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Ammonia emissions and crop yields in China to 2060 under SSP-RCP scenarios with climate change and nitrogen fertilization attribution

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Abstract

Climate change poses unprecedented challenges to agricultural sustainability, with profound implications for environmental quality and crop productivity. However, integrated assessments quantifying the specific contributions of climatic drivers versus management practices to agricultural ammonia (NH₃) emissions and crop yields remain limited in China, constraining precision air pollution control and threatening national food security. This study employed the DNDC model to simulate fertilizer-related NH₃ emissions and crop yields of China's three major crops (rice, maize, and wheat) under current and three representative shared socioeconomic pathways (SSP) representative concentration pathways scenarios (SSP1-1.9, SSP3-7.0, and SSP5-8.5) for 2030, 2050, and 2060, while explicitly partitioning the relative importance of climate change versus nitrogen management variations to agricultural outcomes. Results indicate that fertilizer-related NH₃ emissions totaled 3.00 Tg N yr⁻¹ in 2019, with a combined crop yield of 618.76 Tg. By 2060, fertilizer-related NH₃ emissions were projected to increase by 2.0%, 12.0%, and 84.3% under SSP1-1.9, SSP3-7.0, and SSP5-8.5, respectively, while crop yields would decrease by 16.7%, 16.1%, and 5.8%. Under SSP1-1.9, the relative importance of climate change for fertilizer-related NH₃ emissions (RI_e) maintained approximately 50% throughout 2030–2060, suggesting balanced offsetting effects between climate change and the projected nitrogen fertilizer reduction. Conversely, the relative importance of climate change for crop yields (RI_y) reached 91% by 2060, demonstrating that crop yield losses were predominantly driven by climatic stresses rather than the fertilizer input adjustment. Under SSP5-8.5, substantial increases in nitrogen fertilization reduced the relative importance of climate change, with RI_e and RI_y values dropping to 17% and 59% in 2060, respectively. This pattern demonstrates that enhanced fertilization could not fully offset crop yields losses, while 84% of fertilizer-related NH₃ emissions increases resulted from intensified fertilizer use. This study provides critical insights for precision emission reduction in agricultural-atmospheric systems and supports China's dual goals of food security and carbon neutrality.

1. Introduction

Ammonia (NH_3) represents the primary alkaline gas in the atmosphere, contributing to air pollution through aerosol formation (Balasubramanian *et al* 2015). Beyond its atmospheric impacts, NH_3 deposition causes soil and water acidification, triggers eutrophication, and disrupts ecosystem balance (Clarisse *et al* 2009, Balasubramanian *et al* 2015, Fu *et al* 2015). Given these widespread environmental impacts, controlling NH_3 emissions has become increasingly urgent, particularly in regions with intensive agricultural activities. In China, agricultural systems dominate anthropogenic NH_3 releases, accounting for over 80% of total emissions, with crop production alone contributing approximately 46% of agricultural NH_3 sources (Huang *et al* 2012, Li *et al* 2021). This substantial agricultural contribution makes NH_3 volatilization control essential for effective haze pollution mitigation (Zhao *et al* 2023) and represents a critical component of contemporary atmospheric pollution management strategies (Li *et al* 2024a).

Crop yield serves as a fundamental indicator of food security and primary determinant of nitrogen fertilizer input intensity. In China, mounting pressures from population growth, accelerating urbanization, and evolving dietary preferences are collectively driving increased demand for both quantity and quality of agricultural products (Sheng and Song 2019, The State Council Information Office of the People's Republic of China 2019). Climate change further compounds these challenges by introducing additional uncertainties to crop productivity (Lesk *et al* 2016). Faced with these converging pressures, farmers increasingly adopt intensive nitrogen fertilization strategies to sustain crop yields and meet growing food demand (Wang *et al* 2021b). However, this approach creates a critical dilemma: while enhanced nitrogen inputs can offset climate-induced crop yield losses, they simultaneously intensify fertilizer-related NH_3 volatilization, establishing a fundamental trade-off between emission reduction and food security objectives. Consequently, an integrated assessment of future fertilizer-related NH_3 emissions and crop yield trajectories under evolving conditions is imperative.

In existing studies, projections of future fertilizer-related NH_3 emissions and crop yields indicate substantial changes with significant inter-scenario variations. For instance, Beaudor *et al* (2025) and Yang *et al* (2022) projected that global fertilizer-related NH_3 emissions would increase by 10%–50% under various scenarios by 2100, while Fu *et al* (2020) estimated that China's NH_3 emissions would reach 12.8 and 7.3 Tg N yr⁻¹ in 2030 under current development and emission reduction pathways, respectively. Regarding crop yields, Zhang *et al* (2025), Li *et al*

(2024b), and Chang *et al* (2024) demonstrated considerable scenario-dependent variations for major crops including wheat and rice. However, despite these individual advances, existing research predominantly examines emissions or crop yields in isolation, with limited integrated assessments addressing both components concurrently.

This prevalence of isolated studies stems largely from methodological constraints. Conventional approaches, including emission factor methods (Huang *et al* 2012), empirical agricultural models (Wang *et al* 2021b), and light-use efficiency models (Cheng *et al* 2023), face inherent limitations in simultaneously simulating fertilizer-related NH_3 emissions and crop yields, while suffering from substantial uncertainty (Xu *et al* 2019) and excessive dependence on observational datasets (Sun *et al* 2020). To overcome these constraints, agricultural process models have emerged as powerful tools (Wang *et al* 2022, Chu *et al* 2023). While models like WHCNS (Shi *et al* 2022) and DLEM (Zhang *et al* 2020) have been developed for these purposes, the DNDC model is particularly effective at integrating meteorological factors, soil properties, and management practices to simultaneously estimate gas emissions and crop yields at regional scales (Li *et al* 2012). This process-driven approach enables reliable estimation of NH_3 and multiple greenhouse gas emissions (CO_2 , CH_4 , N_2O) alongside crop yields, with extensive validation demonstrating its robustness (Fu *et al* 2015, Xu *et al* 2018). However, despite these robust simulation capabilities, few studies have explicitly quantified the attribution of future changes. While Beaudor *et al* (2025) quantified climate change contributions to future emissions, comprehensive evaluation of climate impacts on both fertilizer-related NH_3 emissions and crop yields remains largely unexplored. To address these gaps, we employed the DNDC model to simultaneously simulate fertilizer-related NH_3 emissions and crop yields under shared socioeconomic pathways (SSP) representative concentration pathways (RCP) scenarios, utilizing a factorial experimental design to explicitly disentangle the relative importance of climatic drivers versus nitrogen management practices.

Specifically, this study aimed to: (1) simulate current fertilizer-related NH_3 emissions and crop yields for China's major crops (rice, maize, and wheat) in 2019 using the DNDC model; (2) project future changes in fertilizer-related NH_3 emissions and crop yields for 2030, 2050, and 2060 under three representative scenarios (SSP1-1.9, SSP3-7.0, and SSP5-8.5) from the CMIP6 framework; (3) quantify climate change contributions to both agricultural outcomes across different scenarios. In the context of China's 2060 carbon neutrality pledge, the national strategy of 'Synergy between Pollution Reduction

and Carbon Reduction' necessitates a rigorous balance between environmental quality and food security. However, few studies have simultaneously projected how fertilizer-related NH₃ emissions and crop yields will evolve under divergent future climate and socioeconomic pathways. By clarifying these future trajectories, our study aims to offer critical insights for designing targeted ammonia mitigation measures that simultaneously sustain food productivity throughout China's deep decarbonization process.

2. Methods

2.1. DNDC model

The DNDC model (www.dnrc.sr.unh.edu/) represents one of the most widely applied agricultural biogeochemical models for carbon-nitrogen cycling. Originally developed by Li *et al* in the 1990s to dynamically simulate soil organic carbon dynamics (Xie *et al* 2017, Hwang *et al* 2019), microbial processes, and crop development (Li 2000), the model integrates six interconnected sub-modules: soil climate, plant growth, decomposition, nitrification, denitrification, and fermentation (Li *et al* 2012). This integrated framework enables simultaneous quantification of greenhouse gas fluxes, nitrogen losses, and crop productivity across diverse agricultural systems (Giltrap *et al* 2010).

2.1.1. Base database configuration

The DNDC model requires comprehensive input datasets encompassing meteorological variables (daily maximum and minimum temperature, precipitation), soil physicochemical properties (pH, texture, bulk density, clay content), crop parameters (crop types, sowing and harvesting dates), and field management practices (fertilization frequency, timing, and application rates).

Meteorological data were acquired from China meteorological administration's national ground station data (<https://data.cma.cn/>, daily value dataset of Chinese ground climate data (V3.0)). Soil physicochemical properties were extracted from the harmonized world soil database v1.2 (www.fao.org/land-water/databases-and-software/hwsd/en/) at 1 km × 1 km spatial resolution. Crop spatial distributions for rice (early, late, and single-season), maize, and wheat (spring and winter) were derived from datasets utilized by Li *et al* (2021) and Monfreda *et al* (2008), while growing season parameters were obtained from Zheng (2015).

Nitrogen fertilizer application rates for major crops were sourced from the *National Data on the Cost and Profit of Agricultural Products 2020* (National Development and Reform Commission of China 2020) and standardized to urea nitrogen equivalent referring to the *Fertilizer Pure Amount Conversion Table* (www.moa.gov.cn). Provincial crop planting

areas from the *China Agricultural Yearbook 2020* (National Bureau of Statistics 2020a) were integrated with national fertilizer data to generate nitrogen input distribution maps, subsequently converted to DNDC-compatible formats. For parameters without observational data, DNDC default values were applied to maintain simulation consistency.

2.1.2. Future scenario database configuration

Three representative SSP-RCP scenarios (SSP1-1.9, SSP3-7.0, SSP5-8.5) from CMIP6 were selected to represent sustainable development, current trajectory, and high-emission scenarios, respectively (Meinshausen *et al* 2020). Daily meteorological data for 2030, 2050, and 2060 were extracted from CMIP6 ScenarioMIP (<https://esgf-node.ipsl.upmc.fr/projects/cmip6-ipsi/>) and processed into DNDC-compatible formats (figures S1(a) and (b)). By 2060, projected annual mean temperature increases range from 0.64 °C (SSP1-1.9) to 1.75 °C (SSP5-8.5), with SSP5-8.5 demonstrating substantially higher frequencies of extreme weather events (O'Neill *et al* 2016, Su *et al* 2021). The atmospheric CO₂ concentrations were fixed at the 2019 baseline. This configuration reflects the high complexity and uncertainty of CO₂ fertilization effects (Wang *et al* 2013, 2024, Leakey *et al* 2019), which are generally considered less dominant compared to other factors (Mo *et al* 2017). Moreover, recent findings suggest that actual yield benefits may be limited by nutrient constraints (Ainsworth and Long 2020), thus ensuring a conservative estimation of food security risks.

Nitrogen fertilizer projections were derived from IMAGE3.0 outputs within the AR6 scenarios database (Byers *et al* 2022). Relative to baseline levels, application rates by 2060 are projected to decrease by 2.5% under SSP1-1.9 and increase by 19.3% under SSP5-8.5 (figure S1(c)). For the SSP3-7.0 baseline, rates were assumed constant, consistent with China's zero-fertilizer growth policy implemented since 2015. All other parameters, including soil properties and crop distribution, were held constant to isolate the effects of climate and nitrogen fertilization changes.

2.2. DNDC model validation

The model's performance was evaluated by validating simulated fertilizer-related NH₃ emissions at the field scale and crop yields at the provincial scale against 2019 observations. For fertilizer-related NH₃ emissions, a comprehensive dataset of multiple direct measurements across China's major agricultural regions was obtained from existing literature. Provincial crop yield data were obtained from the *China Statistical Yearbook 2020* (National Bureau of Statistics 2020b).

Model validation demonstrated strong agreement between simulated and observed values. Fertilizer-related NH₃ emissions showed

satisfactory performance with $R^2 = 0.80$ and $RMSE = 8.90 \text{ kg N ha}^{-1}$ (figure S2(a)), while crop yields exhibited excellent correlation with $R^2 = 0.92$ and $RMSE = 2.57 \text{ Tg}$ (figure S2(b)). To validate the robustness of these estimates beyond direct observations, we conducted a comparison with existing literature. Our fertilizer-related NH_3 emissions estimates for the baseline period align closely with previous national inventories (table S1) (Zhang et al 2017, Li et al 2021, Wu et al 2021, Xu et al 2021, 2024). Moreover, regarding future projections, the simulated trends for both crop yields and emissions under climate change scenarios are consistent with recent findings from multi-model ensembles and other independent studies (table S2) (Zhao et al 2017, Xu et al 2021, Li et al 2024b, Jin et al 2025, Zhang et al 2025, Meng et al 2026). These metrics confirm the model's reliability for simulating both fertilizer-related NH_3 emissions and crop productivity.

2.3. Quantifying climate change relative importance under future scenarios

To isolate climate change contributions to fertilizer-related NH_3 emissions and crop yields from nitrogen management effects, factorial simulations were conducted for SSP1-1.9 and SSP5-8.5 scenarios using two experimental designs: (1) future climate conditions with scenario-specific nitrogen application rates, and (2) future climate conditions with nitrogen rates held constant at 2019 levels. This factorial approach enabled decomposition of projected agricultural changes into climate-driven and fertilization-driven components.

Climate change relative importance for fertilizer-related NH_3 emissions (RI_e) and crop yields (RI_y) was quantified as:

$$\text{RI} = \frac{|\Delta_C|}{|\Delta_C| + |\Delta_F|} \times 100\%$$

where Δ_C represents changes attributable solely to climate effects, calculated as the difference between future climate simulations (with constant 2019 nitrogen rates) and baseline 2019 conditions; Δ_F represents changes attributable to nitrogen fertilization modifications, calculated as the difference between full scenario simulations (future climate + scenario nitrogen rates) and climate-only simulations. Absolute values ensure that opposing effects of climate and fertilization changes are appropriately weighted in the relative importance calculation.

This framework strictly partitions driving forces into climatic and fertilization factors; thus, the residual relative importance is attributed exclusively to nitrogen management defined by the specific SSP-RCP scenarios. For SSP3-7.0, where nitrogen application rates remain constant throughout the projection period, all simulated changes are attributed entirely to

climate effects, thus separate quantification was not performed for this scenario.

3. Results

3.1. Fertilizer-related NH_3 emissions and crop yield of China's three major crops in 2019

3.1.1. Aggregate and crop-level characteristics

In 2019, China's three major crops produced a total yield of 618.76 Tg while emitting 3.00 Tg N of fertilizer-related NH_3 . Maize was the dominant contributor to both categories, accounting for 47.0% of total emissions ($1.41 \text{ Tg N yr}^{-1}$) and 46.7% of total yield (289.25 Tg). Rice ranked second (36.7% of emissions; 32.8% of yield), followed by wheat (16.0% of emissions; 20.5% of yield).

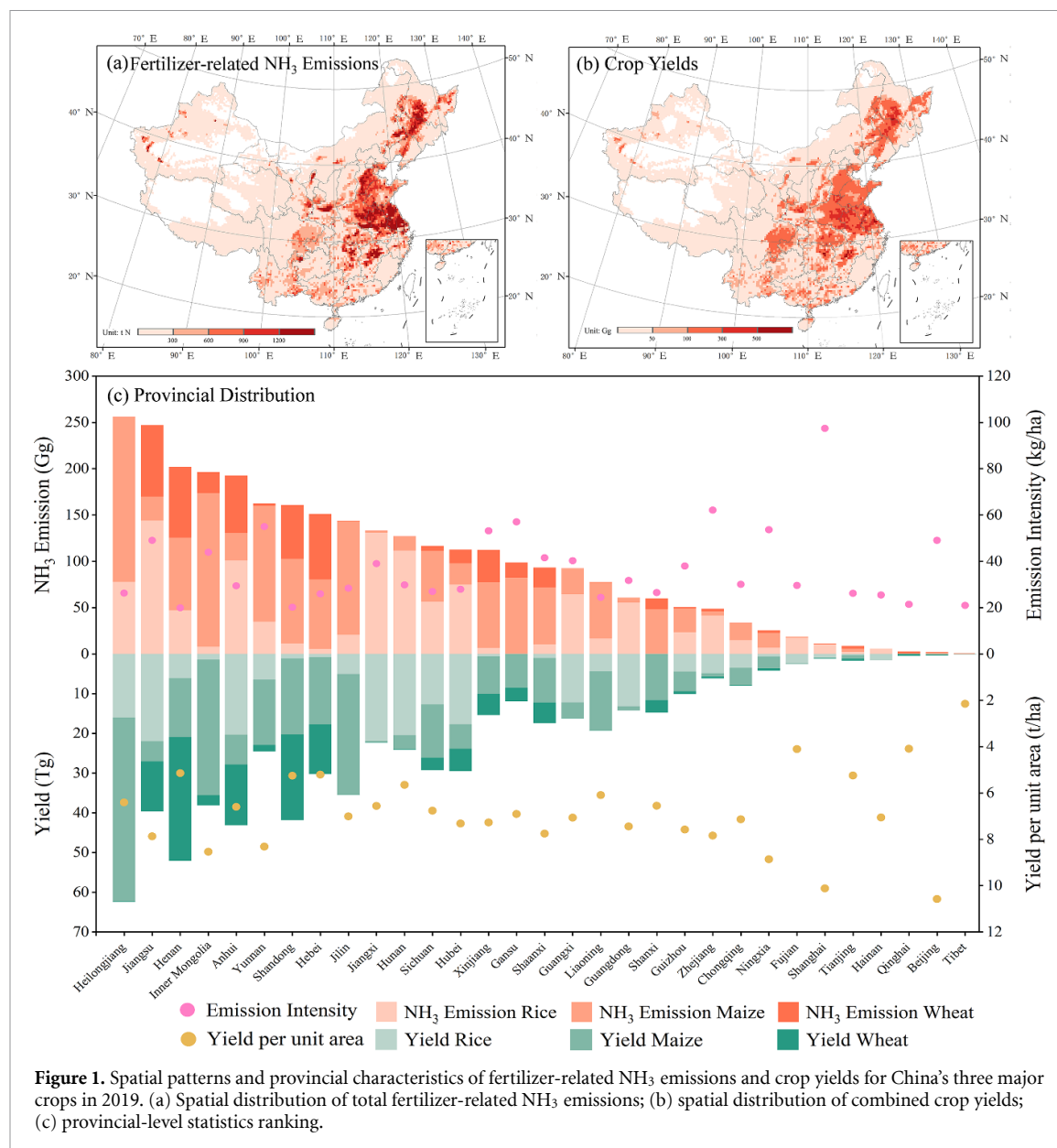
Despite these similar contribution patterns, emission and yield intensities exhibited distinct inter-crop divergences. Rice showed the highest emission intensity ($37.15 \text{ kg N ha}^{-1}$) due to favorable volatilization conditions (Hayashi et al 2006), yet its average yield (6.83 t ha^{-1}) was lower than that of maize. Conversely, maize achieved the highest crop productivity (7.01 t ha^{-1}), benefiting from its superior physiological efficiency (Schmitt and Edwards 1981, Zhou et al 2021), while maintaining a high emission intensity ($34.26 \text{ kg N ha}^{-1}$) driven by concentrated summer fertilization (Yang et al 2015). Wheat exhibited the lowest values for both emission intensity ($20.58 \text{ kg N ha}^{-1}$) and yield (5.35 t ha^{-1}), primarily constrained by heat stress during grain filling (Gong et al 2025).

3.1.2. Spatial and regional distributions

Spatial analysis reveals a high degree of overlap between pollution hotspots and high-productivity zones (figures 1(a) and (b)). Both fertilizer-related NH_3 emissions and crop yields were concentrated in the Northeast Plain, North China Plain, and middle-lower Yangtze River Plain. East China dominated regional statistics, contributing 27.1% of national emissions ($0.81 \text{ Tg N yr}^{-1}$) and 25.4% of crop production (156.95 Tg).

However, a distinct north-south divergence was observed in intensity patterns. Southern China exhibited approximately 25% higher emission intensities than Northern China, consistent with the strong positive correlation between emissions and temperature (Wu et al 2021), whereas Northern China contributed a larger share (55.9%) to the national food supply due to extensive maize and wheat cultivation (figure 1(c)).

At the provincial scale, a strong positive correlation ($r = 0.95$) was identified between total emissions and crop yields (figure 1(c)). Major agricultural provinces such as Heilongjiang, Jiangsu, and Henan recorded the highest absolute values for both metrics, reflecting their extensive cultivated areas. In contrast, municipalities like Shanghai and Beijing



demonstrated the highest intensities for both emissions ($>90 \text{ kg N ha}^{-1}$) and yields ($>10 \text{ t ha}^{-1}$), indicative of intensive management systems characterized by high nitrogen inputs (Xiao *et al* 2021, Chen *et al* 2022).

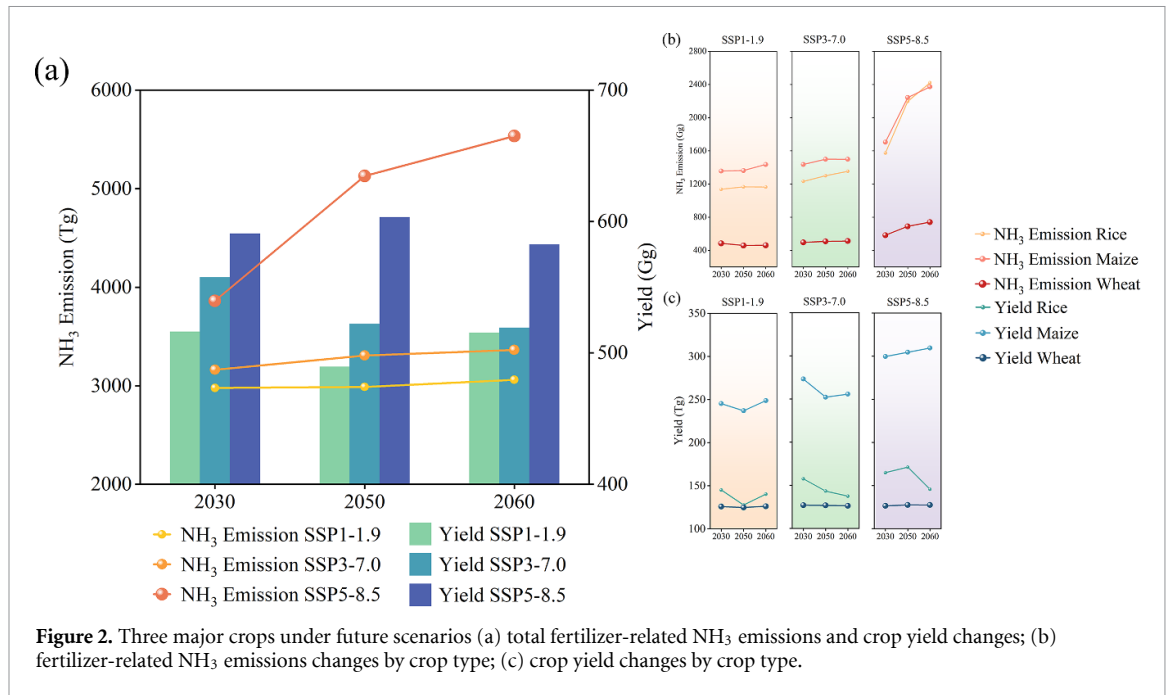
3.2. Fertilizer-related NH₃ emissions and crop yield response of three major crops to future scenarios

3.2.1. Temporal trends and trade-offs

Future projections reveal a widening divergence between environmental and food security outcomes across scenarios (figure 2(a)). By 2060, fertilizer-related NH₃ emissions are projected to increase by 2.0%, 12.0%, and 84.3% under SSP1-1.9, SSP3-7.0, and SSP5-8.5, respectively, relative to 2019 levels. Conversely, crop yields show universal declines, with reductions of 16.7% (SSP1-1.9), 16.1% (SSP3-7.0), and 5.8% (SSP5-8.5).

This divergence highlights a critical trade-off: the high-input SSP5-8.5 pathway mitigates yield losses to 5.8% via intensive fertilization (Ma *et al* 2021) but triggers an exponential surge in emissions (reaching $5.53 \text{ Tg N yr}^{-1}$). In contrast, the sustainable SSP1-1.9 pathway stabilizes emissions ($\sim 3.0 \text{ Tg N yr}^{-1}$) but suffers the largest yield penalty (-16.7%) due to nitrogen reduction exacerbating climate-induced losses.

Drivers of these trends involve complex climate-management interactions. Elevated temperatures generally accelerate volatilization and reduce crop grain filling (Li *et al* 2020, Khan *et al* 2023). Specifically, the $1.75 \text{ }^\circ\text{C}$ warming under SSP5-8.5 contributes a 14.7% emission increase independent of fertilization. Precipitation anomalies also play a role; for instance, the 2050 drought under SSP3-7.0 promotes nitrogen accumulation and subsequent



volatilization (Bintarti *et al* 2025). Among crops, rice exhibits the highest sensitivity to both climate stress and nitrogen inputs (Wang *et al* 2021a), while maize benefits slightly from warming in high latitudes (figures 2(b) and (c)).

3.2.2. Spatial patterns and regional risks

Spatial projections for 2060 demonstrate significant scenario-dependent shifts (figure 3). Under the baseline SSP3-7.0 scenario, fertilizer-related NH₃ emissions and crop yields remain concentrated in traditional agricultural plains (figures 3(a) and (d)). However, comparative analysis relative to this baseline reveals distinct regional differentiation.

In terms of general regional patterns, the sustainable SSP1-1.9 scenario fosters synergistic improvements, particularly in Southern China. Here, cooler climatic conditions effectively alleviate the severe heat stress projected under the baseline, boosting rice yields by 23.5% while maintaining moderate emissions (figures 3(b) and (e)). Conversely, the high-emission SSP5-8.5 scenario presents a stark trade-off between production and environmental quality. While the Northeast and Southwest regions achieve substantial yield gains (>30%) driven by warming benefits for maize and intensified fertilization, this comes at the environmental cost of exponential NH₃ emission surges across all agricultural zones (figures 3(c) and (f)). Furthermore, despite massive fertilizer inputs under SSP5-8.5, major rice-producing areas in the middle-lower Yangtze River Plain experience variable yield losses, indicating that extreme heat stress in this

region overrides the yield-enhancing effects of fertilization.

However, beyond these broad patterns driven by temperature and nitrogen inputs, precipitation heterogeneity exerts a distinct modulating effect on local agricultural outcomes. Our sensitivity analysis, conducted by replacing the projected 2060 SSP1-1.9 precipitation with 2019 baseline data while retaining the 2060 thermal profile, reveals a positive correlation ($r = 0.30$, $P < 0.001$) between precipitation changes and fertilizer-related NH₃ emissions variations at the national scale, suggesting that the promoting effect of moisture-enhanced urea hydrolysis generally outweighs the suppressing effect of leaching in most regions (Zhou *et al* 2016). However, the relatively low coefficient of determination ($R^2 = 0.09$) highlights strong spatial heterogeneity where local hydrological regimes modulate this relationship. Notably, a critical anomaly emerges in central Henan and southern Hebei, where the dominant mechanism shifts. In these regions, precipitation deficits of approximately 30% under SSP1-1.9 and SSP5-8.5 relative to the wetter SSP3-7.0 baseline resulted in a compound penalty characterized by crop yield reductions of 10–20 Gg/grid due to severe water stress alongside a simultaneous increase in fertilizer-related NH₃ emissions. This emission surge under drier conditions is attributed to the alleviation of vertical leaching losses and increased soil air-filled porosity favoring enhanced volatilization (Pan *et al* 2016, Xu *et al* 2021, Sheng *et al* 2025). This contrast confirms that regardless of the emission pathway, regional hydrological limitations can trigger deteriorated outcomes for both crop productivity and pollution control.

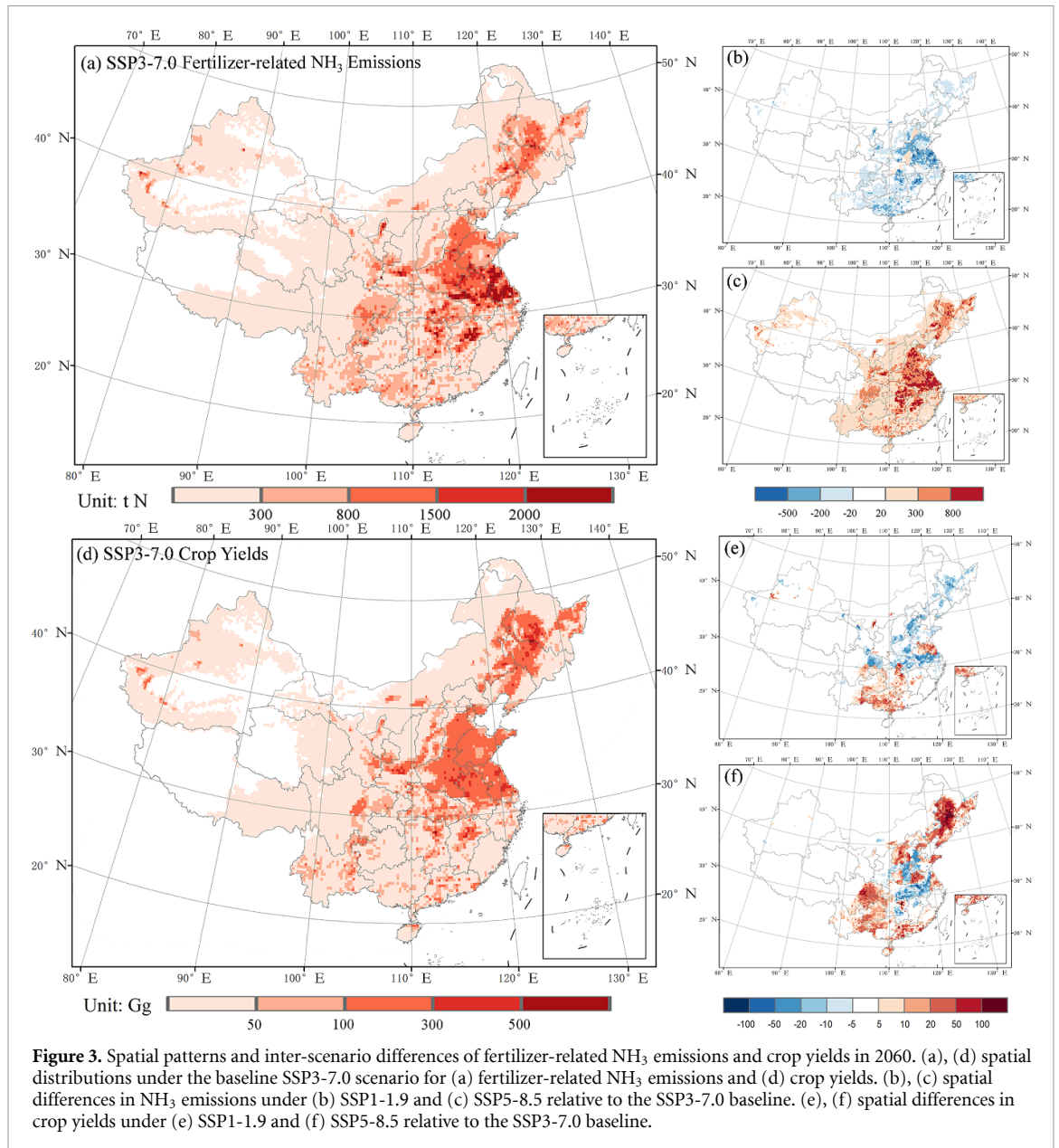


Figure 3. Spatial patterns and inter-scenario differences of fertilizer-related NH_3 emissions and crop yields in 2060. (a), (d) spatial distributions under the baseline SSP3-7.0 scenario for (a) fertilizer-related NH_3 emissions and (d) crop yields. (b), (c) spatial differences in NH_3 emissions under (b) SSP1-1.9 and (c) SSP5-8.5 relative to the SSP3-7.0 baseline. (e), (f) spatial differences in crop yields under (e) SSP1-1.9 and (f) SSP5-8.5 relative to the SSP3-7.0 baseline.

3.3. Quantifying the relative importance (RI) of climate change

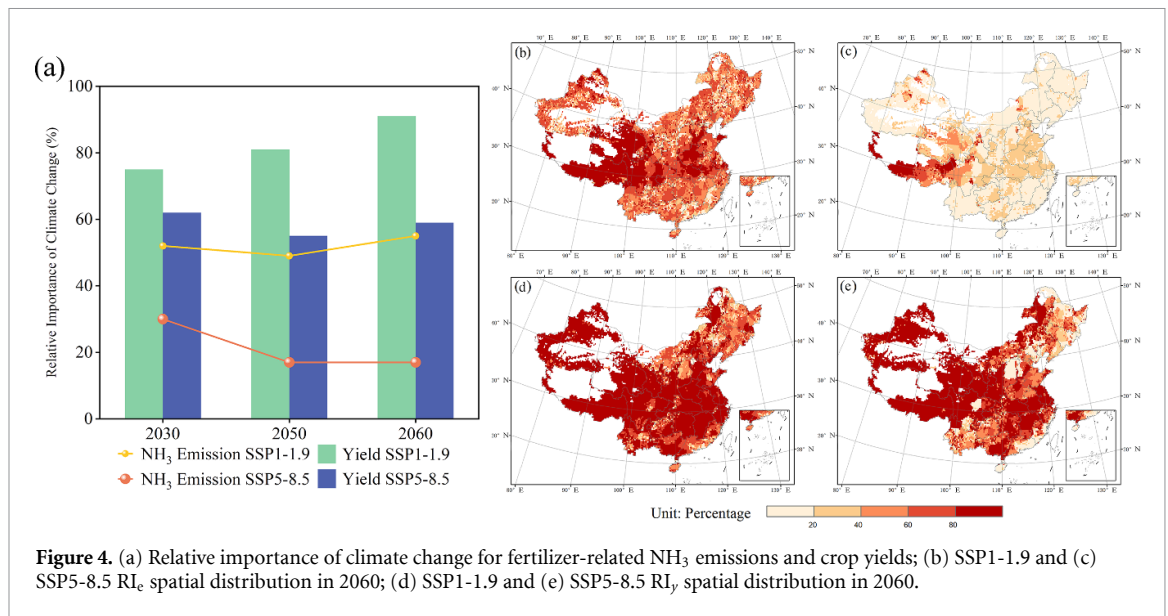
3.3.1. Divergent drivers of emissions and yields

Factorial analysis reveals a fundamental divergence in the driving forces governing environmental versus productivity outcomes (figure 4(a)). For fertilizer-related NH_3 emissions, the relative importance of climate change (RI_e) is highly sensitive to management intensity. Under the sustainable SSP1-1.9 scenario, RI_e maintains approximately 50% throughout the period, indicating a balanced interplay between climate warming and nitrogen reduction policies. Conversely, under the high-input SSP5-8.5 scenario, RI_e drops sharply to 17% by 2060. This confirms that while climate exacerbates volatilization, fertilization intensity remains the dominant control on emission magnitude under high-input pathways.

In stark contrast, crop yield losses are overwhelmingly driven by climatic stress rather than management adjustments. The relative importance of climate for yields (RI_y) consistently exceeds 50% across all scenarios. Under SSP1-1.9, RI_y rises to 91% by 2060, reflecting the inability of reduced nitrogen inputs to buffer against warming. Even under SSP5-8.5, where massive fertilization attempts to compensate for losses, RI_y remains dominant at $\sim 60\%$. This disparity demonstrates that while intensive fertilization can dictate pollution levels (driving $>80\%$ of emission increases), it exhibits diminishing returns in mitigating climate-induced yield gaps.

3.3.2. Spatial consistency of climate sensitivity

Despite the divergence in driving magnitudes, the spatial distributions of climate sensitivity for emissions (RI_e) and yields (RI_y) exhibit strong



consistency (figures 4(b)–(e)). Southwest China records the highest climate contributions for both metrics ($RI > 70\%$ under SSP1-1.9), attributed to the amplification of warming rates in mountainous terrains (Pepin *et al* 2015). Regarding crop productivity, Northwest China exhibits the highest climate contribution, exceeding 90% under both scenarios, indicating that yield losses in this region are almost exclusively driven by climatic stress. This dominance occurs because current nitrogen application rates in the region are already excessive ($273.39 \text{ kg N ha}^{-1}$) (National Development and Reform Commission of China 2020), which saturates crop nitrogen uptake and severely limits the yield-enhancing potential of additional fertilization.

Conversely, Northeast China shows the lowest climate relative importance, reflecting the region's higher latitude where crop physiology is less sensitive to moderate warming compared to tropical zones. South China demonstrates intermediate values, likely due to oceanic thermal regulation moderating extreme temperature fluctuations. This spatial synchronization implies that regions highly vulnerable to climate-driven yield losses are often the same regions where climate plays a significant role in exacerbating pollutant emissions, necessitating spatially targeted adaptation strategies.

4. Conclusions

This study utilized the process-based DNDC model to conduct an integrated assessment of fertilizer-related NH₃ emissions and crop yields in China under future climate and management scenarios. Quantitative projections for 2060 reveal distinct trajectories: under the sustainable SSP1-1.9 scenario, fertilizer-related NH₃ emissions stabilize (increasing only by 2.0%) but crop yields suffer a significant

decline of 16.7% due to reduced nitrogen inputs. The SSP3-7.0 scenario leads to a simultaneous rise in fertilizer-related NH₃ emissions (+12.0%) and decline in crop yields (−16.1%), indicating an inability to adapt to climate stress. Conversely, the high-emission SSP5-8.5 scenario limits crop yield loss to 5.8% through intensified fertilization, but at the cost of a drastic 84.3% surge in NH₃ emissions. Factorial analysis further clarifies that while fertilizer management dictates emission magnitudes, climate change remains the dominant driver (>90%) of crop yield losses across all scenarios.

Admittedly, this study entails uncertainties and limitations as it relies on a single model for simulation. However, our results are consistent with recent multi-model ensembles, demonstrating the robustness of our projections. Additionally, given the high complexity and uncertainty of CO₂ fertilization effects, which are generally considered less dominant compared to other climatic and management factors, the influence of elevated CO₂ concentrations was not explicitly incorporated in this analysis. In future research, we aim to incorporate a broader array of management scenarios and environmental factors to further enhance simulation accuracy and better address the complex challenges of climate change.

Our results indicate a general trend of increased emissions and yield declines across all scenarios, underscoring the urgent need to breed heat-tolerant and drought-resistant varieties to enhance system resilience. Under the high-emission SSP5-8.5 scenario, intensive nitrogen inputs fail to offset yield losses yet result in substantial extra emissions, suggesting decision-makers should prioritize shifting subsidies toward efficiency-enhancing technologies rather than mere production. Conversely, as the sustainable SSP1-1.9 pathway largely offsets the

emission increase induced by climate change, it entails marked yield declines. Navigating this trade-off requires a coordinated policy transformation to deploy advanced agronomic innovations that compensate for these yield gaps, thereby aligning food security with China's 2060 carbon neutrality goal.

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Data availability statement


The data cannot be made publicly available upon publication because they are not available in a format that is sufficiently accessible or reusable by other researchers. The data that support the findings of this study are available upon reasonable request from the authors.


Supplementary Material available at <http://doi.org/10.1088/2515-7647/ae4080/data1>.

Conflict of interest

The authors declare that they have no conflict of interest.

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