralized N from manure) increases crop yield and N harvest by 8–11%, and soil C and N sequestration by 191–230%, while reducing N inputs by 23%, thus also reducing reactive N losses by 40% and the GHG balance from 59 to −2143 kg CO_2-eq ha^{-1}. Although the N surplus was relatively high in the balanced organic and synthetic N fertilization, it did not cause high N losses but achieved high soil C and N sequestration and crop yield, which were not achieved under the optimum synthetic N fertilization.

SIGNIFICANCE: This study emphasizes the benefits of combining organic and synthetic N within an appropriate N management framework, offering a global model for sustainable crop production in croplands. Site-specific adjustments could be necessary when applying these findings to other regions with distinctly different soil or climatic conditions. We should interpret N surplus cautiously because a high N surplus does not necessarily lead to high N losses with manure recycling to croplands.

1. Introduction

Applying synthetic nitrogen (N) fertilizer is crucial for maintaining crop yields and replenishing soil N to avoid mining of N with related soil degradation (Quan et al., 2021; Yan et al., 2020). To increase the food supply for a growing population and changing diets, the synthetic N fertilizer consumption of global croplands has increased to more than 100 Tg N yr^{-1} (Ladha et al., 2020; Xia and Yan, 2023). The combined N inputs from manure, N fixation and N deposition contributed to an N surplus of 91–95 Tg N yr^{-1} which is greater than the crop N harvest of 78–81 Tg N yr^{-1} (Schulte-Uebbing et al., 2022; Zhang et al., 2021b). This cropland N surplus has caused serious unintended problems such as air and water pollution, and greenhouse gas (GHG) emissions as N cascades out of agricultural systems into the wider environment (Sutton et al., 2011), thus exceeding an estimated planetary boundary for the N surplus of 43 Tg N yr^{-1} (Schulte-Uebbing et al., 2022). Sustainable crop production is a global challenge and an increase in nitrogen use efficiency (NUE) is needed to reconcile crop productivity with acceptable N losses, particularly in intensive agricultural regions (Gu et al., 2023; Lassaletta et al., 2023; Schulte-Uebbing and de Vries, 2021).

Best N management practices (or so-called "knowledge-based N management") have been developed in recent decades, such as 4R nutrient stewardship (4Rs, right source, time, rate and place), precise nitrogen fertilizer management, organic fertilization, enhanced efficiency N fertilizers (EEFs), and diversified crop rotations with legumes or other cash crops (Cai et al., 2025; Johnston and Bruulsema, 2014; Shah et al., 2021; Xia et al., 2017a; Xia et al., 2017b). The partial substitution of synthetic fertilizer by organic inputs (combination of synthetic N fertilizer and organic N) can increase crop yields, especially in China where it counteracts soil acidification since liming is often not practiced (Cai et al., 2015, 2021; Xu et al., 2023), reduce N losses and fertilizer dependency on new N resources (Wei et al., 2021b; Zhang et al., 2020b) and enhance the sequestration of carbon (C), thereby improving soil quality and counteracting climate change (Gao et al., 2023; Lessmann et al., 2022). In contrast, using either source alone cannot achieve such synergistic benefits, as synthetic N alone had limited capacity to enhance soil fertility, N mineralization-immobilization turnover and is prone to loss (Cai et al., 2019), while the release of manure N is often too slow to match the high crop N demand during the peak crop growing stage (Zhang et al., 2020b). Enhancing manure recycling by replacing synthetic N fertilizer is thus a promising measure in China where only 40% of the manure is currently recycled to croplands and mainly to the cash crops such as fruits and vegetables, due to the decoupling of crop and livestock farming (Bai et al., 2022; Jin et al., 2020a; Zhang et al., 2019b).

The cropland N cycle is tightly coupled with the C cycle. Applying C-rich organic material, such as manure, not only increases soil N retention capacity by enhancing microbial activity and improving soil quality (Elrys et al., 2023), but also provides better synchrony between crop N demand and soil N supply to enhance yield while minimizing N losses (Elrys et al., 2023; Liang et al., 2013). Soil C sequestration is primarily controlled by soil N availability (Kicklighter et al., 2019; Kirkby et al., 2014; van Groenigen et al., 2017), because of the stoichiometry and homeostasis of soil microbial communities (Bertrand et al., 2019). Moreover, GHG mitigation is closely related to cropland N management practices (Cui et al., 2024). Therefore, combination of organic with synthetic N fertilization may help to realize sustainable crop production and achieve four goals: increased productivity, reduced N pollution, improved soil quality and climate change mitigation.

Many studies have demonstrated that combining manure with synthetic N fertilizer can enhance yield and N use efficiency while reducing N losses at regional to global scales (Elrys et al., 2023; Gu et al., 2023; Ren et al., 2023; You et al., 2023). Nevertheless, few studies have systematically integrated long-term N budgets with changes of soil C and N stock and greenhouse gas (GHG) balances. The long-term experiments are reliable for assessing the above aspects, because the changes of soil C and N stock often require more than a decade to reach a steady state in the soil-crop system when some management practices are changed (van Grinsven et al., 2022). Such integrated and long-term evaluations remain scarce in current meta-analyses and field studies (Duan et al., 2024; Gu et al., 2023), leaving a knowledge gap in assessing the sustainability of nutrient management strategies.

To address this gap, we evaluated crop productivity, N budgets, changes of soil C and N stock, and GHG balances under different C and N management regimes using data from a long-term field experiment (2006–2021) with a wheat-maize double cropping system in the North China Plain. This is one of the most intensive agricultural regions in the world, which produces 23% of China's cereals (Yang et al., 2024). The long-term experiment included four fertilization strategies with or without straw (S) removal: zero-N fertilization (N_0 and SN_0), conventional synthetic N fertilization (N_{con} and SN_{con}), optimum synthetic N fertilization (N_{opt} and SN_{opt}) and balanced organic (Cattle manure/M) with synthetic N fertilization (MN_{bal} and SMN_{bal}). The following indicators were evaluated: (1) crop yield and N harvest; (2) N loss pathways including ammonia (NH_3) volatilization, nitrate (NO_3^-) leaching, nitrous oxide (N_2O) and dinitrogen (N_2) emissions; (3) N budget, N surplus and NUE with consideration of N input from synthetic fertilizer, organic fertilizer, straw, N deposition, biological N fixation, irrigation and seed; (4) changes of soil C and N stock; and (5) the GHG balance. We hypothesized that long-term balanced organic and synthetic N fertilization would achieve high crop yields, enhance soil quality by building up C and N stocks and reduce N loses thereby reducing the environmental impacts, while it may also induce higher N surplus for sustaining soil C sequestration but not N losses.

2. Materials and methods

2.1. Site description

The long-term experiment was established at the Shangzhuang Experimental Station of the China Agricultural University (40°8.40′N, 116°10.80′E) in October 2006. The site is typical of the intensive agricultural region in the North China Plain. Annual average air temperature is 13 °C and annual precipitation is 540 mm, of which 60–70% occurs from June to August (1981–2015). The soil is a calcareous Cambisol according to FAO's Soil Classification, and is known as a fluvo-aquic soil in China (Chinese soil genetic classification) (Wei et al., 2023; Zhang et al., 2022). In 2006, the topsoil (0–20 cm) had a particle size distribution of 28% clay, 32% silt, and 40% sand, a soil organic carbon (SOC) content of 7.7 g kg^{-1}, a total N content of 0.70 g kg^{-1}, pH of 8.1, an Olsen P content of 7.8 mg kg^{-1} and an available K content of 76 mg kg^{-1}. The studied soil was developed from alluvial deposit and characterized by low background SOC (Han et al., 2017; Ju and Zhang, 2017). This low fertility level, both in terms of SOC and Olsen P levels influences the increase in soil fertility in response to fertilizer and manure additions, including an increase in Olsen P levels to >30 mg kg^{-1}, as reported in our previous publication (Zhang et al., 2021a). The site had a wheat-maize double cropping rotation, which is typical of farming in the North China Plain. The wheat was sown in early October and harvested in mid-June of the following year, followed immediately by direct seeding of maize which was harvested in early October in the same year (Wei et al., 2023; Zhang et al., 2022). The study site is relatively representative of the North China Plain due to region's relatively uniform climatic and edaphic conditions, cropping systems, and agronomic management (Xin and Tao, 2020; Liu et al., 2022).

2.2. Design of the long-term experiment and field management

Eight treatments were set up in 2006 with different C and N management including: (1) N_0, zero-N fertilization and straw removed; (2) SN_0, zero-N fertilization and straw returned; (3) N_{con}, conventional synthetic N fertilization and straw removed; (4) SN_{con}, conventional synthetic N fertilization and straw returned; (5) N_{opt}, optimum synthetic N fertilization and straw removed; (6) SN_{opt}, optimum synthetic N fertilization and straw returned; (7) MN_{bal}, balanced organic with synthetic N fertilization and straw removed; (8) SMN_{bal}, balanced organic with synthetic N fertilization and straw returned. A randomized complete block design with three replicates and a plot size of 64 m^2 (8 m × 8 m) was used.

Fertilizer N rates of the N_{con} and SN_{con} treatments were determined according to local farmer's practice, with 300 kg N ha^{-1} for wheat and 260 kg N ha^{-1} for maize. The fertilizer N rates are very high in the North China Plain (Ju et al., 2009), partly due to the high losses caused by poor management of fertilizer applications. Fertilizer N rates for the so-called "optimum synthetic N fertilization (N_{opt} and SN_{opt})" were determined by a soil mineral N test, which was calculated by the target crop N demand subtracted by the soil nitrate-N stock in the root zone (Cui et al., 2013b), with a wheat N demand of 100 kg N ha^{-1} at the basal dressing and 200 kg N ha^{-1} at the top dressing, while maize N demand was 100 kg N ha^{-1} at the 4-leaf stage and 160 kg N ha^{-1} at 10-leaf stage (Qiu et al., 2012). After five years of fertilization, we found that fertilizer N rates for the two optimum management treatments did not vary much with seasons. Therefore, synthetic N fertilizer rates of 150 kg N ha^{-1} in wheat and 130 kg N ha^{-1} in maize were applied from October 2011, according to the N rate in the previous crop seasons (this rate took into account the soil N supply). In June 2017, we changed the above synthetic N fertilizer rates to 160 kg N ha^{-1} in both wheat and maize seasons, to meet the crop demand for a relatively high target yield. The temporal change of N management of the optimum synthetic N fertilization is shown in Fig. S1 and Table S1.

The N fertilizer (synthetic and organic) rates in the balanced organic with synthetic N fertilization (MN_{bal} and SMN_{bal}) treatments were determined by an N balance calculation in the soil-crop system. It is equal to the N output at harvest minus soil nitrate-N at seeding. N output included aboveground N harvest and target residual nitrate-N in root zone at harvest; aboveground N harvest was calculated to be 180 kg N ha^{-1} in wheat and 160 kg N ha^{-1} in maize (these are aboveground crop N uptake and different from the crop N demand in the soil mineral N test method which means "N supply" from fertilizer and soil), and the target residual nitrate-N was set to be 100 kg N ha^{-1} for both crops (Qiu et al., 2012). This amount of nitrate-N can maintain a high yield in upland areas of the study region (Cui et al., 2013a). A fresh weight of 30 t ha^{-1} of decomposed cattle manure (equivalent to 15 t ha^{-1} of dry weight on average, 1.5% N on average) was applied annually at the sowing of wheat. It was estimated that 40% and 20% of total N in the manure was available N in the first wheat and second maize season after their annual application for the N rate calculation, respectively (Eghball and Power, 1999; Beegle et al., 2008). The gap between the calculated N rates and mineralized N from manure was filled by synthetic N fertilizer. Similar to the N_{opt} and SN_{opt} treatments, the balanced N rate did not vary much with seasons after five-years of fertilization, we therefore applied 170 kg N ha^{-1} to wheat and 180 kg N ha^{-1} to maize as fertilizer N (this includes synthetic and organic mineralized N, with an average synthetic N rate of 106 kg N ha^{-1} in wheat and 148 kg N ha^{-1} in maize) to the balanced organic with synthetic N fertilization after October 2011, according to the N rate in the previous crop seasons. The temporal change of N management of the balanced organic with synthetic N fertilization is also shown in Fig. S1, Table S1 and S2.

The synthetic N fertilizer type was urea. In the wheat season, half of the urea-N was applied during basal fertilization and the other half during topdressing under the optimum and conventional synthetic N fertilization, while one-third of urea-N was applied during basal fertilization and two-thirds during topdressing under the balanced organic with synthetic N fertilization. Cattle manure was applied once at basal fertilization. The basal fertilizers were surface-broadcast and then plowed using a deep plow (approximately 20 cm). Topdressed fertilizer N was surface-broadcast and then irrigated. In the maize season, half of the urea-N was applied at the four-leaf fertilization stage and the other half at the ten-leaf fertilization stage by banding at a depth of 5–7 cm in the fertilization treatments.

All the treatments received the same phosphorus (P), potassium (K) and zinc (Zn) synthetic fertilizer and irrigation. The P and K fertilizers were applied at a rate of 70 kg P ha^{-1} yr^{-1} and 75 kg K ha^{-1} yr^{-1}, respectively, and applied as basal fertilizer at the seeding of wheat. Due to the occurrence of P and K deficiency symptoms in the maize season in 2013, the P and K fertilizer rates were increased to 87 kg P ha^{-1} yr^{-1} and 166 kg K ha^{-1} yr^{-1} late on, and half of them were applied during basal fertilization stage of wheat and the other half during 4-leaf topdressing stage of maize. Moreover, 12 kg Zn ha^{-1} yr^{-1} was applied to maize from 2016 to meet the crop demand.

Irrigation during the wheat season was scheduled on the basis of soil moisture and applied three to five times at rates of 28–70 mm per event. Maize was primarily rain-fed and irrigated only when dry conditions occurred at seeding, with application rates of 45–60 mm. Details of the irrigation amount in each event are in Table S3. The aim was to maintain the soil water content between 45% and 80% of plant available water content, which was determined by water holding capacity and the corresponding wilting point (Meng et al., 2012). Deep plowing (20 cm) was carried out at the sowing of wheat, and direct seeding of maize with no-tillage after the harvest of wheat. In the straw return treatments, maize straw was shredded and incorporated into the soil by deep plowing, wheat straw was shredded and mulched on the soil surface, the straw amount was 2.5–6.0 t ha^{-1} of wheat and 4.8–8.0 t ha^{-1} of maize.

2.3. Calculation of N budget

N input (N_{input}, kg N ha^{-1} yr^{-1}), N output (N_{output}, kg N ha^{-1} yr^{-1}), changes of soil N stock ($N_{\Delta soil}$, kg N ha^{-1} yr^{-1}), N surplus ($N_{surplus}$ kg N ha^{-1} yr^{-1}) and *NUE* (%) were calculated by Eqs. (1)–(5), respectively (Zhang et al., 2020a).

$$N_{input} = N_{syn} + N_{man} + N_{dep} + N_{fix} + N_{irr} + N_{seed} \quad (1)$$

$$N_{output} = N_{har} + N_{loss} \quad (2)$$

$$N_{\Delta soil} = \mathrm{N_{input}} - \mathrm{N_{output}} \quad (3)$$

$$\mathrm{N_{surplus}} = N_{input} - N_{har} \quad (4)$$

$$NUE = N_{har}/N_{input} \times 100\% \tag{5}$$

where N_{syn}, N_{man}, N_{dep}, N_{fix}, N_{irr} and N_{seed} are the N inputs from synthetic fertilizer, manure, atmospheric deposition, biological N fixation, irrigation and seed, respectively. N harvest (N_{har}, kg N ha^{-1} yr^{-1}) refers to grain N harvest under complete straw return, while it refers to aboveground (grain and straw) N harvest under straw removal. N loss (N_{loss}) includes leaching, and emission of NH_3, N_2 and N_2O. The changes in soil N stock ($N_{\Delta soil}$) calculated by Eq. (3) contains uncertainties (error) from the input and output terms (Zhang et al., 2020a), therefore, we also define this indication as $N_{\Delta soil+uncer}$. Data sources of the N input from atmospheric deposition, biological N fixation, irrigation and seed, and the measurements of crop biomass and N harvest, can be found in the supplementary material.

2.4. Measurements of changes of soil C and N stock

We measured soil C and N stocks in years 2006 and 2021. Ten soil cores were collected to a depth of 1.0 m using a 30 mm diameter soil auger. Each soil core was separated into 0.2 m intervals and then mixed to form a composite sample for each layer. Each treatment had three replications. Soil samples were air-dried and sieved (2 mm mesh) to remove plant detritus, soil total nitrogen (TN) and organic carbon (SOC) was determined by Kjeldahl method and wet oxidation method, respectively (Zhang et al., 2023a). Soil bulk density (BD) was measured using the ring knife method before the establishment of the experiment. Three soil pits were dug randomly in the experimental plots to obtain soil samples at depths of 10, 30, 50, 70 and 90 cm, which represented the BD of 0–20, 20–40 cm, 40–60 cm, 60–80 cm and 80–100 cm. In 2021, all the experimental plots were sampled to a depth of 40 cm to measure the BD of 0–20, 20–40 cm layers, while BD below 40 cm still used the data from 2006. SOC and TN stock (SOC_{stock}, kg C ha^{-1}; TN_{stock}, kg N ha^{-1}) and changes in soil C and N stock (SOC_{change} kg C ha^{-1} yr^{-1}; TN_{change}, kg N ha^{-1} yr^{-1}) in each layer were calculated as follows:

$$TN_{stock} = c \times BD \times 20/10 \tag{6}$$

$$SOC_{stock} = c \times BD \times 20/10 \tag{7}$$

$$TN_{change} = \left(TN_{stock\_2021} - TN_{stock\_2006}\right)/15 \tag{8}$$

$$SOC_{change} = \left(SOC_{stock\_2021} - SOC_{stock\_2006}\right/15 \tag{9}$$

where c is SOC or TN concentration (mg kg^{-1}), BD is soil bulk density (g cm^{-3}), 20 is the soil thickness (cm) and 10 is the unit conversion coefficient. Changes of soil C and N stock in the 0–100 cm soil were calculated by summing the results from the five soil layers.

2.5. Measurements of N losses

We measured ammonia (NH_3) volatilization using the dynamic chamber and nitrous oxide (N_2O) emissions using the static chamber method in the rotation cycle of 2017–2018 and 2018–2019 (Wei et al., 2023; Zhang et al., 2023b), The N_2O fluxes were annualized using the linear interpolation between adjacent measurements to estimate emissions on non-sampling days. We quantified the N_2 emissions by dividing the measured field N_2O emissions by the seasonal and annual ratio of N_2O to N_2O plus N_2 emissions (R_{N2O}) using the gas-flow-soil-core technique under laboratory conditions (Wang et al., 2022). The N losses via leaching were measured using the suction cup method in the rotations of 2010–2011, 2011–2012 and 2012–2013 (Huang et al., 2017). The detailed fluxes of the above N loss pathways can be found in our previous published paper (Huang et al., 2017; Wang et al., 2022; Wei et al., 2023; Zhang et al., 2023b), and we only show the amount of N losses in the rotation cycle of each N loss pathway in the present study. We used the above-mentioned average N losses measured in the 2–3 year period by assuming that these losses are representative for the N losses over during the whole experimental period in the N budget calculation. All the major measurements and key references can be also found in the summary table in supplementary materials (Table S4).

2.6. Calculation of greenhouse gas balance

We calculated the GHG balance on the field scale based on changes of soil C stock in 0–100 cm soil and N_2O emissions. We did not include CH_4 emissions in this study because they have been consistently shown to be negligible in the upland soils of the North China Plain (approximately −1 kg C ha^{-1} yr^{-1}) (Hu et al., 2013; Huang et al., 2018). The annual GHG emissions from N_2O (GHG_{N2O}, kg CO_2-eq ha^{-1} yr^{-1}) were calculated as follows:

$$GHG_{N2O} = N_2O - N \times 44/28 \times 273 \tag{10}$$

where N_2O-N (kg ha^{-1} yr^{-1}) is the annual N_2O emissions in the rotation cycle of 2017–2018 and 2018–2019. 44/28 is the conversion coefficients from N to N_2O. The global warming potential used to convert N_2O to CO_2-eq based on a 100-year horizon was 273 (IPCC, 2021).

The SOC sequestration (ΔC, kg CO_2-eq ha^{-1} yr^{-1}) was calculated from the changes of soil C stock in 0–100 cm between 2006 and 2021 (Eq. (9)) according to:

$$\Delta C = -SOC_{change} \times 44/12 \tag{11}$$

where SOC_{change} is derived from Eq. (9), 15 is the number of years between the two sampling years and 44/12 is the conversion coefficient from C into CO_2. The negative ΔC denote the C sink while positive ΔC denote C source.

Finally, the GHG balance (kg CO_2-eq ha^{-1} yr^{-1}) was calculated as follows:

$$\text{GHG balance} = GHG_{N2O} + \Delta C \tag{12}$$

2.7. Calculation of comprehensive evaluation index

The comprehensive evaluation index (*CEI*) was used to assess the sustainability of various C and N management practices by considering yield, crop N harvest, changes of soil C and N stock, reactive N losses and the GHG balance. The *CEI* is based on the Entropy-TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution). It employs entropy weights to objectively determine criterion weights, thereby minimizing subjective bias. This method assigns higher weights to indicators with greater variability in the dataset, as they provide more distinguishing information. We first standardized the raw data, computed entropy values, and normalized the weights to sum to 1. These entropy weights were then integrated into the TOPSIS procedure, which involved weighting the decision matrix, calculating the weighted ideal and anti-ideal solutions, and ranking alternatives based on their proximity to the ideal solution. This method was successfully employed by Yang et al. (2024) to assess the multiple functions of diversified cropping systems. Mover details of the procedures can be found in the supplementary material (Delgado and Romero, 2016; Yang et al., 2024).

2.8. Data analysis

The data for 2009–2010 was excluded from the 15-rotation cycles because of the large yield decrease caused by a natural disaster (extreme drought). All statistical analyses were performed using SPSS 20.0 (IBM Corp., Armonk, NY, USA). The differences in grain yield, crop N harvest, grain N concentration, N losses, N surpluses, NUE and the GHG balance

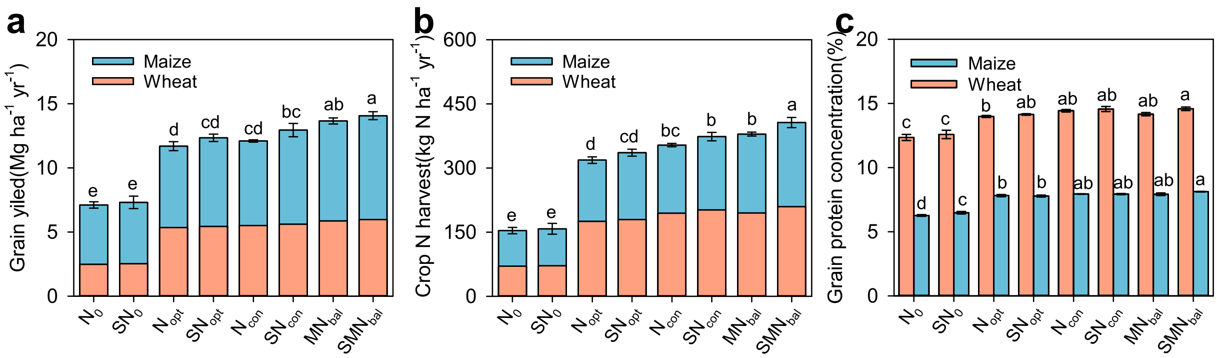


Fig. 1. Grain yield (a), crop N harvest (b) and grain protein concentration (c). Crop N harvest is aboveground N uptake and includes grain and straw. The vertical lines in a-b are the standard errors ($n = 3$) of annual grain yield summed over wheat and maize, the vertical lines in c are the standard errors ($n = 3$) of each crop type. Different lowercase letters are significant differences between the treatments at $P < 0.05$. We first averaged the multiple-year data of each replication, then mean and standard deviation was based on the above three replications of each treatment. N_0, N_{opt}, N_{con} and N_{bal} are no N fertilizer, optimum N, conventional N and balanced N rate, respectively. S and M are straw and cattle manure, respectively.

on the treatments were determined using Duncan's test with a significance level of $P < 0.05$. Data on total N losses and total N inputs were fitted using nonlinear regression models.

3. Results

3.1. Crop productivity and quality

Long-term balanced organic manure with synthetic N fertilization and straw return (SMN_{bal}) significantly increased grain yield (14.1 Mg ha^{-1} yr^{-1}) by 9–20% (average 15%) compared to all the synthetic N fertilization treatments (N_{opt}, SN_{opt}, N_{con} and SN_{con}, Figs. 1a, S2a-c). Balanced manure with synthetic N fertilization without straw (MN_{bal}) significantly increased grain yield (13.7 Mg ha^{-1} yr^{-1}) by 11–17% (average 13%) compared to the N_{opt}, SN_{opt} and N_{con} treatments, while no significant differences were found between the MN_{bal} and SN_{con} treatments. Grain yield under the optimum synthetic N fertilization was comparable to that under conventional synthetic N fertilization with the same level of straw return (11.7 in N_{opt} vs. 12.1 Mg ha^{-1} yr^{-1} in N_{con}, and 12.4 in SN_{opt} vs. 13.0 Mg ha^{-1} yr^{-1} in SN_{con}). Long-term straw incorporation had no significant effects on grain yields (Figs. 1a, S2a-c).

Long-term balanced organic with synthetic N fertilization and straw incorporation achieved the highest crop N harvest of all treatments (406 kg N ha^{-1} yr^{-1}), which was significantly higher by 7–28% (average 16%) than the other five N fertilization treatments (N_{opt}, SN_{opt}, N_{con}, SN_{con} and MN_{bal}). The MN_{bal} treatment significantly increased crop N harvest (380 kg N ha^{-1} yr^{-1}) by 13–19% (average 16%) compared to the optimum synthetic N fertilization, while no significant differences in crop N harvest were found between the MN_{bal} and conventional synthetic N fertilization. Crop N at harvest under the optimum synthetic N fertilization was significantly lower by 10% compared to the conventional synthetic N fertilization at the same level of straw return, i.e., 319 in N_{opt} vs. 354 kg N ha^{-1} yr^{-1} in N_{con}, 336 in SN_{opt} vs. 374 kg N ha^{-1} yr^{-1} in SN_{con} (Figs. 1b, S2d-f). This coincided with a lower grain N concentration under the optimum synthetic N compared to the conventional synthetic N fertilization, despite there being no significant differences (Fig. S3). Straw incorporation significantly increased the crop N harvest by 7% under the balanced organic with synthetic N fertilization (Figs. 1b, S2d-f).

There was a small variation of grain protein concentration under N fertilization, ranging from 14.0% to 14.6% (average 14.3%) for wheat and 7.8% to 8.1% (average 7.9%) for maize. However, the long-term balanced organic with synthetic N fertilization and straw return treatment (SMN_{bal}) significantly increased grain protein concentrations, compared to the optimum synthetic N fertilization without straw (N_{opt}) (Fig. 1c), indicating the benefits of long-term co-application of organic manure and synthetic N fertilizer in improving crop quality.

3.2. N budgets

Under N fertilization, total N inputs ranged from 369 to 646 kg N ha^{-1} yr^{-1}, of which 77–87% were from manure and synthetic N fertilizer. The rest accounted for 86 kg N ha yr^{-1} from deposition, biological N fixation, irrigation and seed. Crop N harvest ranged from 219 to 380 kg N ha^{-1} yr^{-1}, N losses represented 10–15% of total N inputs (Fig. 2a). By subtracting N harvest and N losses from the total N input, changes of soil N stock estimated by the difference method were 218–315 kg N ha^{-1} yr^{-1} under the conventional synthetic N fertilization, but much lower at 72–184 kg N ha^{-1} yr^{-1} under the balanced organic with synthetic N fertilization and SN_{opt} treatments. It was 6 kg N ha^{-1} yr^{-1} in the N_{opt} treatment (Fig. 2a).

The N surplus and NUE fluctuated between years in the first 10-year rotation cycles and tended to stabilize beyond that (Fig. S4). During the 15-year rotation cycles, average N surpluses showed differences in each management practice: it was 292–411 kg N ha^{-1} yr^{-1} under the conventional synthetic N fertilization, then followed by balanced organic with synthetic N fertilization (121–243 kg N ha^{-1} yr^{-1}), and optimum synthetic N fertilization (51–156 kg N ha^{-1} yr^{-1}). Straw return significantly increased the N surplus (Fig. 2b). NUE ranged from 51% to 86% under the balanced organic with synthetic N fertilization and optimum synthetic N fertilization, while NUE under the conventional synthetic N fertilization was much lower (36–55%). Straw return significantly decreased NUE (Fig. 2c).

3.3. Changes of soil C and N stock

During the 15-years of fertilization, the soil C stock increased at an annual rate of 729–821 kg C ha^{-1} yr^{-1} under the balanced organic with synthetic N fertilization, being significantly higher than that in the N_{opt} treatment (−195 kg C ha^{-1} yr^{-1}). The rate of increase in soil C stock was 135–334 kg C ha^{-1} yr^{-1} in the other three N fertilization treatments, being lower than the balanced organic with synthetic N fertilization, although the difference was not significant (Fig. 3a). The rate of increase in the measured soil N stock was 107–123 kg N ha^{-1} yr^{-1} under the balanced organic with synthetic N fertilization. This soil N stock change was significantly higher than in the N_{con}, SN_{con} and SN_{opt} treatments (31–60 kg N ha^{-1} yr^{-1}), while N_{opt} treatment was again significantly lower (−12 kg N ha^{-1} yr^{-1}) (Fig. 3b). These results indicate the importance of applying manure to soil in building up soil C and N stock.

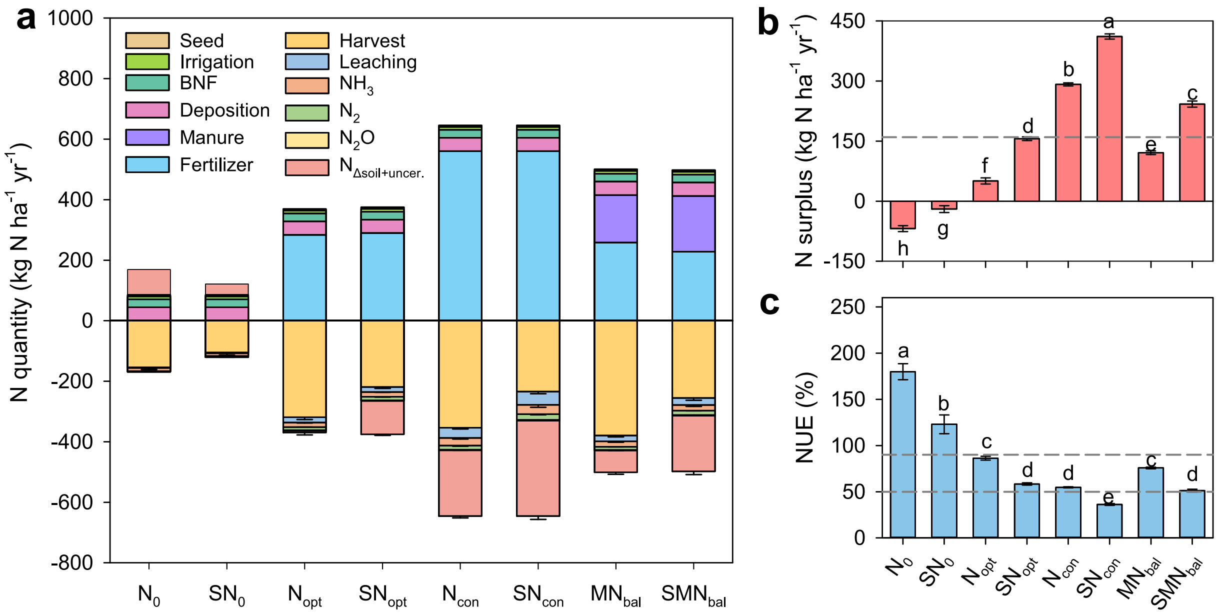


Fig. 2. Mean nitrogen budget (a), N surplus (b) and N use efficiency (NUE, c) in different treatments. All the N inputs, N harvest, surplus and the NUE were calculated as the mean across 15 years, while mean N losses (N leaching, NH_3, N_2 and N_2O emissions) were based on measurements during a 2–3 year period from 2017 to 2019. In a, changes of soil N stock ($N_{\Delta soil+uncer.}$) were calculated by subtracting N output from N input, the N harvest in straw return treatments refer to grain N harvest while in the straw removal treatments refer to the sum of grain and straw N harvest (also see the materials and methods for more information). The vertical lines are the standard errors ($n = 3$) in b and c different lowercase letters are significant differences between the treatments at $P < 0.05$. The dashed line in b is the N surplus benchmark in wheat-maize double cropping system in the North China Plain (Zhang et al., 2019a), and the dashed lines in **c** are the acceptable range of NUE in crop production (EU Nitrogen Expert Panel, 2015). N_0, N_{opt}, N_{con} and N_{bal} are no N fertilizer, optimum N, conventional N and balanced N rate, respectively. S and M are straw and cattle manure, respectively.

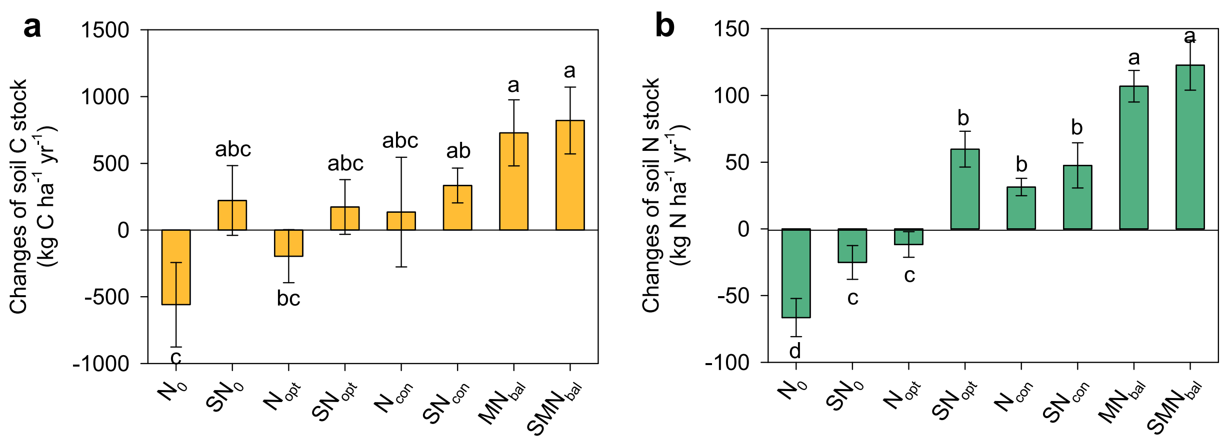


Fig. 3. Changes of soil C (a) and N (b) stock in the 0–100 cm soil. The vertical lines are the standard errors ($n = 3$), different lowercase letters are significant differences between the treatments at $P < 0.05$. N_0, N_{opt}, N_{con} and N_{bal} are no N fertilizer, optimum N, conventional N and balanced N rate, respectively. S and M denote straw and cattle manure, respectively.

3.4. N losses

Total N losses increased exponentially with the increase of N inputs (Fig. 4a). It was 74–96 kg N ha^{-1} yr^{-1} under the conventional synthetic N fertilization, and significantly higher than that in other treatments, then followed by the SMN_{bal} treatment (58 kg N ha^{-1} yr^{-1}), the MN_{bal} treatment and optimum synthetic N fertilization (44–49 kg N ha^{-1} yr^{-1}) (Fig. 4b). The balanced organic with synthetic N and optimum synthetic N fertilization had comparable yield-scaled N losses (3.6–4.1 kg N Mg^{-1}), which were significantly lower than those under conventional synthetic N fertilization (6.1–7.4 kg N Mg^{-1}) (Fig. 4c). There were similar N loss pathways under N fertilization, with leaching making up the largest share (36–46%), particularly under the conventional synthetic N fertilization, NH_3 volatilization was the second largest loss (32–37%), followed by N_2 losses (19–26%), and the least was N_2O emission (2–3%) (Fig. 4b).

3.5. GHG emissions

In the fertilization treatments, the SN_{con} treatment had the highest N_2O emissions of 1073 kg CO_2-eq ha^{-1} yr^{-1}, followed by the SMN_{bal}, N_{con} and SN_{opt} treatments (670–805 kg CO_2-eq ha^{-1} yr^{-1}), and the MN_{bal} and the N_{opt} treatments (564–592 kg CO_2-eq ha^{-1} yr^{-1}). The N_{opt} treatment caused a reduction in soil C sequestration, leading to positive CO_2-eq emissions (716 kg CO_2-eq ha^{-1} yr^{-1}), while other N treatments enhanced soil C sequestration (Fig. 5). The C sink induced by balanced organic with synthetic N fertilization (−3011 to −2672 kg CO_2-eq ha^{-1} yr^{-1}) was higher than in the SN_{opt}, N_{con} and SN_{con} treatments, which

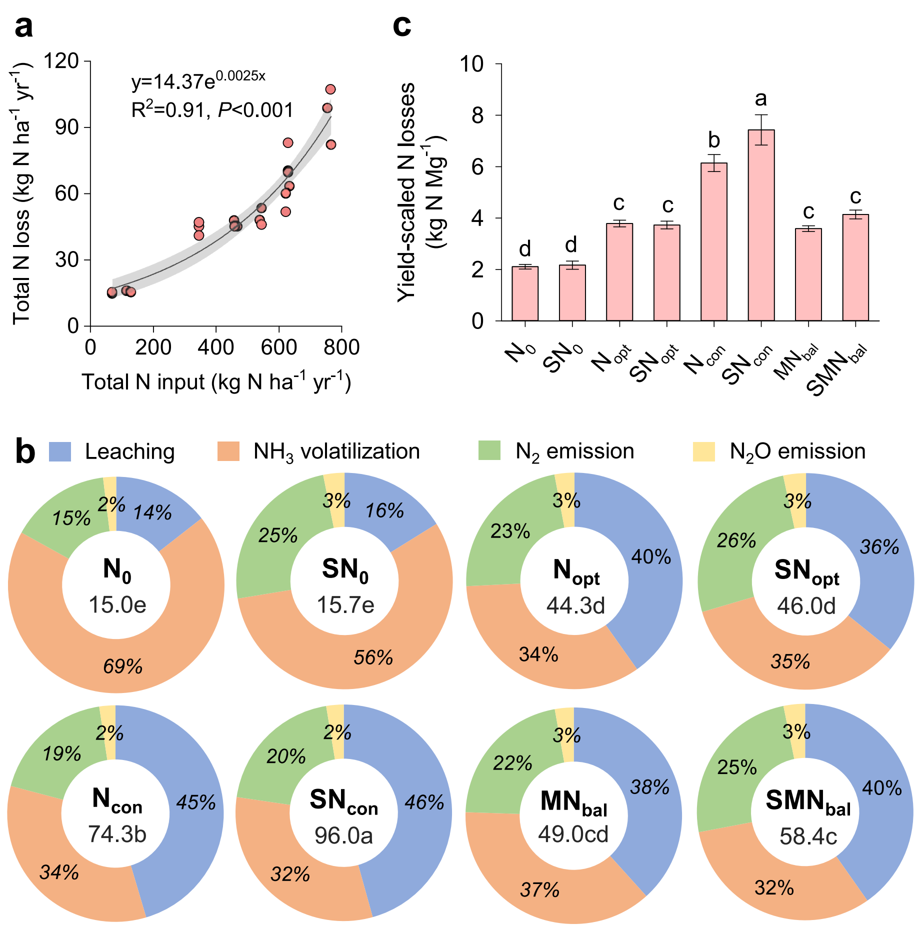


Fig. 4. N losses. (a) Relationship between total N inputs and total N losses; (b) Proportion of different N loss pathways; (c) Yield-scaled N losses. In a, the gray area around the regression line is the 95% confidence interval; In b, numbers under each treatment code are total N losses (kg N ha^{-1} yr^{-1}), percentages on the ring are the proportion of different N loss pathways. The vertical lines are the standard errors (n = 3) in b. In b and c, different lowercase letters are significant differences between the treatments at $P < 0.05$. N_0, N_{opt}, N_{con} and N_{bal} are no N fertilizer, optimum N, conventional N and balanced N rate, respectively. S and M are straw and cattle manure, respectively.

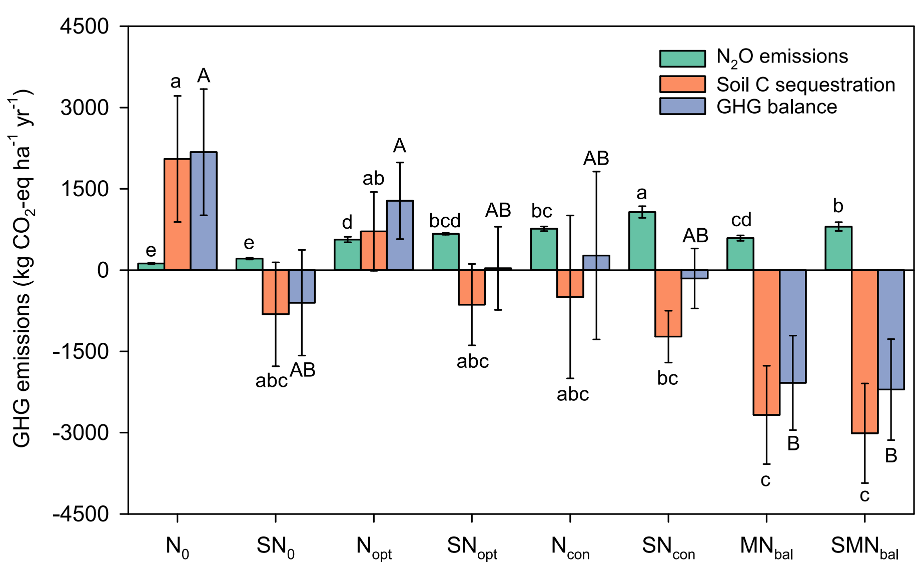


Fig. 5. Greenhouse gas balance. The vertical lines are the standard errors (n = 3), uppercase letter compared GHG balance among treatments, and the lowercase letter compared N_2O emissions or soil C sequestration among treatments, different letters are significant differences between the treatments at $P < 0.05$. N_0, N_{opt}, N_{con} and N_{bal} are no N fertilizer, optimum N, conventional N and balanced N rate, respectively. S and M are straw and cattle manure, respectively.

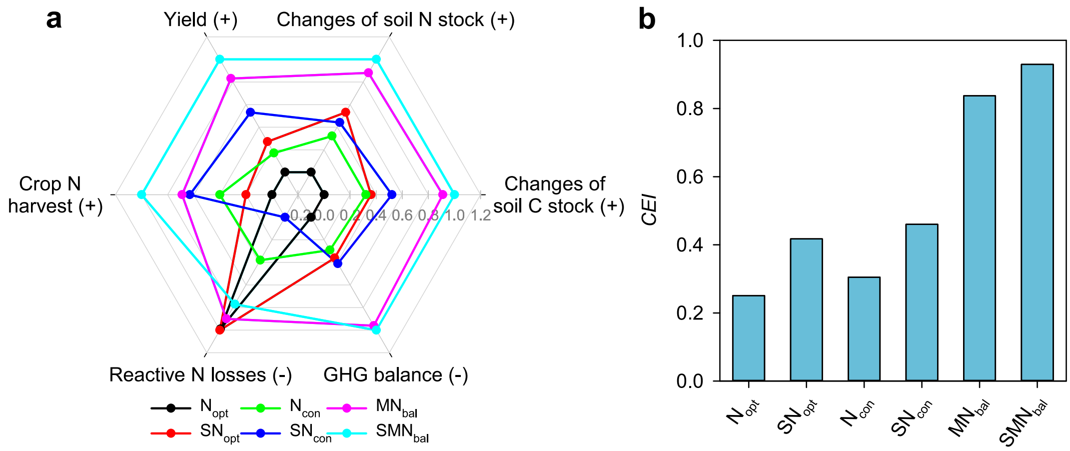


Fig. 6. Comprehensive assessments of the sustainability of different management practices. (a) radar map to assess the different indicators of the various C and N management; (b) comprehensive evaluation index (*CEI*). In a, values are normalized, the positive indicator (+) was normalized as $(X\text{-}X_{min})/(X_{max}\text{-}X_{min})$, and the negative indicator (−) was normalized as $(X_{max}\text{-}X)/(X_{max}\text{-}X_{min})$, the closer the value to 1 the better performance of the indicator. In b, a *CEI* close to 1 represents high sustainability of the management. N_0, N_{opt}, N_{con} and N_{bal} are no N fertilizer, optimum N, conventional N and balanced N rate, respectively. S and M are straw and cattle manure, respectively.

ranged from −1226 to −495 kg CO_2-eq ha^{-1} yr^{-1}, although the difference was not significant. Due to the higher SOC sequestration, the GHG balance in the balanced organic with synthetic N fertilization (−2206 to −2080 kg CO_2-eq ha^{-1} yr^{-1}) was much lower (more cooling) than the SN_{opt}, N_{con} and SN_{con} treatments (−153 to 271 kg CO_2-eq ha^{-1} yr^{-1}), although the effect was not significant (Fig. 5). The N_{opt} treatment inversely was causing warming (1280 kg CO_2-eq ha^{-1} yr^{-1}).

3.6. Sustainability assessment

Long-term balanced organic with synthetic N fertilization achieved high crop yields, N harvest, changes in soil C and N pools, but also resulted in low reactive N losses and a small GHG balance when compared against the different C and N management practices. Although the optimum synthetic N treatment had much lower reactive N losses compared to the conventional synthetic N fertilization, it didn't achieve the high target yield or such large gains in soil C and N stocks (Fig. 6a). We further compared the sustainability of different management practices using a comprehensive evaluation index (*CEI*), which makes an integrated assessment of yield, crop N harvest, changes of soil C and N stocks, reactive N and the GHG balance. The results showed that the long-term balanced organic with synthetic N fertilization achieved the highest *CEI* of 0.84–0.93, in contrast to the long-term synthetic N fertilization which had a much lower *CEI* of 0.25–0.46 (Fig. 6b).

The yield (or N harvest), NUE, N surplus are commonly used indicator to assess N management performance. Under the conventional synthetic N fertilization, although the yield is relatively high, its NUE was the lowest and N surplus was the highest, resulting in a sustainable index (CEI) lower than 0.5. The optimum synthetic N treatments achieved a desirable NUE and surplus; however, the N harvest was the lowest across the treatments, and increase of soil C and N stock were also low, leading to a CEI lower than that of conventional management. In contrast, the long-term balanced organic with synthetic N fertilization achieved the highest crop yield and N harvest and the soil C/N stock increase, acceptable NUE and N surplus, and ultimately attained the highest sustainability (CEI of 0.84 to 0.93) (Figs. 1–3, 6).

4. Discussion

4.1. Sustainable crop production by long-term balanced organic with synthetic N fertilization

Long-term field experiments offer a unique opportunity to evaluate the sustainability of agricultural systems. Not only do they provide a platform for assessing multiple performance indicators, but also define the real response of the crop-soil-environment nexus to management interventions (van Grinsven et al., 2022; Zhao et al., 2024). Our 15-year experiment demonstrates that the long-term balanced organic with synthetic N fertilization exhibited strongly positive effects on agro-ecosystem services, and achieved higher crop yields and soil quality with lower fertilizer dependency on new N resources, low N pollution and climate change burdens when compared against conventional N management practices which provide excess synthetic N inputs and a lower input of organic matter. Long-term balanced organic with synthetic N fertilization also had a much better performance in crop productivity, soil fertility and GHG emission mitigation than optimum synthetic N fertilization (Fig. 6a). The planting area of the wheat-maize double cropping system in the North China Plain is 10.6 Mha yr^{-1} (Liu et al., 2022). Compared with conventional synthetic N fertilization, long-term balanced organic with synthetic N fertilization could increase grain yield by 17 Mt. yr^{-1} (standardized at 14% moisture) (Cui et al., 2018), equivalent to 6.0% of China's annual maize production (National Bureau of Statistics of China, 2023), and increse crop N harvest by 0.3 Mt. N yr^{-1}. This change would also reduce reactive N losses by 0.3 Mt. N yr^{-1}, offsetting 2.2% of annual reactive N emissions in Chinese cropping systems, respectively (Gu et al., 2015), and reduce the GHG balance by 23.3Mt CO_2-eq yr^{-1}. When adopting optimum synthetic N fertilization, reactive N losses would be reduced by 0.3 Mt. N yr^{-1}, however, the N harvest would be also reduced by 0.4 Mt. N yr^{-1}, while GHG balance would be increased by 6.4 Mt. CO_2-eq yr^{-1} (Fig. 7).

The so-called "optimum synthetic N fertilization" achieves an equivalent yield with much lower N losses than conventional synthetic N fertilization. However, the crop N harvest was significantly decreased under the optimum synthetic N fertilization compared to conventional practice, indicating the risk of sacrificing N harvest when tightly synthetic N inputs (Fig. 1), probably because the "tight N cycle" status cannot compensate for stresses such as temporal N shortage induced by occasional heavy rainfall, which thus reduce crop N harvest (Tian et al., 2023). We should pay attention to the N harvest indicator together with yield when evaluating crop productivity because it directly links nutrient supply to humanity.

Long-term balanced organic together with synthetic N fertilizer addresses the above problem, and also contributes to improved soil quality by enhancing the SOC content (Abrol et al., 2024) and adding base cations, thus mitigates the soil acidification process induced by intensive N fertilization (Cai et al., 2015). The soil investigated in this study had a

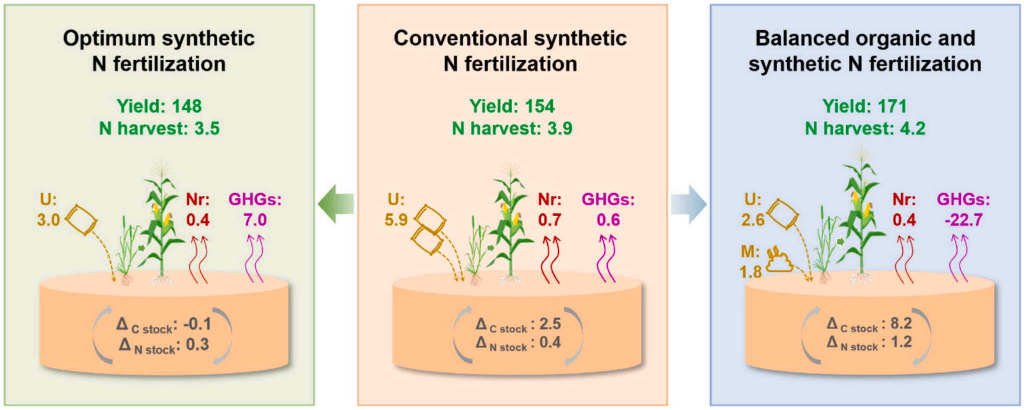


Fig. 7. Performance of different management in the North China Plain. The unit for yield is Mt. yr^{-1}, for urea and manure N inputs, N harvest, Nr losses and changes of soil N stock is Mt. N yr^{-1}, for changes of soil C stock is Mt. C yr^{-1}, for GHG balance is Mt. CO_2-eq yr^{-1}. Data of each scenario derived from average of straw return and removal, this figure was calculated based on the harvest area of 10.6 Mha yr^{-1} of wheat-maize rotation in the North China Plain. Yield was standardized at 14% of moisture, N harvest denote aboveground uptake, U and M denote urea and manure N inputs, Nr represents reactive N losses, GHGs represent GHG balance.

high mineralization-immobilization turnover with high N retention, supporting a good synchrony of N supply with crop demand, thus contributing to the higher yields and lower N losses (Elrys et al., 2023; Liang et al., 2013). The organic fertilizers also provide macro- and micronutrients to crops thus enhancing crop yields (Gil et al., 2008). Long-term balanced organic with synthetic N fertilization increased soil C sequestration thus significantly offsetting CO_2-eq emissions and resulting in a low GHG balance (Fig. 5). However, N immobilization is needed to sustain the C sequestration (de Vries, 2018; van Groenigen et al., 2017), which is reflected by the results that the balanced organic N fertilization needs more N input than the optimum synthetic fertilization (Fig. 2). It should be noted that the SOC sequestration was estimated using two-point measurements, which may induce uncertainties due to potential temporal variability. In future studies, annual sampling and measurement of SOC would help reduce these uncertainties.

4.2. *Long-term N budgets provide new insights into sustainable crop production*

The N budgets help to guide us on how to reconcile crop productivity, environment and soil quality in intensive cropping systems (Zhang et al., 2021b). We established long-term N budget under various C and N management practices that allow us to establish benchmark indicators for more sustainable N use. Recent advances have shown that long-term observations of N indicators are essential to reflect the performance of N management practices (Quan et al., 2021; Zhang et al., 2020a; Zhang et al., 2021b). We found a high NUE of 86% under the optimum synthetic N fertilization (N_{opt}), but its grain yield and crop N harvest, changes of soil C and N stock were the lowest among the N fertilization treatments (Figs. 1, 2 and 3), indicating that pursuing high NUE may compromise soil quality and crop N harvest (Lassaletta et al., 2014; Zhang et al., 2015). The NUE under conventional synthetic N fertilization reached as high as 55%, and was in the desirable range (50%–90%) recommended by the EU Nitrogen Expert Panel (EU Nitrogen Expert Panel, 2015), but its N losses were very high (Figs. 2 and 4). Therefore, it is better to interpret NUE together with other indicators such as N surplus, N yield, and soil N accumulation.

The N surplus was 51 kg N ha^{-1} yr^{-1} under the optimum synthetic N fertilization with straw removal, which is much lower than the N surplus benchmark of 160 kg N ha^{-1} yr^{-1} in the North China Plain (Zhang et al., 2019a), but its crop N harvest was significantly lower than the conventional synthetic N fertilization (Fig. 1). Although we had a relatively high N surplus (243 kg N ha^{-1} yr^{-1}) under the balanced organic with synthetic N fertilization with straw return, compared to the N surplus benchmarks (160 kg N ha^{-1} yr^{-1}), it achieved a high yield and N harvest with low N losses and GHG balance, and has the largest increase of soil C and N stock. N surplus is generally regarded as a proxy indicator of N losses due to the assumption of no changes of soil N stock (Zhang et al., 2019a), however, we found the high surplus N contributes greatly to the enlargement of soil N stock, and this is the major fate of surplus N rather than loss to environment under the long-term manure application (Fig. S6), indicating that the surplus N is contributing to build up soil N stock. This surplus N also contributes to SOC sequestration through microbial immobilization due to the stoichiometric demands of C and N (van Groenigen et al., 2017). Moreover, forming and mineralizing new soil organic matter through plant-microbe interactions helps synchronize crop N demands with soil N availability in a self-reinforcing loop that reduces N losses (Grandy et al., 2024). In our study, a high N surplus after combining manure with synthetic N fertilizer does not necessarily cause high N losses. Instead, we observed the build-up of the soil organic N stock. This is because of the low soil C and N stock at the start of the field experiment, and the far reach of saturation status (Zhao et al., 2024). The result represents historical changes of soil C stock in the studied region, with the lowest point around 1980s, followed by increases between 1980s and 2010s in the last century due to improved soil and crop management, especially fertilization and straw return (Han et al., 2017; Zhao et al., 2018). However, the fate of this legacy N buildup is strongly influenced by climatic and edaphic factors. For instance, under conditions of high rainfall or in coarse-textured soils, the buildup of N from surplus N might be more susceptible to mineralization and leaching rather than retention (Basu et al., 2022). Therefore, this measure must be coordinated within the crop N demand and region specific. Conversely, the long-term large N surplus may lead to significant N losses due to limitations in crop N uptake and soil N retention capacity.

4.3. *Toward sustainable crop production at the regional and country scales*

China is often considered a “too much” country that produces crop production using large amounts of synthetic N fertilizer, causing serious environmental problems with large direct and upstream GHG emissions (Zhang et al., 2015; Zhang et al., 2021b). Using numerous on-farm experiments, scientists found that optimizing synthetic N fertilization is key to ensure food security and reduce environmental costs and GHG emissions in China's cereal production (Chen et al., 2011; Cui et al., 2018; Ju et al., 2009), thus the “Zero Increase in Chemical Fertilizer Use after 2020” was proposed and has been implemented since 2015 (Ju et al., 2016). This policy demands a decrease in the consumption of synthetic N fertilizer in China (Yu et al., 2022). The findings of this study suggest that the next transition of Chinese agriculture should consider the recycling of manure to cropland, thus producing more high-quality food with less reactive N and GHG emissions, whilst improving soil fertility. We found that straw had a minor positive effect on sustainable crop production under synthetic N fertilization, compared to the balanced organic with synthetic N fertilization. This is probably because the manure has a better capacity to stimulate bacterial diversity than straw (Liu et al., 2021; Sun et al., 2015) as well as having a narrow C/N ratio, and thus can contribute to the formation of healthier soils. It was demonstrated that soil health is positively correlated with yield and soil C sequestration while negatively correlated with the GHG balance (Xing et al., 2025; Yang et al., 2024). To date, straw return is widely adopted in the main agricultural regions of China (Yang et al., 2020; Zhang et al., 2019a), but manure is less applied and represents no more than 19% of total N input in cropland, mainly due to the decoupling of crop and livestock production (Jin et al., 2020a; Zhang et al., 2023c). A large share of the manure produced is dumped into rivers resulting in serious environmental impacts. Promoting good use of livestock manure represents not only a priority to reduce pollution but also a great opportunity to reduce the use of synthetic fertilizers (Bai et al., 2022; Gu, 2022; Jin et al., 2020b; Zhang and Lassaletta, 2022). The outcome of our long-term experiment highlights the importance of using manure to realize more sustainable crop production, particularly in regions with low soil organic C. Our study supported the policies introduced in recent years in China, including "Policy Guidance on Accelerating the Resource Utilization of Animal Manure" (initiated in 2017) and "Guiding Opinions on Promoting the Land Application of Livestock Manure and Strengthening the Pollution Control according to Law" (initiated in 2019) (Wei et al., 2021a).

Although our results are derived from a long-term dataset at a single experimental site, they offer strong regional relevance for the North China Plain. This relevance stems from the broad similarities across much of the North China Plain in key factors such as climate, edaphic conditions, cropping systems and agronomic management practices (Xin and Tao, 2020; Liu et al., 2022). Moreover, the results may also offer valuable insights for other major global grain-producing regions facing similar challenges in balancing productivity with resource use efficiency. However, we acknowledge that existing heterogeneity may hamper direct extrapolation to the entire North China Plain or other regions, particularly given localized variations in soil properties, irrigation regimes and specific on-farm management practices. Nevertheless, the core principles and trends identified in this study are likely representative of most areas of the North China Plain and some intensive agricultural regions worldwide, site-specific adjustments could be necessary when applying these findings to marginal zones or areas with distinctly different soil or climatic conditions. While N loss and GHG measurements were conducted over two to three rotation cycles instead of the full 15-year experimental period due to constraints in the resources, extending these results to the entire period introduces uncertainties, particularly when thinking about the climate instability. Nevertheless, we are confident that this extrapolation does not introduce substantial bias, as temperature and rainfall pattern showed a relatively stable trend during the study period (Yang et al., 2021). Furthermore, the N loss and GHG measurements align with prior synthesis studies from multiple sites across the region (Ju and Zhang, 2017; Pan et al., 2018). Still, extending the monitoring duration in future studies would help reduce uncertainties in estimates of the N budget and GHG balance.

Regarding the availability of organic fertilizer, our analysis indicates that balancing the manure and synthetic fertilizer N input by the crop N demand would require 1.8 Mt. N yr^{-1} in wheat-maize systems (Fig. 7). This is equivalent to 45% of the livestock manure produced in the region (Han et al., 2023), making it feasible for North China Plain. However, challenges remain in manure recycling due to inadequate manure storage, treatment, transportation and application technologies (Chadwick et al., 2015; Wei et al., 2021a). Additionally, the low adoption rate of manure application in the cereal crops may also be a constraint because farmers often apply manure to cash crops (e.g., fruits and vegetable) (Chen et al., 2023). To promote manure on cropland, more advice, incentives or subsidies are needed to reduce farmers' costs, which could be stimulated by the aforementioned and future policies. An additional benefit arising from enhanced manure recycling is the need for reduced P fertilizer inputs. Olsen P levels often exceed 30 mg kg^{-1} being above the required soil P status, implying the potential for P inputs to exceed the crop P demand (Sun et al., 2025). This could limit the manure P requirements while bringing the P fertilizer input to zero (Xu et al., 2023). Globally, the importance of crop-livestock reconnection has recently grown in the scientific communities and policy agenda, particularly in the Europe and China (Lassaletta et al., 2024). This long-term case study provides further evidence to support its adoption, particularly in regions with soil and climate similar to the North China Plain.

5. Conclusions

We observed large benefits of long-term balanced organic with synthetic N fertilization in intensively managed cropland, which not only offers more food production with less N pollution, but also contributes to GHG mitigation and soil quality improvement. Overall, balanced organic with synthetic N fertilization achieved the highest comprehensive evaluation index and provided multiple benefits, including yield, environment, soil quality and climate change, which could be a model of achieving sustainable crop production in croplands. Despite these results from a single site in China, the practice can be replicated in other regions or countries, particularly in regions with soil and climate similarity, for example, the arid and semi-arid areas with low soil fertility and manure recycling rates, and the regions with a sharp decline of soil fertilities. The practices support agroecosystem service by coupling terrestrial C and N cycles and strongly promote the delivery of global sustainable development goals adopted by the United Nations. Implementation of the practice requires structural adjustments to current agricultural practices in order to relocate livestock production to match manure production potential with carrying capacity in mixed agricultural systems and also need to be supported by appropriate incentive policies (subsidies, third-party enterprises to transport the manure and other specialized service) and farmer training to promote the manure recycling to croplands. The choice of manure can be adapted according to local resources, market supply and regulations.

CRediT authorship contribution statement

Chong Zhang: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization. **Xin Zhang:** Writing – review & editing. **Robert M. Rees:** Writing – review & editing. **Wim de Vries:** Writing – review & editing. **Luis Lassaletta:** Writing – review & editing. **Jagdish K. Ladha:** Writing – review & editing. **Xiaotang Ju:** Conceptualization, Funding acquisition, Resources, Writing – review & editing.

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.

Acknowledgments

This work was supported by National Natural Science Foundation of China (42207348, U24A20625, 12411530100) and Hainan University Startup Fund (KYQD(ZR)-20098, KYQD(ZR)-21028). We thank Shaojun Qiu, Tao Huang, Xiaotong Song and Huanhuan Wei from China Agricultural University and Xue Tian from Hainan University for field work contributions.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2026.104653.

Data availability

Data will be made available on request.

References

Abrol, V., Sharma, P., Chary, G.R., Srinivasarao, C., Maruthi Sankar, G.R., Singh, B., et al., 2024. Integrated organic and mineral fertilizer strategies for achieving sustainable maize yield and soil quality in dry sub-humid inceptisols. Sci. Rep. 14 (1), 27227.
Bai, Z., Fan, X., Jin, X., Zhao, Z., Wu, Y., Oenema, O., et al., 2022. Relocate 10 billion livestock to reduce harmful nitrogen pollution exposure for 90% of China's population. Nat. Food 3 (2), 152–160.
Basu, N.B., Van Meter, K.J., Byrnes, D.K., Van Cappellen, P., Brouwer, R., Jacobsen, B.H., et al., 2022. Managing nitrogen legacies to accelerate water quality improvement. Nat. Geosci. 15 (2), 97–105.
Beegle, D.B., Kelling, K.A., Schmitt, M.A., 2008. Nitrogen from animal manures. In: Nitrogen in Agricultural Systems, pp. 823–881.
Bertrand, I., Viaud, V., Daufresne, T., Pellerin, S., Recous, S., 2019. Stoichiometry constraints challenge the potential of agroecological practices for the soil C storage. A review. Agron. Sustain. Dev. 39 (6), 54.
Cai, Z., Wang, B., Xu, M., Zhang, H., He, X., Zhang, L., et al., 2015. Intensified soil acidification from chemical N fertilization and prevention by manure in an 18-year field experiment in the red soil of southern China. J. Soils Sediments 15 (2), 260–270.
Cai, A., Xu, M., Wang, B., Zhang, W., Liang, G., Hou, E., et al., 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).
Cai, Z., Wang, B., Zhang, L., Wen, S., Xu, M., Misselbrook, T.H., Carswell, A.M., Gao, S., 2021. Striking a balance between N sources: mitigating soil acidification and accumulation of phosphorous and heavy metals from manure. Sci. Total Environ. 754, 142189.
Cai, S., Zhao, X., Yan, X., 2025. Towards precise nitrogen fertilizer management for sustainable agriculture. Earth Crit. Zone 2 (100026).
Chadwick, D., Jia, W., Tong, Y.A., Yu, G.H., Shen, Q.R., Chen, Q., 2015. Improving manure nutrient management towards sustainable agricultural intensification in China. Agric. Ecosyst. Environ. 209, 34–46.
Chen, X.P., Cui, Z.L., Vitousek, P.M., Cassman, K.G., Matson, P.A., Bai, J.S., et al., 2011. Integrated soil-crop system management for food security. Proc. Natl. Acad. Sci. USA 108 (16), 6399–6404.
Chen, B.H., Ren, C.C., Wang, C., Duan, J.K., Reis, S., Gu, B.J., 2023. Driving forces of nitrogen use efficiency in Chinese croplands on county scale. Environ. Pollut. 316, 120610.
Cui, Z.L., Chen, X.P., Zhang, F.S., 2013a. Development of regional nitrogen rate guidelines for intensive cropping systems in China. Agron. J. 105 (5), 1411–1416.
Cui, Z., Yue, S., Wang, G., Zhang, F., Chen, X., 2013b. In-season root-zone N management for mitigating greenhouse gas emission and reactive N losses in intensive wheat production. Environ. Sci. Technol. 47 (11), 6015–6022.
Cui, Z., Zhang, H., Chen, X., Zhang, C., Ma, W., Huang, C., et al., 2018. Pursuing sustainable productivity with millions of smallholder farmers. Nature 555 (7696), 363–366.
Cui, X., Bo, Y., Adalibieke, W., Winiwarter, W., Zhang, X., Davidson, E.A., et al., 2024. The global potential for mitigating nitrous oxide emissions from croplands. One Earth 7 (3), 401–420.
de Vries, W., 2018. Soil carbon 4 per mille: a good initiative but let's manage not only the soil but also the expectations. Geoderma 309, 111–112.
Delgado, A., Romero, I., 2016. Environmental conflict analysis using an integrated grey clustering and entropy-weight method: a case study of a mining project in Peru. Environ. Model Softw. 77, 108–121.
Duan, J., Liu, H., Zhang, X., Ren, C., Wang, C., Cheng, L., et al., 2024. Agricultural management practices in China enhance nitrogen sustainability and benefit human health. Nat. Food 5 (5), 378–389.
Eghball, B., Power, J.F., 1999. Phosphorus- and nitrogen-based manure and compost applications corn production and soil phosphorus. Soil Sci. Soc. Am. J. 63 (4), 895–901.
Elrys, A.S., Wang, J., Meng, L., Zhu, Q., El-Sawy, M.M., Chen, Z., et al., 2023. Integrative knowledge-based nitrogen management practices can provide positive effects on ecosystem nitrogen retention. Nat. Food 4 (12), 1075–1089.
EU Nitrogen Expert Panel, 2015. Nitrogen Use Efficiency (NUE) – An Indicator for the Utilization of Nitrogen in Agriculture and Food Systems. http://inms.iwlearn.org/inms-meeting-lisbon/NExpertPanelNUESession1.pdf.
Gao, S., Li, S., Zhou, G., Cao, W., 2023. The potential of green manure to increase soil carbon sequestration and reduce the yield-scaled carbon footprint of rice production in southern China. J. Integr. Agric. 22 (7), 2233–2247.
Gil, M.V., Carballo, M., Calvo, L., 2008. Fertilization of maize with compost from cattle manure supplemented with additional mineral nutrients. Waste Manag. 28 (8), 1432–1440.
Grandy, A.S., Daly, A.B., Bécu, T., Cardinael, R., Fontaine, S., Jilling, A., et al., 2024. A microbial framework for nitrogen cycling solutions in agroecosystems. One Earth 7 (12), 2103–2107.
Gu, B., 2022. Recoupling livestock and crops. Nat. Food 3 (2), 102–103.
Gu, B., Ju, X., Chang, J., Ge, Y., Vitousek, P.M., 2015. Integrated reactive nitrogen budgets and future trends in China. Proc. Natl. Acad. Sci. USA 112 (28), 8792–8797.
Gu, B., Zhang, X., Lam, S.K., Yu, Y., van Grinsven, H.J.M., Zhang, S., et al., 2023. Cost-effective mitigation of nitrogen pollution from global croplands. Nature 613 (7942), 77–84.
Han, D.R., Wiesmeier, M., Conant, R.T., Kühnel, A., Sun, Z., Kögel-Knabner, G.I., et al., 2017. Large soil organic carbon increase due to improved agronomic management in the North China plain from 1980s to 2010s. Glob. Chang. Biol. 24 (3), 987–1000.
Han, Z., Han, C., Shi, Z., Li, J., Luo, E., 2023. Rebuilding the crop-livestock integration system in China ——based on the perspective of circular economy. J. Clean. Prod. 393, 136347.
Hu, X.K., Su, F., Ju, X.T., Gao, B., Oenema, O., Christie, P., et al., 2013. Greenhouse gas emissions from a wheat-maize double cropping system with different nitrogen fertilization regimes. Environ. Pollut. 176, 198–207.
Huang, T., Ju, X., Yang, H., 2017. Nitrate leaching in a winter wheat-summer maize rotation on a calcareous soil as affected by nitrogen and straw management. Sci. Rep. 7, 42247.
Huang, T., Hu, X., Gao, B., Yang, H., Huang, C., Ju, X., 2018. Improved nitrogen management as a key mitigation to net global warming potential and greenhouse gas intensity on the North China plain. Soil Sci. Soc. Am. J. 82 (1), 136–146.
IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
Jin, S., Zhang, B., Wu, B., Han, D., Hu, Y., Ren, C., et al., 2020a. Decoupling livestock and crop production at the household level in China. Nat. Sustainability 4 (1), 48–55.
Jin, X., Bai, Z., Oenema, O., Winiwarter, W., Velthof, G., Chen, X., et al., 2020b. Spatial planning needed to drastically reduce nitrogen and phosphorus surpluses in China's agriculture. Environ. Sci. Technol. 54 (19), 11894–11904.
Johnston, A.M., Bruulsema, T.W., 2014. 4R nutrient stewardship for improved nutrient use efficiency. Procedia Eng. 83, 365–370.
Ju, X.T., Zhang, C., 2017. Nitrogen cycling and environmental impacts in upland agricultural soils in North China: a review. J. Integr. Agric. 16 (12), 2848–2862.
Ju, X.T., Xing, G.X., Chen, X.P., Zhang, S.L., Zhang, L.J., Liu, X.J., et al., 2009. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. Proc. Natl. Acad. Sci. USA 106 (9), 3041–3046.
Ju, X.T., Gu, B.J., Wu, Y.Y., Galloway, J.N., 2016. Reducing China's fertilizer use by increasing farm size. Glob. Environ. Chang. Hum. Policy Dimens. 41, 26–32.
Kicklighter, D.W., Melillo, J.M., Monier, E., Sokolov, A.P., Zhuang, Q., 2019. Future nitrogen availability and its effect on carbon sequestration in northern Eurasia. Nat. Commun. 10 (1), 3024.
Kirkby, C.A., Richardson, A.E., Wade, L.J., Passioura, J.B., Batten, G.D., Blanchard, C., et al., 2014. Nutrient availability limits carbon sequestration in arable soils. Soil Biol. Biochem. 68, 402–409.
Ladha, J.K., Jat, M.L., Stirling, C.M., Chakraborty, D., Pradhan, P., Krupnik, T.J., et al., 2020. Achieving the sustainable development goals in agriculture: the crucial role of nitrogen in cereal-based systems. Adv. Agron. 163, 39–116.
Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J., Garnier, J., 2014. 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. Environ. Res. Lett. 9 (10), 105011.
Lassaletta, L., Einarsson, R., Quemada, M., 2023. Nitrogen use efficiency of tomorrow. Nat. Food 4 (4), 281–282.
Lassaletta, L., Sanz-Cobeña, A., Pinsard, C., Ma, L., Spiegal, S., Reidsma, P., 2024. Special issue opening editorial: reducing nitrogen waste through crop and livestock reconnection. Agric. Syst. 214 (103816).
Lessmann, M., Ros, G.H., Young, M.D., de Vries, W., 2022. Global variation in soil carbon sequestration potential through improved cropland management. Glob. Chang. Biol. 28 (3), 1162–1177.
Liang, B., Zhao, W., Yang, X.Y., Zhou, J.B., 2013. Fate of nitrogen-15 as influenced by soil and nutrient management history in a 19-year wheat-maize experiment. Field Crop Res. 144, 126–134.
Liu, Z., Zhou, H., Xie, W., Yang, Z., Lv, Q., 2021. Long-term effects of maize straw return and manure on the microbial community in cinnamon soil in northern China using 16S rRNA sequencing. PLoS One 16 (4), e0249884.
Liu, Z.J., Liu, Y.S., Dong, J.W., Baig, M.H.A., Chi, W.F., Peng, L.Y., et al., 2022. Patterns and causes of winter wheat and summer maize rotation area change over the North China plain. Environ. Res. Lett. 17 (4), 044056.
Meng, Q.F., Sun, Q.P., Chen, X.P., Cui, Z.L., Yue, S.C., Zhang, F.S., et al., 2012. Alternative cropping systems for sustainable water and nitrogen use in the North China plain. Agric. Ecosyst. Environ. 146 (1), 93–102.
National Bureau of Statistics of China, 2023. China Statistical Yearbook 2023. China Statistics Press.
Pan, Y., Tian, S., Zhao, Y., Zhang, L., Zhu, X., Gao, J., et al., 2018. Identifying ammonia hotspots in China using a national observation network. Environ. Sci. Technol. 52 (7), 3926–3934.
Qiu, S.J., Ju, X.T., Lu, X., Li, L., Ingwersen, J., Streck, T., et al., 2012. Improved nitrogen management for an intensive winter wheat/summer maize double-cropping system. Soil Sci. Soc. Am. J. 76 (1), 286–297.
Quan, Z., Zhang, X., Fang, Y.T., Davidson, E.A., 2021. Different quantification approaches for nitrogen use efficiency lead to divergent estimates with varying advantages. Nat. Food 2 (4), 241.

Ren, K.Y., Sun, Y., Zou, H.Q., Li, D.J., Lu, C.A., Duan, Y.H., et al., 2023. Effect of replacing synthetic nitrogen fertilizer with animal manure on grain yield and nitrogen use efficiency in China: a meta-analysis. Front. Plant Sci. 14 (1153235).
Schulte-Uebbing, L., de Vries, W., 2021. Reconciling food production and environmental boundaries for nitrogen in the European Union. Sci. Total Environ. 786, 147427.
Schulte-Uebbing, L.F., Beusen, A.H.W., Bouwman, A.F., de Vries, W., 2022. From planetary to regional boundaries for agricultural nitrogen pollution. Nature 610 (7932), 507–512.
Shah, K.K., Modi, B., Pandey, H.P., Subedi, A., Aryal, G., Pandey, M., et al., 2021. Diversified crop rotation: an approach for sustainable agriculture production. Adv. Agric. 2021 (1), 8924087.
Sun, R.B., Zhang, X.X., Guo, X.S., Wang, D.Z., Chu, H.Y., 2015. Bacterial diversity in soils subjected to long-term chemical fertilization can be more stably maintained with the addition of livestock manure than wheat straw. Soil Biol. Biochem. 88, 9–18.
Sun, W.K., Ros, G.H., Zhu, Q.C., Xu, D.H., Hou, Y., de Vries, W., 2025. Optimization of manure recycling and fertilizer use to meet crop nutrient demands and reduce nutrient losses, a case study in Quzhou, China. Agric. Syst. 226, 104321.
Sutton, M.A., Howard, C.M., Erisman, J.W., Billen, G., Bleeker, A., Grennfelt, P., et al., 2011. The European Nitrogen Assessment: Sources, Effects and Policy Perspectives. Cambridge University Press.
Tian, X., Zhang, C., Ju, X.T., 2023. Crop responses to application of optimum nitrogen fertilizers on soils of various fertilities formed from long-term fertilization regimes. Eur. J. Agron. 148, 126857.
van Grinsven, H.J.M., Ebanyat, P., Glendining, M., Gu, B., Hijbeek, R., Lam, S.K., et al., 2022. Establishing long-term nitrogen response of global cereals to assess sustainable fertilizer rates. Nat. Food 3 (2), 122.
van Groenigen, J.W., van Kessel, C., Hungate, B.A., Oenema, O., Powlson, D.S., van Groenigen, K.J., 2017. Sequestering soil organic carbon: a nitrogen dilemma. Environ. Sci. Technol. 51 (9), 4738–4739.
Wang, R., Pan, Z.L., Liu, Y., Yao, Z.S., Wang, J., Zheng, X.H., et al., 2022. Full straw incorporation into a calcareous soil increased N_2O emission despite more N_2O being reduced to N_2 in the winter crop season. Agric. Ecosyst. Environ. 335, 108007.
Wei, S., Zhu, Z., Zhao, J., Chadwick, D.R., Dong, H., 2021a. Policies and regulations for promoting manure management for sustainable livestock production in China: a review. Front. Agric. Sci. Eng. 8 (1), 45–57.
Wei, Z., Hoffland, E., Zhuang, M., Hellegers, P., Cui, Z., 2021b. Organic inputs to reduce nitrogen export via leaching and runoff: a global meta-analysis. Environ. Pollut. 291, 118176.
Wei, H., Song, X., Liu, Y., Wang, R., Zheng, X., Butterbach-Bahl, K., et al., 2023. In situ ^{15}N-N_2O site preference and O_2 concentration dynamics disclose the complexity of N_2O production processes in agricultural soil. Glob. Chang. Biol. 29 (17), 4910–4923.
Xia, L.L., Yan, X.Y., 2023. Maximizing earth's feeding capacity. Nat. Food 4 (5), 353–354.
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. Chang. Biol. 23 (5), 1917–1925.
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 (13), 7450–7457.
Xin, Y., Tao, F., 2020. Developing climate-smart agricultural systems in the North China plain. Agric. Ecosyst. Environ. 291, 106791.
Xing, Y.Y., Xie, Y.X., Wang, X.K., 2025. Enhancing soil health through balanced fertilization: a pathway to sustainable agriculture and food security. Front. Microbiol. 16, 1536524.
Xu, D., Zhu, Q., Ros, G.H., Xu, M., Wen, S., Zhang, F., de Vries, W., 2023. Model-based optimal management strategies to mitigate soil acidification and minimize nutrient losses for croplands. Field Crop Res. 292, 108827.
Yan, M., Pan, G., Lavallee, J.M., Conant, R.T., 2020. Rethinking sources of nitrogen to cereal crops. Glob. Chang. Biol. 26 (1), 191–199.
Yang, X.M., Cheng, L.L., Huang, X.L., Zhang, Y., Yin, C.B., Lebailly, P., 2020. Incentive mechanism to promote corn stalk return sustainably in Henan, China. Sci. Total Environ. 738, 139775.
Yang, Y., Tang, S., Yu, L., Chen, F., Ding, Y., Zhang, P., 2021. Trend analysis on temperature and precipitation over North China Plain for past five decades. In: Paper Presented at the IOP Conference Series: Earth and Environmental Science. https://doi.org/10.1088/1755-1315/675/1/012014.
Yang, X., Xiong, J., Du, T., Ju, X., Gan, Y., Li, S., et al., 2024. Diversifying crop rotation increases food production, reduces net greenhouse gas emissions and improves soil health. Nat. Commun. 15 (1), 198.
You, L., Ros, G.H., Chen, Y., Shao, Q., Young, M.D., Zhang, F., et al., 2023. Global mean nitrogen recovery efficiency in croplands can be enhanced by optimal nutrient, crop and soil management practices. Nat. Commun. 14 (1), 5747.
Yu, Z., Liu, J., Kattel, G., 2022. Historical nitrogen fertilizer use in China from 1952 to 2018. Earth Syst. Sci. Data 14 (11), 5179–5194.
Zhang, X., Lassaletta, L., 2022. Manure management benefits climate with limits. Nat. Food 3 (5), 312–313.
Zhang, X., Davidson, E.A., Mauzerall, D.L., Searchinger, T.D., Dumas, P., Shen, Y., 2015. Managing nitrogen for sustainable development. Nature 528 (7580), 51–59.
Zhang, C., Ju, X., Powlson, D., Oenema, O., Smith, P., 2019a. Nitrogen surplus benchmarks for controlling N pollution in the main cropping systems of China. Environ. Sci. Technol. 53 (12), 6678–6687.
Zhang, C., Liu, S., Wu, S., Jin, S., Reis, S., Liu, H., et al., 2019b. Rebuilding the linkage between livestock and cropland to mitigate agricultural pollution in China. Resour. Conserv. Recycl. 144, 65–73.
Zhang, X., Davidson, E.A., Zou, T., Lassaletta, L., Quan, Z., Li, T., et al., 2020a. Quantifying nutrient budgets for sustainable nutrient management. Glob. Biogeochem. Cycles 34 (3), e2018GB006060.
Zhang, X.Y., Fang, Q.C., Zhang, T., Ma, W.Q., Velthof, G.L., Hou, Y., et al., 2020b. Benefits and trade-offs of replacing synthetic fertilizers by animal manures in crop production in China: a meta-analysis. Glob. Chang. Biol. 26 (2), 888–900.
Zhang, C., Rees, R.M., Ju, X.T., 2021a. Fate of ^{15}N-labelled urea when applied to long-term fertilized soils of varying fertility. Nutr. Cycl. Agroecosyst. 121 (2–3), 151–165.
Zhang, X., Zou, T., Lassaletta, L., Mueller, N.D., Tubiello, F.N., Lisk, M.D., et al., 2021b. Quantification of global and national nitrogen budgets for crop production. Nat. Food 2 (7), 529–540.
Zhang, C., Song, X.T., Zhang, Y.Q., Wang, D., Rees, R.M., Ju, X.T., 2022. Using nitrification inhibitors and deep placement to tackle the trade-offs between NH_3 and N_2O emissions in global croplands. Glob. Chang. Biol. 28 (14), 4409–4422.
Zhang, C., Ju, X., Zhang, J., Rees, R.M., Müller, C., 2023a. Soil pH and long-term fertilization affect gross N transformation and N_2O production pathways in Chinese and UK croplands. Biol. Fertil. Soils 59 (5), 527–539.
Zhang, C., Wang, D.D., Zhao, Y.J., Xiao, Y.L., Chen, H.X., Liu, H.P., et al., 2023b. Significant reduction of ammonia emissions while increasing crop yields using the 4R nutrient stewardship in an intensive cropping system. J. Integr. Agric. 22 (6), 1883–1895.
Zhang, Q., Chu, Y., Yin, Y., Ying, H., Zhang, F., Cui, Z., 2023c. Comprehensive assessment of the utilization of manure in China's croplands based on national farmer survey data. Sci. Data 10 (1), 223.
Zhao, Y., Wang, M., Hu, S., Zhang, X., Ouyang, Z., Zhang, G., et al., 2018. Economics- and policy-driven organic carbon input enhancement dominates soil organic carbon accumulation in Chinese croplands. Proc. Natl. Acad. Sci. USA 115 (16), 4045–4050.
Zhao, X., Wang, Y., Cai, S., Ladha, J.K., Castellano, M.J., Xia, L., et al., 2024. Legacy nitrogen fertilizer in a rice-wheat cropping system flows to crops more than the environment. Sci. Bull. 69 (9), 1212–1216.