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Research article

Integrated nitrogen management strategies for mitigating carbon and nitrogen footprints in the North China Plain

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ABSTRACT

Excessive nitrogen (N) fertilization in intensive cropping systems induces substantial carbon (C) and reactive nitrogen (Nr) emissions. To address the challenge of synergistic C-N emission reduction while ensuring agricultural sustainability, a two-year field experiment studied the effects on this of N input reduction (OU), deep placement of fertilizer (DP), alternative fertilizers (calcium ammonium nitrate, CAN), enhanced-efficiency N fertilizers (controlled-release urea [CRU], urease inhibitors [UI], nitrification inhibitors [NI], a microbial agent [UB]) and organic substitution (organic manure plus urea [UOM] or urea amended with urease inhibitors [ULOM]). Life cycle assessment (LCA) and scenario analysis applied the results to the whole of the North China Plain (NCP). The key findings were: (1) N reduction was fundamental. Advanced strategies decreased C and Nr emissions by 4.2–15.2 % (excluding CAN) and 20.6–59.3 %, respectively, compared to conventional practices. (2) A multi-criteria assessment highlighted three key treatments with the best performing strategies being CRU and UI, but also with ULOM as a strategic measure for reducing N emissions. Specifically, compared to OU, CRU and UI reduced the C footprint (CF) by 14.7 and 15.8 %, the N footprint (NF) by 54.4 and 54.6 %, and increased the net eco-economic benefit (NEEB) by 21.9 and 28.1 %, respectively. ULOM reduced CF by 1.9 %, NF by 51.6 %, and enhanced NEEB (+18.4 %). (3) Significant regional disparities in emission patterns were identified, with Beijing and Henan as hotpots for C and Nr emissions, respectively. (4) Scenario analysis validated that UI and CRU reduced CF by 26.9 %, NF by 61.4 %, and environmental damage cost (EDC) by 26.3 %. To harmonize environmental security with agricultural transition we propose a regional integrated "emission reduction-efficiency enhancement" framework. Prioritizing CRU and UI technologies, alongside synergistic organic-inorganic fertilizer combinations, offers a scalable pathway for sustainable intensification in the NCP.

1. Introduction

Agricultural ecosystems, as complex carbon (C) and nitrogen (N) coupled systems, face global environmental challenges from their major contribution to reactive nitrogen (Nr) and greenhouse gas (GHG) emissions and fossil fuel C use. Research has shown that cropland C-N dynamics directly regulate soil organic C (SOC) sequestration, N use efficiency, and GHG emission intensity (Xiang et al., 2024), thereby influencing the four pillars of agricultural sustainability: food security, economic benefit, resource efficiency and ecological stewardship (Cui et al., 2021). Global agricultural production emits 5.2 Gt CO_2-eq annually, with N fertilizer production and application contributing 13.5 t CO_2-eq per ton of N fertilizer applied, stemming from coal-dependent production processes and excessive field application (Fan et al., 2022a; Ma et al., 2012; Zhang et al., 2013), underscoring the central role of improved N management in emission mitigation. In China, the C

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footprint (CF) of 72 % of grain production originates from crop cultivation (Li et al., 2022), and excessive mineral N application (180 kg N ha^{-1} in conventional practices) drives high NH_3 volatilization and N_2O emissions, accounting for 24–31 % of the N footprint (NF) in wheat and maize systems (Wen et al., 2025). A systematic quantification of CF/NF and eco-economic benefits is essential for identifying integrated N management strategies that can concurrently mitigate climate change and agricultural pollution (Kang et al., 2023).

Wheat and maize are two core staple crops in China, with their rotation system being irreplaceable for ensuring food security. In major grain-producing regions such as the North China Plain (NCP) and Huang-Huai-Hai region, the wheat-maize rotation covers over 12 million ha of farmland and contributes approximately 30 % of the nation's total cereal production (Xue et al., 2015). Yet, this system epitomizes the tension between high productivity and environmental costs. In the NCP, N overuse not only exacerbates Nr losses but also triggers deep-layer C release through nitrate leaching, challenging traditional assumptions about deep C pool stability (Qiao et al., 2018). DNDC model simulations reveal that N fertilizer production/transportation and field NH_3 volatilization contribute 40.2 %–56.4 % of CF and 42.7 %–60.2 % of NF, respectively (Geng et al., 2021). However, optimized practices have demonstrated significant mitigation potential: the application of efficiency-enhancing N fertilizer reduced Nr losses, and increased net economic and environmental benefits (NEEB) by $32.93- $188.85 (Wang et al., 2025), while 50 % substitution of organic fertilizers (i.e. manures) for chemical fertilizers enhanced the sustainability of crop yields and reduced the CF under the wheat - maize system (Niu et al., 2024). By taking adequate and effective large-scale emission reduction measures, C emissions can be reduced by 80 % by 2050 (Gao and Serrenho, 2023). While these studies validate individual technologies, a critical gap remains in the systematic, side-by-side comparison of their synergistic effects on the coupled C-N cycle and, crucially, their translation into economically viable strategies at a regional scale. To bridge this gap, a more pluralistic perspective that incorporates international and novel approaches to N management is essential. A series of studies by Zamparas et al. (2019, 2020, 2021) underscored the potential of recycled aquatic materials and composite controlled-release fertilizers to create synergistic nutrient supply, reducing N loss and GHG emissions. This calls for adopting the "waste-to-resource" concept and a circular economy model to build comprehensive technical pathways.

Causes of CF and NF vary significantly across agricultural eco-zones in China (Abdo et al., 2024). In semi-arid regions, farmland C and N emissions primarily originate from irrigation and fertilizer inputs, with N fertilizer production and application contributing 49.5 %–72.9 %, and irrigation electricity consumption 15 %–30 % of the CF (Qin et al., 2024; Zhang et al., 2018). Therefore, moving beyond the current research focus on single-factor measures such as N reduction, organic fertilizer substitution, and machinery efficiency improvement is imperative (Jiang et al., 2019; Niu et al., 2024). This study posits that achieving sustainable intensification requires an integrated assessment framework that bridges the disconnect between isolated technological efficacy and scalable, socio-economically practical solutions.

To this end, our study is designed to provide a comprehensive evaluation that spans from field-scale experimentation to regional policy-scenario analysis. We first systematically investigated the effects of N management strategies, including not only N reduction but also advanced fertilizers and organic integration, on CF, NF and NEEB, and chose the optimized measures with high emission reduction potential that are easy to implement. Then, we analyzed the status of C and Nr emissions in the NCP, based on 13,643 and 12,233 sets of research data for wheat and maize production, respectively. Leveraging this foundation, we hypothesized that all smallholders use these N management strategies and explored the potential for reducing environmental risk using different strategies. Ultimately, by synthesizing field evidence with large-scale spatial data, our work aims to transcend conventional analysis and deliver a prioritized, region-specific technology roadmap. Results indicate that the application of urease inhibitor amended urea and controlled release urea have the highest potential to reduce CF, NF and environmental damage costs (EDC) effectively, moving towards achieving both food security and C neutrality goals in the NCP.

2. Materials and methods

The research comprised two parts: we first analyzed CF and NF based on a field experiment using Life Cycle Analysis (LCA), a critical tool for quantifying CF and NF, incorporating both farm management and ecosystem processes within its system boundaries (Hu et al., 2023). This was followed by a scenario analysis based on fertilization survey data in wheat-maize rotations in the NCP to quantify C and Nr emissions, CF, NF and EDC for a range of N management strategies.

2.1. Field experiment

2.1.1. Experimental site

A two-year field experiment was carried out from 2019 to 2021 at Quzhou Experiment Station (37.3°N, 115.6°E) of China Agricultural University, Hebei Province (Fig. 1). The site has a warm temperate continental monsoon climate, with an annual mean temperature of 13.5 °C and a mean annual precipitation of 490 mm; the frost-free period is 200 days a year and the annual sunshine is 2557 h. The topsoil properties before the experiment were reported by (Wang et al., 2022a).

2.1.2. Experimental design

A comparison of 11 strategies for N fertilization was made with an experimental design of completely randomized blocks. The eleven treatments were: (1) CK, no N application; (2) CU, conventional fertilization as practiced by farmers; (3) OU, optimized fertilization based on previous research and development (Sha et al., 2023); (4) DP, deep placement of fertilizer; (5) CAN, calcium ammonium nitrate instead of urea; (6) CRU, controlled release urea; (7) UI, urea amended with a urease inhibitor ((Limus®, 75 % N-(n-butyl) thiophosphoric triamide (NBPT) + 25 % N-(n-propyl) thiophosphoric triamide (NPPT) at 0.1 % (w/w), BASF SE, Germany); (8) NI, urea amended with the nitrification inhibitor (DMPP, 3,4-dimethylpyrazol phosphate, 5.6 mL kg^{-1}, BASF SE, Germany); (9) UB, urea amended with the microbial agent (BiOWiSH®, with *Bacillus subtilis*, Bacillus amylolyticus, *Bacillus licheniformis* and *Bacillus pumilus* as the active ingredients, at 0.2 % (w/w), BiOWiSH Technologies Inc.); (10) UOM, 50 % organic fertilizer + 50 % urea; (11) ULOM, 50 % organic fertilizer (manure) + 50 % urea amended with the

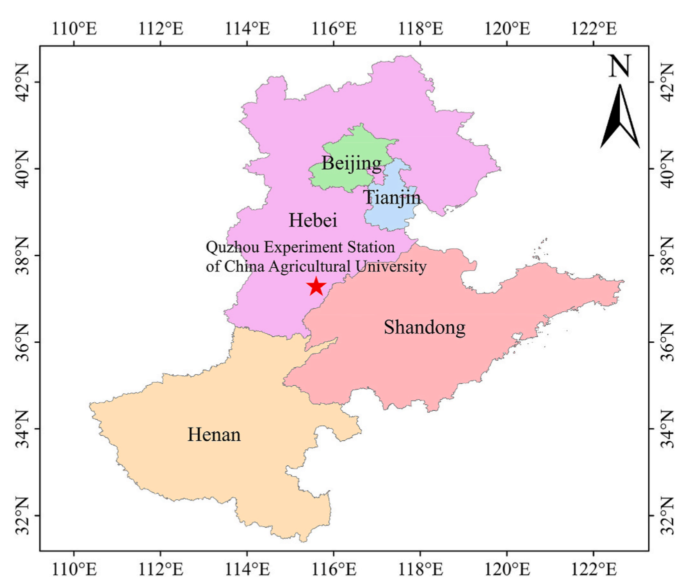

Fig. 1. Experimental site.

urease inhibitor. The N content of the organic fertilizer was 12 %. The N application rates were 270 kg N ha^{-1} and 180 kg N ha^{-1} for wheat and maize, respectively, under the CU treatment, and were reduced to 180 kg N ha^{-1} and 120 kg N ha^{-1} in all the optimized treatments, as detailed in Table S2. Phosphate fertilizer (90 kg P_2O_5 ha^{-1}) and potassium fertilizer (60 kg K_2O ha^{-1}) were applied before sowing and the seeding rates were 225 kg ha^{-1} and 38 kg ha^{-1} for wheat and maize, respectively. Other management practices were reported by (Wang et al., 2023a,b).

2.1.3. Crop yields

At crop maturity, grain samples of wheat and maize were collected from areas of 4 m^2 and 9 m^2, respectively. The samples were initially deactivated at 150 °C for 30 min and then oven-dried at 75 °C to constant weight. Yields were calculated based on 13 % and 14 % moisture content for wheat and maize, respectively.

2.1.4. Research boundary

Agricultural production and the planting of wheat and maize were set as the boundary of this study (Fig. 2). Nr emissions included those from agricultural production and transportation and losses during the whole growth period of crops. C emissions (as CO_2-equivalents) included direct N_2O emissions, indirect N_2O emissions (from deposited NH_3 emissions and N leaching), CH_4 emissions, CO_2 emissions and SOC change.

2.1.5. Calculations

(1) N footprint evaluation

NF (g N kg^{-1} grain) was calculated as follows:

$$NF = \left(\sum A_i \times \varepsilon_i + EN_2O + ENH_3 + EN_{leaching}\right) / Yield$$

$\sum A_i \times \varepsilon_i$ is the cumulative Nr emission from agricultural production, A_i is the agricultural input (Table S3), ε_i is Nr emission factor of agricultural production (Table S4); EN_2O and ENH_3 are the cumulative emissions of N_2O and NH_3, which were measured using closed static chambers with gas chromatography and the Dräger Tubes method, respectively (Wang et al., 2023a,b); $EN_{leaching}$ is the N leached from the wheat-maize rotation, obtained by multiplying the N input by the coefficient of urea and organic fertilizer (Table S5). The $EN_{leaching}$ of other treatments was calculated by combing N leached caused by urea application with the emission reduction ratio of corresponding treatments (Li et al., 2018; Xia et al., 2017; Xiong et al., 2001; Zhang et al., 2019); Yield $\left(t\ ha^{-1}\right)$ is the annual grain yield of wheat and maize as determined by (Wang et al., 2023a,b).

(2) C footprint evaluation

CF (g CO_2-eq kg^{-1} grain) was calculated as follows:

$$CF = \left(\sum A_i \times \beta_i + ECH_4 \times 27.9 + EN_2O \times 273 - \delta SOCS\right) / Yield$$

$$EN_2O = N_2O_{direct} + 1\% \times NH_3 + 0.75\% \times N_{leaching}$$

$$SOCS = SOC \times H \times BD / 10$$

$$\delta SOCS = (SOCS_{2021} - SOCS_{2019}) / 2 \times 44 / 12 \times 1000$$

$\sum A_i \times \beta_i$ is the cumulative C emissions from agricultural production; A_i is the agricultural input (Table S3); β_i is the C emission factor of agricultural production (Table S6); ECH_4 and EN_2O are the cumulative CH_4 and N_2O emissions over the whole growing period of wheat and maize; 27.9 and 273 are the coefficients of the century-long global warming potentials of CH_4 and N_2O, respectively (IPCC, 2021); N_2O_{direct} is the direct N_2O emissions; 1 % and 0.75 % are the factors converting NH_3 and N leaching to indirect N_2O emissions (Klein et al., 2006), respectively; SOCS $\left(Mg\ ha^{-1}\right)$ is soil C sequestration; SOC $\left(g\ kg^{-1}\right)$ is soil organic C (SOC) content; H (m) is soil depth (20 cm); BD $\left(g\ cm^{-3}\right)$ is soil bulk density, measured using a cutting ring; 10 is a unit conversion factor; δSOCS $\left(kg\ CO_2\text{-eq}\ ha^{-1}yr^{-1}\right)$ is the annual SOC sequestration from 2019 to 2021; 2 is the experimental period in years; 44/12 is the factor for converting C to CO_2; 1000 is a unit conversion factor.

(3) Net eco-economic benefit

NEEB (\$ ha^{-1}) was calculated as follows:

$$NEEB = Yield\ income - Input\ cost - EDC$$

$$EDC = \sum Nr_iA \times P_i + GHGA \times P_{GHG}$$

Yield income $\left(\$\ ha^{-1}\right)$ is the income from grain yield, obtained by multiplying the crop yield by the local market price for wheat and maize; Input cost $\left(\$\ ha^{-1}\right)$ is the input cost of agricultural production; EDC $\left(\$\ ha^{-1}\right)$ is the environmental damage cost; Nr_iA is the cumulative Nr loss; P_i is the environmental damage cost coefficient per unit Nr loss on human health and ecosystems (Table S7); GHGA is the cumulative of GHG emissions; P_{GHG} is the damage cost per unit GHG emission on climate warming.

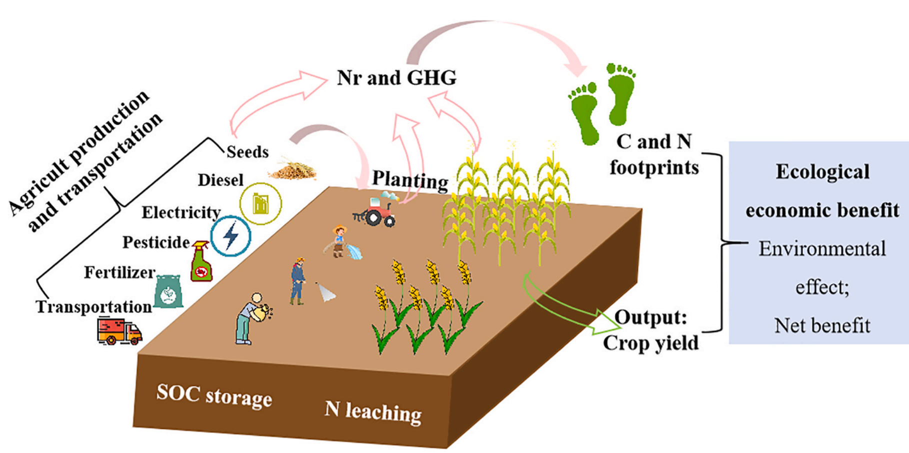

Fig. 2. The research boundary of the nitrogen (NF) and carbon (CF) footprints in the wheat-maize rotation (redrawn according to Xing et al. (2025)).

2.2. Scenario analysis

2.2.1. Questionnaire

The survey was carried out using fixed-point monitoring of farmers, an electronic questionnaire and data collection covering 5 provinces of the NCP. The survey focused on fertilizer applications and crop yields. Some 16,343 and 12,233 valid questionnaires were collected over the wheat and maize season, respectively.

2.2.2. Scenario design

An assessment of the C and N mitigation potential of Chinese crop rotation systems is a new approach to achieving agricultural green development for sustainable N management in China. Reducing the N rate and applying synergistic N fertilizers are potentially effective methods for reducing CF and NF. Thus, to reduce Nr losses and C emissions, we designed Scenario (S1), where fertilizer inputs were optimized to achieve a zero nutrient surplus. The optimal fertilization rate was calculated as follows (Li et al., 2024):

$$Opt_{Fer} = Fer_{input}\text{-}Fer_{loss}\text{-}Fer_{surplus}$$

Opt_{Fer} $\left(kg\ ha^{-1}\right)$ is the optimal fertilization rate; Fer_{input} $\left(kg\ ha^{-1}\right)$ is the actual amount of fertilizer applied from survey data; Fer_{loss} $\left(kg\ ha^{-1}\right)$ is the loss from fertilizer including N_2O emissions, NH_3 volatilization and N leaching; N_2O and NH_3 losses were based on the emission coefficients obtained from field experiments, N leaching was calculated by multiplying the N input by the coefficient of fertilizer loss (Table S5); P and K losses were ignored. $Fer_{surplus}$ $\left(kg\ ha^{-1}\right)$ is the apparent nutrient surplus, which was defined as the fertilizer input minus above-ground crop nutrient uptake. The relationship between maize and wheat yield and their above-ground nutrient uptake was obtained from the database (Table S8).

To further reduce Nr losses and C emissions, we defined four additional scenarios (S2-S5) with the same fertilizer application rates as the baseline scenario (S1). Scenario 2 (S2) employed urea amended with a urease inhibitor, and Scenario 3 (S3) controlled release urea. These N management strategies (UI and CRU) were selected for their high potential in simultaneous emission mitigation and NEEB enhancement. In addition, Scenarios 4 (S4) and 5 (S5) were designed to further address the problem of the mismatch between livestock production and crop production in North China by incorporating organic fertilizer with urea, with S4 and S5 designated UOM (combination of organic fertilizer and urea) and ULOM (combination of organic fertilizer and urea amended with the urease inhibitor), respectively.

2.2.3. Estimation of NF, CF and EDC

The calculation formulae for Nr losses, C emissions, NF, CF and EDC were the same as in section 2.1.4, but SOC was not considered. Agricultural inputs refer to the average amounts of agricultural materials used by farmers in the reference area.

2.3. Data analysis

Data were compiled using Excel 2019 and graphs drawn using Origin 2021. The spatial distribution of N losses and C emissions was performed using ArcGIS version 10.3.

3. Results

3.1. Crop yields

Over the two-year period, compared to the farmers' conventional fertilization practice (CU), reducing the N rate maintained stable crop yields (Fig. 3), with crop yield increasing the longer organic fertilizer

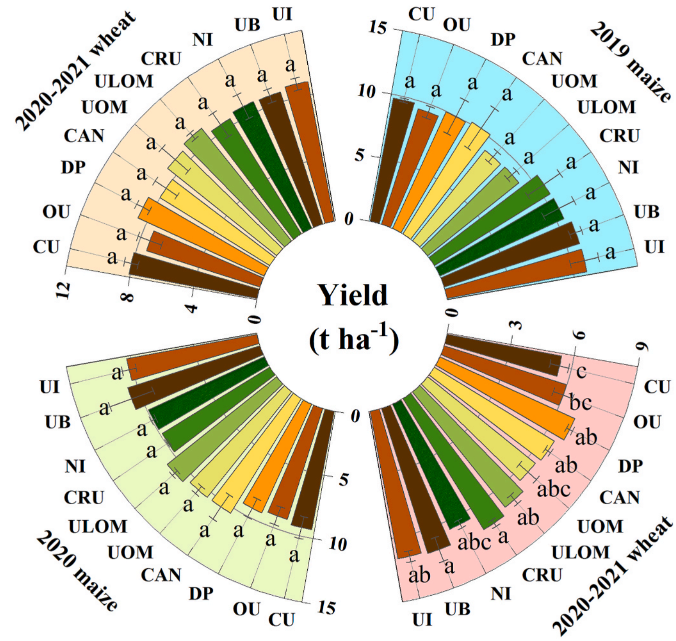

Fig. 3. Crop yields under different treatments in the wheat-maize rotation from 2019 to 2021. Error bars are standard deviations and different letters in a group represent significant differences at the 0.05 level.

was applied. Maize yields showed no significant differences among all fertilization treatments in both 2019 (9.0–11.0 t ha^{-1}) and 2020 (9.0–10.9 t ha^{-1}). In contrast, wheat yields in 2019–2020 varied significantly across treatments. The yield of the OU treatment was 5.4 t ha^{-1}, significantly lower than those of CRU and UB by 16.7 % and 15.5 %, respectively.

3.2. Nitrogen and carbon footprints

The annual Nr loss was 51.4–126.2 kg N ha^{-1} yr^{-1} over the wheat-maize rotation, with the CU treatment having the highest loss (Fig. 4a). At the same N application rate, compared to OU, optimizing N management reduced the Nr loss by 19.0–47.0 % except in the NI and UB treatments. NH_3 emissions and N leaching dominated Nr losses, especially NH_3 emissions, which accounted for 36.7–74.4 % of the total loss. The results of the NI treatment were the opposite, and 14 % of the N loss in this treatment could be explained by agricultural production and transportation, which was higher than that of N leaching (11.3 %).

Total CO_2 emissions ranged from 6147.3 to 7958.5 kg CO_2-eq ha^{-1} yr^{-1} (Fig. 4b). Compared to farmers' practice (CU), substituting CAN for urea increased total C emissions by 9.8 %, while other treatments reduced them by 4.2–15.2 %. In addition, under equivalent fertilizer inputs, the substitution of 50 % organic fertilizer for urea resulted in higher total C emissions compared to using urea alone. CO_2 emissions from electricity consumption for irrigation were the primary contributing factor on the CF treatment at 37.0–47.9 %. CO_2 emissions from the production and transportation of N fertilizers was the second most important contributor. However, the opposite was found under the CAN treatment, where the main source of C emissions was N fertilizer production and transportation, accounting for 45.5 % of the total.

Over all the treatments, NF ranged from 2.8 to 7.7 g N kg^{-1} grain (Fig. 5a). Reducing the N rate significantly reduced NF by 20.1 %. Further optimization by changing N fertilizer type or application method led to additional reductions in the NF. The CRU and UI treatments exhibited the lowest NF, with significant reductions of 54.4 % and 54.6 %, respectively, compared to the OU treatment.

Reducing the N rate was also an effective measure for decreasing CF when urea alone was applied, with a reduction of 11.2 % (Fig. 5b). In

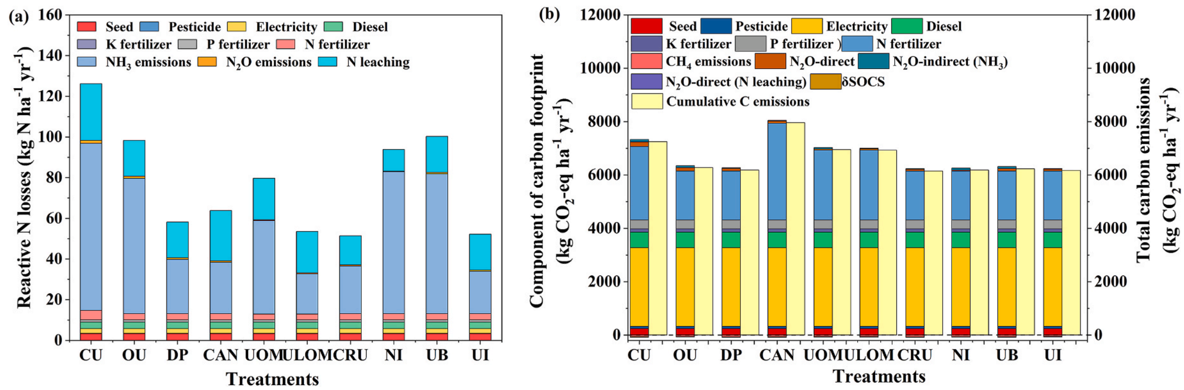

Fig. 4. Nitrogen losses (a), components of carbon emissions and total carbon emissions (b) under the 10 treatments in the wheat-maize rotation.

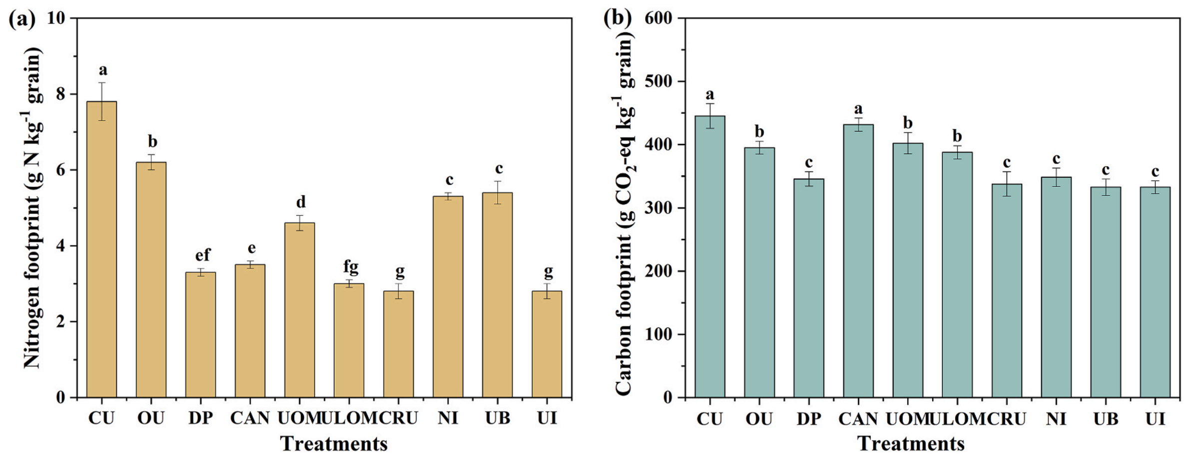

Fig. 5. Nitrogen footprint (a) and carbon footprint (b) of the annual wheat-maize rotation. Error bars are standard errors and different letters in a group represent significant differences at the 0.05 level.

addition, compared with the OU treatment, urea deep placement or using enhanced efficiency urea significantly reduced CF by 11.9–15.8 %.

3.3. Net eco-economic benefit

The agricultural input costs ranged from \$1494.5 to \$1733.5 ha^{-1} yr^{-1} (Fig. 6), with the OU treatment having the lowest and the ULOM treatment the highest cost. Environmental damage costs amounted to \$279.7–\$638.0 ha^{-1} yr^{-1}. Nr losses were the primary contributing factor to environmental damage costs, with NH_3 emissions accounting for over 79.4 % of total Nr losses. Optimized N management practices significantly enhanced the NEEB of the wheat-maize rotation, particularly under the UI treatment: compared to the CU and OU treatments, the UI treatment increased NEEB by 44.3 % and 28.1 %, respectively.

3.4. Screening N strategies

Compared to the conventional fertilization practices of farmers, reducing the N application rate served as the foundation for decreasing CF an NF and mitigating environmental damage. Optimizing N fertilizer type (the CAN and UOM treatments) while reducing the N rate minimized Nr losses, but increased C emissions from fertilizer production and

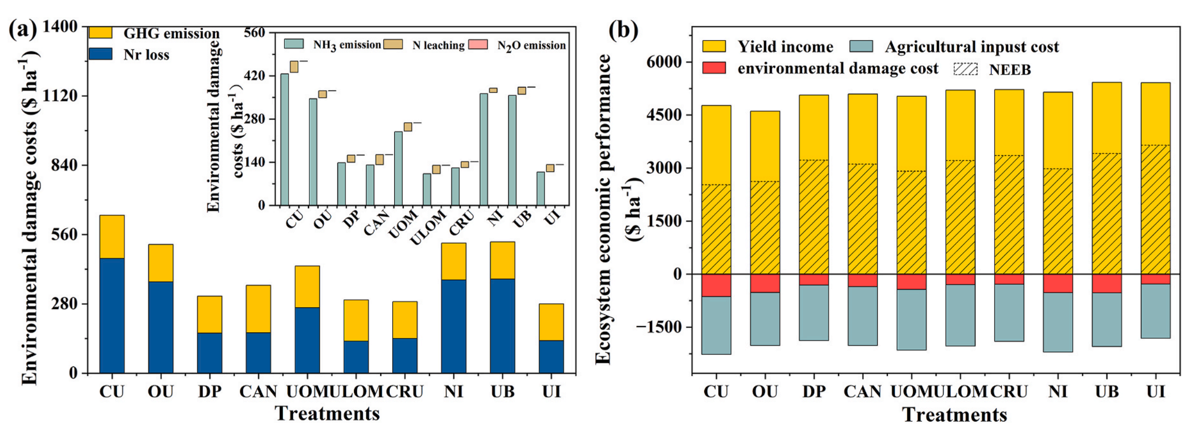

Fig. 6. Environmental damage costs (a) and net ecosystem economic performance (b) in the wheat-maize rotation.

application (Fig. 7). Treatments involving NI and UB showed no significant impact on Nr. From the perspective of overall environmental benefit and economic returns, the UI and CRU treatments synergistically achieved emission reductions and increased net income.

3.5. C and N emissions in the north China Plain

In the NCP, the calculated C emissions (AC) from maize and wheat were 3614.9 kg CO_2-eq ha^{-1} and 3877.3 kg CO_2-eq ha^{-1}, respectively (Fig. 8a–g). exhibiting pronounced spatial heterogeneity. In the maize season, C emissions were higher in the South and lower in the North: C emissions were highest at 3803.5 kg CO_2-eq ha^{-1} in Henan province, and lowest at 3340.7 kg CO_2-eq ha^{-1} in Hebei province. During the wheat season, Beijing was one of the emission hotpots producing 4333.9 kg CO_2-eq ha^{-1}, while C emissions from Tianjin were relatively low at 3409.kg CO_2-eq ha^{-1}.

In the NCP, the average Nr losses for maize and wheat were 67.6 and 42.4 kg N ha^{-1}, respectively (Fig. 9a–g). As with C emissions, Nr emissions showed regional differences. During the maize season, Tianjin and Henan provinces were Nr emissions hotpots where Nr losses ranged from 69.2 to 75.0 kg N ha^{-1}. During the wheat season, Nr losses in Beijing were 56.9 kg N ha^{-1}, higher than those from other provinces.

The NF of maize cultivation in the NCP ranged from 3.8 to 27.6 g N kg^{-1} grain, with the highest average value observed in Henan Province at 10.0 g N kg^{-1} grain (Fig. 10). Similarly, the CF ranged from 237.4 to 1302.9 g CO_2-eq kg^{-1} grain, with Henan Province reporting the highest average CF of 509.0 g CO_2-eq kg^{-1} grain. The EDC varied between \$55.6 and \$167.8 ha^{-1} $year^{-1}$, with Henan Province having the highest cost at \$92.4 ha^{-1} in an average.

3.6. Scenario analysis

During the maize season, optimizing N strategies effectively reduced C emissions by 26.0 %–33.6 %, with S3 having the highest emission reduction efficiency (Fig. 8b–f). For wheat, C emission trends under different management scenarios mirror those of maize (Fig. 8h–m). Emissions under S1 to S5 ranged from 3127.5 to 3483.8 kg CO_2-eq ha^{-1}, among which S2 and S3 exhibited the greatest mitigation potential, reducing emissions by 19.3 % and 19.1 % respectively.

Nr losses during the maize season ranged from 15.9 to 32.0 kg N ha^{-1} (a reduction of 52.7–76.5 %) under the various scenarios (Fig. 9b–f), while those in the wheat season ranged from 23.1 to 31.9 kg N ha^{-1} (a reduction of 24.8–45.5 %) (Fig. 9h–m). Applying CRU (S3) produced the lowest Nr losses and highest mitigation potential. Additionally, S5 in the wheat season was another effective mitigation measure, with no significant difference from S3.

Optimizing N management significantly reduced the NF by 54.8–77.0 %, CF by 27.3–34.6 % and EDC by 26.1–33.8 %, with S2 and S3 delivering the most substantial improvements (Fig. 10). Similarly, optimizing practices during the wheat season effectively decreased the NF by 25.7–46.1 %, CF by 10.6–19.7 % and EDC by 10.6–19.7 %, with S2 and S3 showing optimal performance.

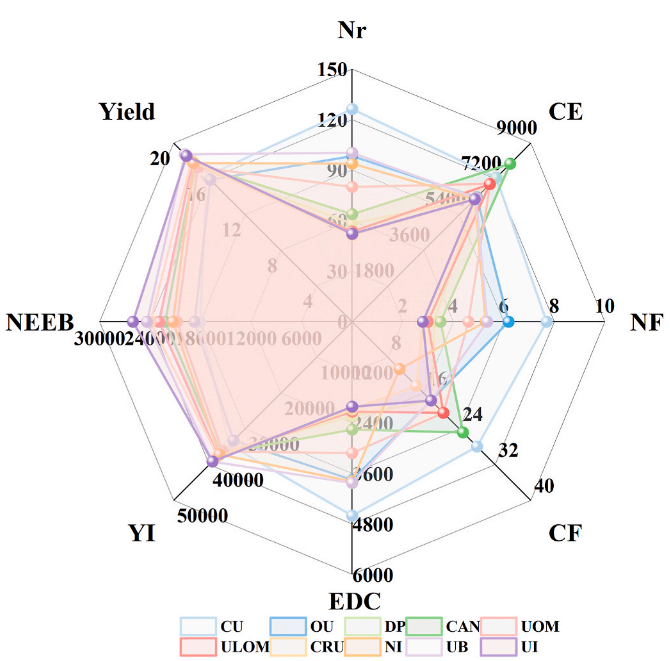

Fig. 7. Comprehensive effect analysis of optimized measures. Nr, CE, NF, CF, EDC, YI, NEEB and Yield represent reactive N loss, C emission, N footprint, C footprint, environmental damage cost, yield income, net eco-economic benefit and crop yields, respectively.

4. Discussion

4.1. Spatial heterogeneity of C and N emissions in the NCP

Spatial analysis of emissions from the NCP revealed significant heterogeneity, primarily stemming from the coupling effects between the climate during crop growth and agronomic management practices (Kumar et al., 2021; Wang et al., 2022b). This heterogeneity is driven by a distinct north-south climatic gradient that governs microbial N transformation pathways (Chen et al., 2010; Jin et al., 2023). In the northern regions, spring droughts lead to soil N accumulation after fertilization, with the accumulated N pool undergoing rapid microbial denitrification, resulting in a pulsed release as N_2O when the abrupt onset of the rainy season creates transient anaerobic microsites in the soil (Zhou et al., 2016). Conversely, frequent torrential summer rains in southern areas can create sustained anaerobic conditions that enhance the completeness of denitrification with almost exclusively N_2 emissions (Yang et al., 2018). In addition, regional planting patterns are an indirect yet critical factor. Wheat is predominantly cultivated in irrigated areas, such as the Yellow River irrigation zone, where intensive cultivation leads to excessive fertilizer inputs. In contrast, maize grown in arid regions such as northern Hebei relies more on rain-fed production with relatively lower fertilizer application rates (Wang et al., 2024). This spatiotemporal pattern explains the observed difference in C emission intensity between maize (3615 kg ha^{-1}) and wheat (3877 kg ha^{-1}), along with their spatial heterogeneity.

Fundamental differences in crop management between wheat and maize systems further amplify this heterogeneity. Specifically for wheat, multiple management factors converge to elevate its C emission risks. The survey data indicated that N and P application rates during the wheat growing season exceed those for maize, coupled with lower N use efficiency in wheat, resulting in a larger residual soil nitrate pool that served as a primary substrate for denitrifying, making it more prone to conversion into N_2O via denitrification (Li et al., 2025a). Additionally, high P inputs may inhibit specific soil enzyme activities and microbial communities, possibly through phosphorus-induced suppression of key enzymes such as C-degrading hydrolases or N-cycle enzymes, indirectly reducing C and N cycling efficiency (Liu et al., 2022). Furthermore, the high water demand of wheat necessitates frequent irrigation, which not only increases energy consumption, but also facilitates N leaching into deep soil layers, enhancing denitrification-derived CO_2 emissions (Niu et al., 2021). Irrigation-induced soil moisture fluctuations exacerbate dry-wet cycles, physically disrupting soil aggregates, accelerating organic C decomposition of previously protected organic matter and triggering pulsed N_2O emissions (Braun and Bremer, 2018). Differences in straw incorporation methods also contribute to variation in C emissions between wheat and maize systems. In the NCP, wheat is sown following maize straw incorporation via deep ploughing, which buries C-rich residues into anaerobic subsoil layers, altering the soil pore structure and restricting CO_2 diffusion, leading to a sustained emission

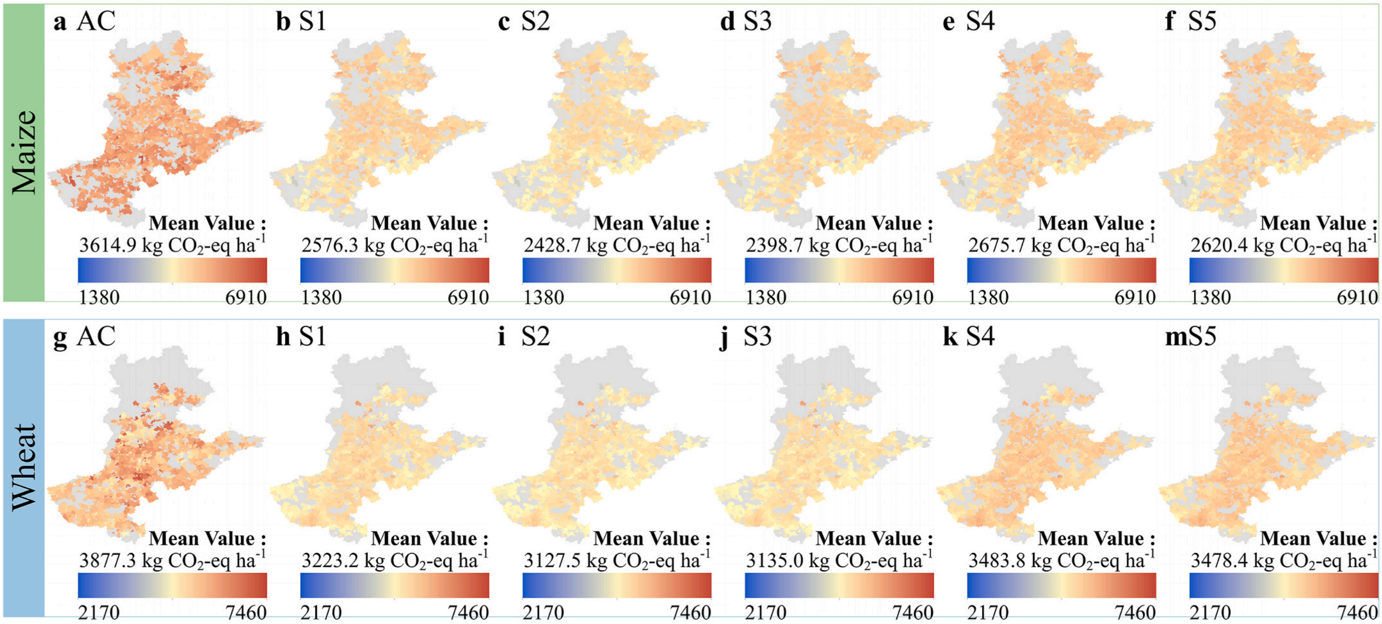

Fig. 8. Spatial variation of C emissions from maize and wheat in the North China Plain under different scenarios. AC: conventional fertilization, actual situation of farmers; S1: baseline, optimized fertilization rate; S2: urea amended with a urease inhibitor; S3: controlled release urea; S4: combination of organic fertilizer and urea; S5: combination of organic fertilizer and urea amended with the urease inhibitor.

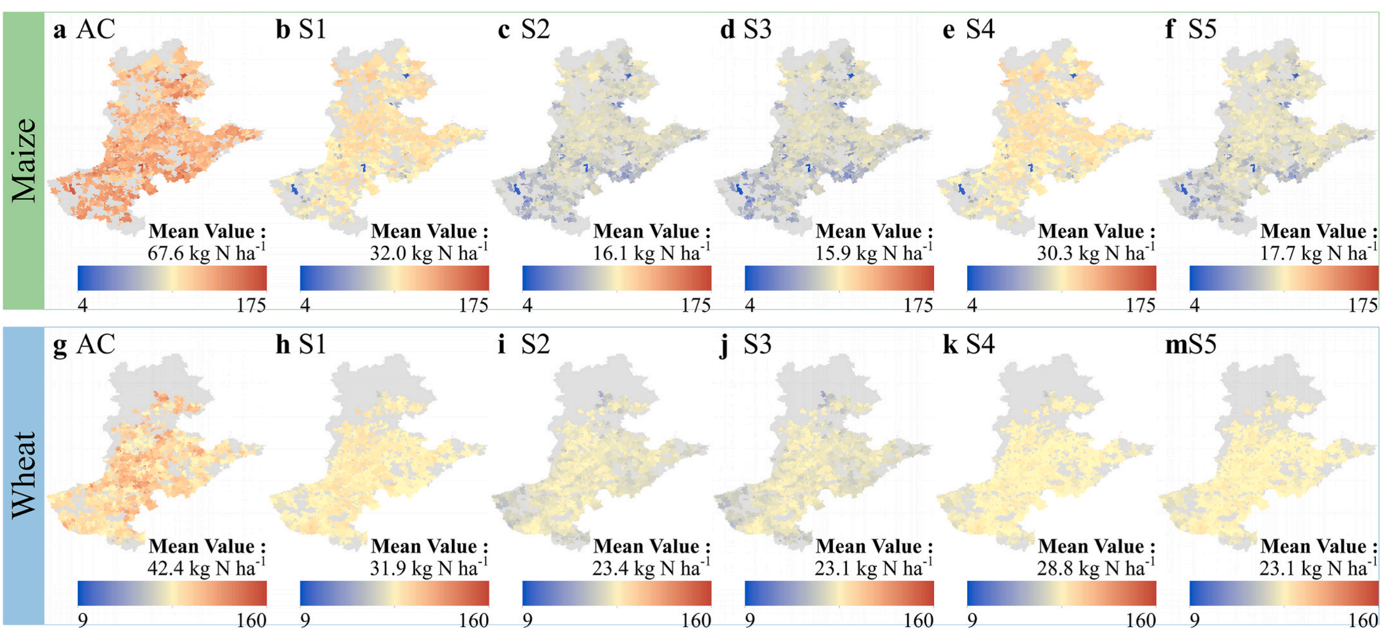

Fig. 9. Distribution of Nr losses from maize and wheat in the North China Plain under different scenarios. AC: conventional fertilization, actual situation of farmers; S1: baseline, optimized fertilization rate; S2: urea amended with a urease inhibitor; S3: controlled release urea; S4: combination of organic fertilizer and urea; S5: combination of organic fertilizer and urea amended with the urease inhibitor.

pattern (Li et al., 2024; Wang et al., 2023a,b). Maize is typically sown using no-till methods with wheat straw mulching, favoring aerobic decomposition at the soil surface and generally reducing net CO_2 emissions. Moreover, the distinct composition of wheat root exudates, characterized by a higher C/N ratio compared to maize, may also provide ample energy substrates for microbes, potentially triggering a priming effect that accelerates the mineralization of native SOC, leading to higher seasonal CO_2 emissions (Cai et al., 2022; Dong et al., 2023). This comprehensive analysis of spatial and crop-specific heterogeneity provides a critical foundation for developing targeted emission reduction strategies.

4.2. Emission mitigation mechanisms and regional application of N management strategies

Irrigation electricity consumption emerged as the dominant factor influencing CF and NF in the wheat-maize rotation. This is attributed to severe over-exploitation of groundwater and inefficient irrigation practices in the NCP, leading to high energy demands (Liu et al., 2013). Additionally, the C emission factor of the regional power grid in the NCP is significantly higher than the national average, further amplifying the CF of irrigation (Feng et al., 2023; Wei et al., 2024). N fertilizer production and transportation represented another major source,

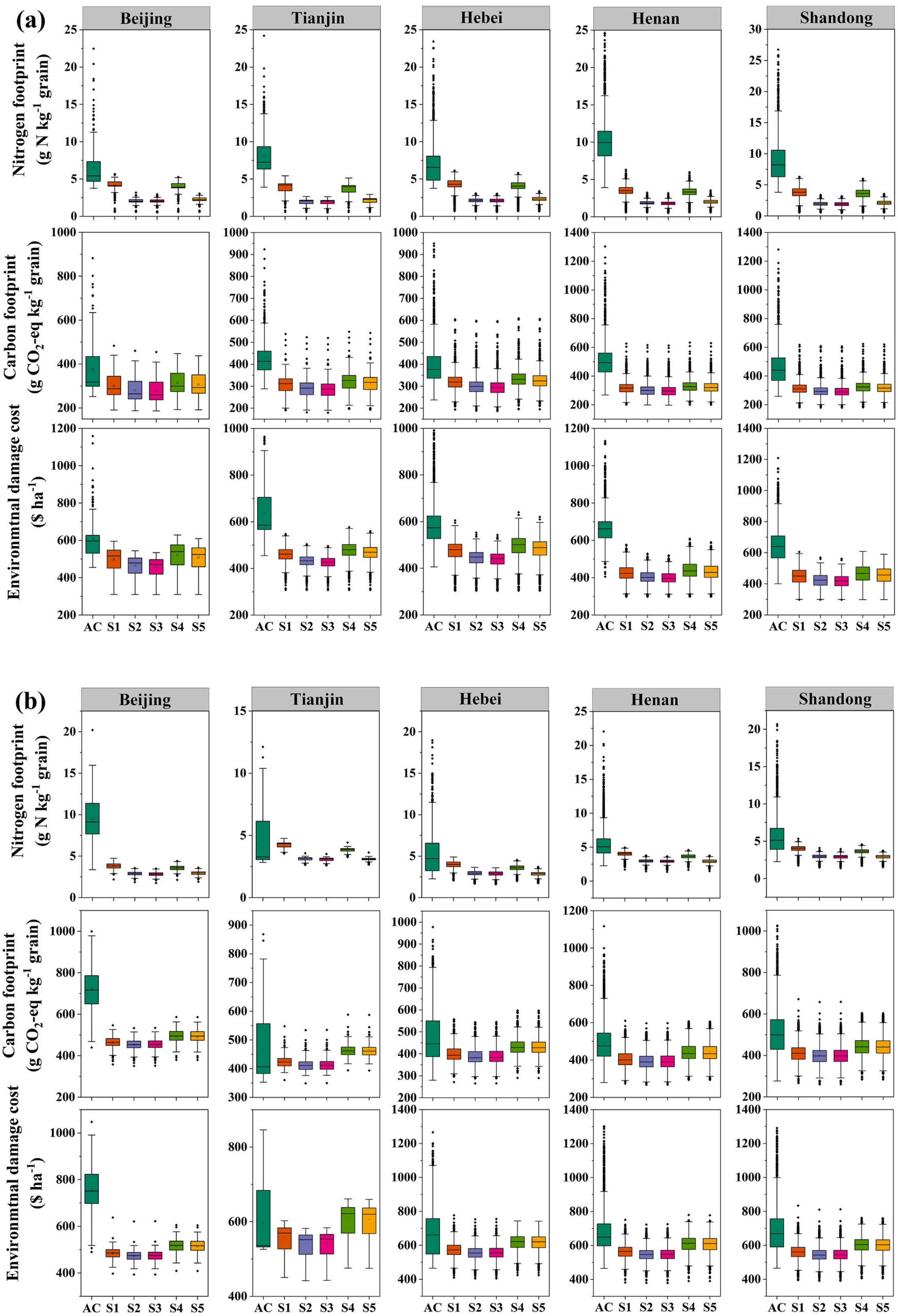

Fig. 10. Nitrogen (g N kg^{-1} grain) and carbon footprints (g CO_2-eq kg^{-1} grain) and the environmental damage cost ($ ha^{-1}) of maize (a) and wheat (b) in the North China Plain under different scenarios. AC: conventional fertilization, actual situation of farmers; S1: baseline, optimized fertilization rate; S2: urea amended with a urease inhibitor; S3: controlled release urea; S4: combination of organic fertilizer and urea; S5: combination of organic fertilizer and urea amended with the urease inhibitor.

accounting for 29.8–45.6 % of total emissions and revealing a “production-process dependence”, where the high emissions from the ammonia oxidation step are inherently embedded in the product, especially for the CAN and UOM treatments (Di et al., 2024). In contrast, conventional urea follows a simpler and less emission-intensive synthesis pathway, underscoring that fertilizer emissions are fundamentally shaped by industrial production routes (Abdo et al., 2024). In N footprint studies, Nr losses associated with agricultural input production/-transportation and field operations were significantly lower than those during the entire growth cycle of wheat-maize rotations, a finding consistent with previous research (Huang et al., 2021). However, due to the current incompleteness of emission factor databases, the differences in NF from fertilizer production and transportation between treatments could not be rigorously compared (Castner et al., 2017). Future studies should prioritize the establishment of comprehensive databases to enhance the robustness of such assessments.

Excessive N fertilizer application remained a primary driver of agricultural C emissions and Nr losses (Li et al., 2025b). The fundamental mechanism involved an overload of the soil N pool, which not only directly enhanced N_2O from nitrification and NH_3 emissions, but more importantly, reshaped the soil microbial community by promoting nitrifiers and denitrifies, thereby increased the C-N emission intensity of the ecosystem (Chen et al., 2021; Ma et al., 2022). Applying less N decreased emissions from fertilizer production while mitigating field-level Nr losses, thereby directly or indirectly reducing CF and NF (Zhang et al., 2013), indicating that it should be a prerequisite for alleviating ecological footprints. However, since CF and NF are intrinsically linked to grain yield, emission reductions do not invariably translate to lower ecological footprints (Jiang et al., 2019).

Among optimized practices, the ULOM treatment elevated C emissions from fertilizer production but applying organic fertilizer stimulated soil microbial activity, leading to microbial N assimilation and full denitrification in localized anaerobic micro-environments. Meanwhile, it potentially formed stable humus for long-term C sequestration, achieving a coordinated net reduction of both C and N emissions (Ling et al., 2025). The NI (nitrification inhibitor DMPP) and UB (BiO-WiSH®-enhanced urea) treatments reduced CF and NF through dual mechanisms - yield enhancement and N_2O mitigation (Hashmi et al., 2024) - and DMPP reduced N leaching, further contributing to footprint reductions (Wang et al., 2025). However, by specifically inhibiting ammonia-oxidizing bacteria (AOB) or enhancing urease activity, these treatments led to the accumulation of NH_4^+-N in topsoil, increasing NH_3 volatilization risk and partially offsetting other environmental benefits (Sun et al., 2020; Wang et al., 2023a,b). Controlled-release urea (CRU) establishes a “supply-demand synchronization” mechanism through a physical diffusion barrier formed by the polymer coating, synchronizing N release with crop N uptake, shortening the residence time of N in the soil, and significantly reducing the “exposure window” of NH_4^+-N and NO_3^--N, thereby cutting off the main substrates for N_2O production and NH_3 volatilization at source (He et al., 2025; Ma et al., 2023). In contrast, the urease inhibitor (UI) targeted biochemical processes by inhibiting soil urease activity, moderating NH_4^+ release and preventing sharp localized pH spikes, thereby directly curbing NH_3 volatilization and indirectly reducing N_2O emissions and the risk of nitrate leaching (Götze et al., 2025; Schoof et al., 2025). Thus, although CRU and UI operated through different pathways, both interventions targeted the initial or key steps in the N cycle, constituting the core mechanism behind their optimal environmental benefits.

Building on the observed crop-specific heterogeneity, tailored management strategies is essential. Scenario simulations demonstrated that CRU (S3) is the optimal improved N measure for maize production in the NCP, which could reduce Nr losses and C emissions by 76.5 % (0.6 Tg) and 33.6 % (13.9 Tg), respectively. Mechanistically, the S-shaped release curve of CRU aligns perfectly with the pronounced N demand peak of maize from jointing to tasseling, drastically reducing the temporal mismatch for N loss and enhancing N use efficiency (Liu et al., 2023). Furthermore, regional application of CRU for maize could decrease EDC by 339.4 million dollars, translating to substantial economic and ecological benefits. Additionally, its single-application aligns with local broadcasting practices that, with the reduction of labor inputs, could increase maize yields by an average of 7.23 % (Zhu et al., 2020), confirming its technical feasibility, so it should be more widely adopted.

In contrast, wheat production exhibited generally lower emission reduction efficiency compared to maize, potentially due to temperature-dependency: lower soil temperatures can slow the degradation of CRU polymer coatings and suppress nitrifier activity, weakening the synchronization effect, while also reducing root metabolic activity and nutrient uptake capacity, prolonging the residence time of mineral N (Legesse et al., 2023; Sentek et al., 2023). For wheat, both S2 (UI) and S3 (CRU) were effective in synergistically reducing C-N emissions and EDC. UI could provide immediate protection against NH_3 volatilization from surface-applied urea, whereas CRU offers a delayed release that better matches wheat’s extended uptake pattern. Regional application of these optimized strategies could reduce Nr losses by an average of 0.2 Tg, C emissions by 9.0 Tg, and EDC by 219.1 million dollars. Notably, the combination of organic fertilizer and urease inhibitor-enhanced urea (S5) showed significant potential for Nr emission mitigation. The organic matrix promotes microbial immobilization of mineral N, while the UI ensures that the urea-N component is not rapidly lost as NH_3, allowing for a more controlled N supply. Future research should focus on developing low-C production methods for organic fertilizers (Xing et al., 2025) to reconcile mismatches between livestock development and agricultural production in the NCP.

4.3. Coordinated optimization of environmental and economic benefits

Achieving widespread adoption of improved agricultural practices hinges on demonstrating clear economic incentives for farmers. Our analysis established that enhanced N management could generate such incentives by aligning environmental mitigation with economic gains, primarily through a more efficient allocation of resources. The economic viability of these strategies was underscored by quantifying the environmental damage cost in this experiment, with NH_3 volatilization and GHG emissions confirmed to be the two largest contributors to environmental damage costs from farmland, consistent with previous findings (Xia et al., 2016). This was primarily because NH_3 volatilization served as the primary pathway for Nr to enter the regional environment. After undergoing atmospheric transformation and deposition, it triggered a chain of ecological effects such as water eutrophication and soil acidification, the mitigation of which incurs extremely high costs (Guo et al., 2023). In contrast, the damage caused by GHGs manifested on a global scale. Their strong global warming potential leads to long-term climate change, resulting in incalculable socio-economic losses (Yin et al., 2023). Consequently, mitigation strategies synergistically reducing both pollutants could maximize environmental benefits across both regional and global scales.

The improvement in NEEB revealed a synergistic pathway for achieving both environmental and economic benefits, which fundamentally stemmed from a marked increase in resource use efficiency. For key strategies such as CRU and UI, the economic advantage did not only depend on yield increases, but also on more efficiently directing limited N fertilizer resources toward the target variable (crop yield), and reducing resource waste through environmental loss pathways (Gu et al., 2023). In fact, under equivalent N application rates, optimized fertilization practices (excluding NI and UB) reduced environmental damage costs by 16.8 %–46.2 %, highlighting that each unit of N input generates higher economic returns by avoiding the external costs associated with environmental pollution (Zhou et al., 2019). Ultimately, compared to OU, the yield benefits from optimized practices outweighed the increase in input costs, resulting in a 10.0 %–28.1 % improvement in NEEB. This demonstrated synergy between ecological and economic performance provides a compelling argument for transitioning to more efficient N management in the NCP.

4.4. Uncertainty analysis and challenges

In this study, optimized N fertilizer management demonstrated significant potential for reducing environmental footprints and improving eco-economic benefits, but uncertainties persist in the calculations, originating from the fundamental complexity and spatiotemporal heterogeneity of agricultural ecosystems (Fan et al., 2022b). First, the C emission factors and Nr emission factors for agricultural materials production and transportation were primarily derived from previous studies. Due to the multi-sectoral complexity of agricultural materials production, relevant inventories remain challenging to collect, slow to update and regionally dependent (Dong et al., 2024), necessitating further refinement. Second, uncertainties in NF arise from the emission factors calculated for N leaching from fertilizers. While multiple optimization measures were explored, current research on the impacts of practices like urease inhibitors on N leaching remains limited, and environmental conditions cannot be fully accounted for (Song et al., 2021). Thus, enhanced monitoring of N leaching under diverse measures in the NCP is imperative. Additionally, market fluctuations in agricultural input costs and grain prices introduce unavoidable uncertainties in NEEB. Nevertheless, our results provide critical references for evaluating the integrated environmental effects and eco-economic benefits of fertilization practices, supporting the selection of optimized N management technologies.

Beyond these methodological uncertainties, our assessment and the wider adoption of promising technologies face pragmatic challenges. For instance, while organic fertilizer substitution for a percentage of the urea applied and its combined application with UI-enhanced urea effectively reduced NF and CF (vs. CU), their mitigation potential was generally weaker than using UI or CRU. Critically, this study focused solely on the production, transportation and application of organic fertilizers, omitting the ecological and economic benefits of reducing organic resource waste (Zhang et al., 2024), which warrants comprehensive evaluation in future work. Despite the demonstrated advantages of UI and controlled-release urea (CRU), their adoption faces practical barriers. First, higher costs of CRU and UI compared to conventional urea under equivalent fertilization rates necessitate policy subsidies or scaled production to reduce costs; second, limited quantitative awareness among smallholder farmers regarding the environmental costs of Nr losses and C emissions, highlights the need for technical training and effective extension services (Sang et al., 2021).

To address these challenges and refine future assessments, future research should prioritize the development of a dynamic, region-specific emission factor database. Furthermore, integrating LCA and multi-objective optimization models is crucial to balance the long-term ecological and economic effects of management strategies, thereby providing targeted decision-making support for regional green agricultural transitions (Li et al., 2023; Sakamoto et al., 2023).

5. Summary and conclusions

Based on a comprehensive approach that integrated field experiments with LCA in wheat-maize production of the NCP, this study demonstrated that optimized N management strategies could effectively reduce CF and NF to varying degrees. The results clearly identified CRU and UI as the most promising options, which under equivalent N application rates, reduced CF and NF by 14.7 %–15.8 % and 54.4 %–54.6 %, respectively, compared with ordinary urea application (OU), while simultaneously increasing NEEB by 21.9 %–28.1 %.

This plot-scale evidence was further extended to the regional scale through scenario analysis, which revealed distinct C-N emission patterns across the NCP and identified Beijing and Henan Province as specific hotspots for C-N emissions. The regional simulation quantified the profound mitigation potential of widespread adoption of these optimized practices, showing that CRU and UI could, on average, reduce CF, NF and EDC by 26.9 %, 61.4 % and 26.3 %, respectively.

In conclusion, this study moved beyond the identification of effective technologies to deliver a scalable framework for agricultural sustainability. Our findings provided robust, multi-scale evidence that CRU and UI are pivotal strategies for achieving coordinated environmental risk reduction and improved eco-economic benefits in the NCP. Therefore, future efforts should prioritize these technologies and tailor their implementation based on region-specific emission patterns and resource advantages. We propose the adoption of the integrated "emission reduction-efficiency enhancement" N management framework developed in this study to effectively guide the agricultural green transition and achieve sustainable development goals in the region and beyond.

CRediT authorship contribution statement

Jingxia Wang: Writing – original draft, Funding acquisition, Formal analysis, Data curation. **Yongkang Duan:** Validation, Formal analysis. **Shaohui Huang:** Writing – review & editing, Funding acquisition. **Huimin Yang:** Validation. **Liangliang Jia:** Writing – review & editing, Funding acquisition. **Shenglin Hou:** Writing – review & editing. **Xuejun Liu:** Writing – review & editing, Supervision, Methodology. **Keith Goulding:** 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.128134.

Data availability

No data was used for the research described in the article.

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