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Can the Spatial Planning of Livestock Production Tackle Future Nitrogen Pollution in China?

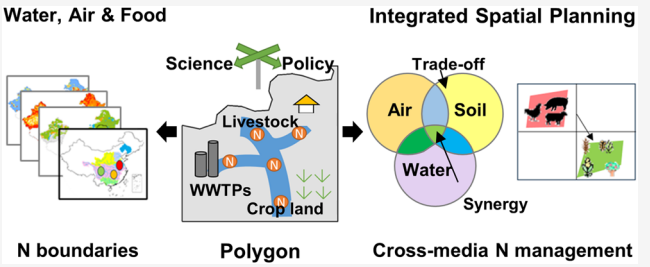
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ABSTRACT: Nitrogen (N) pollution from livestock production significantly threatens China's air and water quality, necessitating innovative solutions to balance food security and environmental sustainability. Studies have mostly overlooked the spatial heterogeneity of N-related environmental impacts and the trade-offs between reducing ammonia (NH_3) emissions and N concentrations in water. This study develops a spatially explicit multiscale model system encompassing 13,000 polygons across China to assess soil N balance, NH_3 emission intensity, and N concentrations in surface water, aiming to explore integrated spatial-planning (SP) strategies that maximize synergy and minimize trade-offs. Our findings reveal that single-purpose SP scenarios (e.g., reducing NH_3 emissions or instream N concentrations) can effectively address one N-related issue but produce substantial trade-offs, leaving >50% of China's population exposed to at least another N-related problem. However, an integrated SP approach could reduce harmful N exposures for 90% of China's population while ensuring food security. This approach involves reallocating 14% of livestock production, reducing livestock numbers by one-third relative to the 2050 baseline, and implementing advanced technologies to mitigate N pollution hotspots. Thus, our findings emphasize the importance of spatially explicit N boundaries and multicriteria planning to tackle N pollution in air and water simultaneously, supporting cross-media N management policy-making and region-specific strategies.



KEYWORDS: *nitrogen, planetary boundary, surface water quality, air quality, food security, spatial planning*

INTRODUCTION

Nitrogen (N) is essential for food security, yet its excess imposes significant pressure on the environment, to the extent that the safe planetary boundary (PB) for N has been exceeded several times.[1,2] Since 1961, China has increased its N use by >40-fold, far exceeding crop demand, to ensure a sufficient food supply for nearly one-fifth of the world's population.[3−5] However, this has rapidly increased ammonia (NH_3) emissions into the atmosphere[6,7] and N losses to watercourses.[8,9] Currently, in China, the exceedance of the PB related to NH_3 emissions,[2,10] and the eutrophication of surface water owing to elevated N concentrations[9,11] is more severe than those in other countries. Although these forms of pollution have slightly improved over the past decade,[12,13] there remains an urgent need to reduce N losses without compromising food security.

Most N losses are attributed to intense crop and livestock production,[4,14,15] particularly in China, where these sectors often operate in isolation rather than in tandem.[16,17] Key mitigation strategies include the implementation of 4R (the right source, rate, time, and place) nutrient stewardship in crop production,[18,19] application of enhanced-efficiency fertilizer,[20,21] improvement of soil[22,23] and manure management,[24,25] and changing of dietary patterns.[26,27] Despite these measures being reported to substantially reduce national N losses, populations and agricultural lands are still considerably exposed to N pollution, compounded by pronounced regional asymmetries between air and water pollution.[2,14,26,28−30] This results from a misalignment between the socioeconomic drivers of N pollution and the inherent spatial heterogeneity of regional biophysical boundaries,[14,15,28] leading to markedly different levels of exceedance in air and water. For instance, in 2012, ∼15% of China's counties accounted for 50% of livestock production in standard livestock units (LUs) and 45% of agriculture-derived N losses,[14] while N concentrations exceeded 1.0 mg L^{-1} (the national surface water quality standard[31]) in 57% of China's rivers,[28,32] many of which flow through regions holding ∼75% of the national population.[28] In 2020, cumulative N losses in China exceeded the national boundaries by 54% for atmospheric N release but by 262% for N runoff to surface

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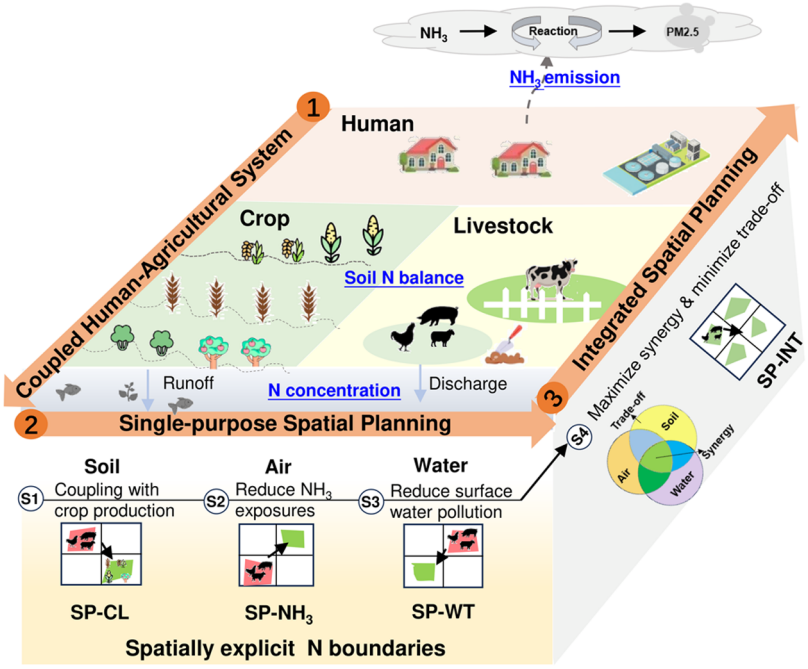


Figure 1. Conceptual framework to reallocate livestock production following spatially explicit nitrogen (N) boundaries. The three-dimensional representation comprises three interconnected surfaces. The first surface (1) delineates the foundational "Coupled Human-Agricultural System," detailing the modeled soil nitrogen balances, N concentrations in surface water, and NH_3 emissions. The second surface (2) illustrates the "Single-purpose Spatial Planning" conducted according to the "Spatially explicit N boundaries" based on thresholds of soil (soil nitrogen balance), air (NH_3 emission intensity), and water (N concentration). The third surface (3) presents the "Integrated Spatial-Planning" (SP-INT) paradigm, designed to simultaneously satisfy all three boundaries. Three single-purpose spatial planning scenarios include spatial planning following regional N boundaries based on NH_3 emission intensity thresholds (SP-NH_3), the crop−livestock integration criterion (SP-CL), and surface water quality thresholds (SP-WT). SP-INT refers to integrated spatial planning based on all three criteria.

water.[30] Studies have shown that neither whole-food-chain nutrient management nor cross-sector technical mitigation can close a gap of this magnitude.[14,30] Consequently, resolving this spatially rooted, cross-media asymmetry demands a shift from uniform mitigation to spatially explicit management that reallocates the dominant N sources to align with the regional biophysical boundaries.

The spatial reallocation of livestock production appears to be more effective than traditional mitigation measures in resolving the heterogeneity problems of N pollution,[14,15,29] especially in China, because livestock is responsible for a major portion of N losses to the environment[10,33] and depends less on climatic conditions, landforms, and feed availability.[15] Bai et al.[15] showed that the reallocation of livestock among counties to meet an NH_3 emission boundary effectively reduced the unequal NH_3 emissions from agriculture by ∼80%; however, this was at the cost of an increased exposure of the population to polluted surface water in China.[34] This outcome is partly due to the differences in regional N boundaries for different N-related pollutions[2] and to one-sided reallocation measures, which reduce NH_3 emissions while leaving the population's exposure to N-polluted surface water unchanged or even higher, thereby hindering the reduction of both simultaneously.[15,34] Moreover, Bai et al.[15] represented water pollution by the county N losses to water, without the hydrology and the instream retention that determine the N concentrations in rivers, so that the conflict between the boundaries for air and water could neither be located nor resolved. More generally, studies on the spatial reallocation of livestock production[15,29,35] lack an understanding of the detailed spatial levels where both agriculture and policy operate and counterfactual effects among the needs for providing sufficient N for crop production, integrating crop−livestock systems, minimizing NH_3 emissions and instream N concentrations simultaneously within associated N-related thresholds, and reducing the majority of the population's exposure to N pollutions. This necessitates both the holistic and region-specific spatial planning (SP) of livestock production following spatially explicit N boundaries to simultaneously meet associated N-related thresholds (Figure 1).

We have developed a spatially explicit multiscale model system that encompasses 13,000 polygon units across China. The model system employs a bottom-up approach to assess the environmental impacts of, and derive spatially explicit N boundaries following associated thresholds for, surface water quality (dissolved inorganic N concentrations), NH_3 emission intensities (agricultural NH_3−N emissions per square kilometer), and soil N balance (N requirements for crop production) for each of the polygons, thereby filling these crucial knowledge gaps. To balance the complex synergies and trade-offs among these N-related indicators, we have also formulated a multicriterion SP approach. Through this integrative model system, our objectives are (1) to gain a comprehensive understanding of the spatially explicit soil N balance, NH_3 emission intensities, and N concentrations in surface water, as well as the synergies and trade-offs among these N-related environmental impacts; and (2) to explore an integrated SP strategy that maximizes synergies and minimizes trade-offs among N-related environmental problems, while reducing the number of people exposed to the risks associated with these three indicators.

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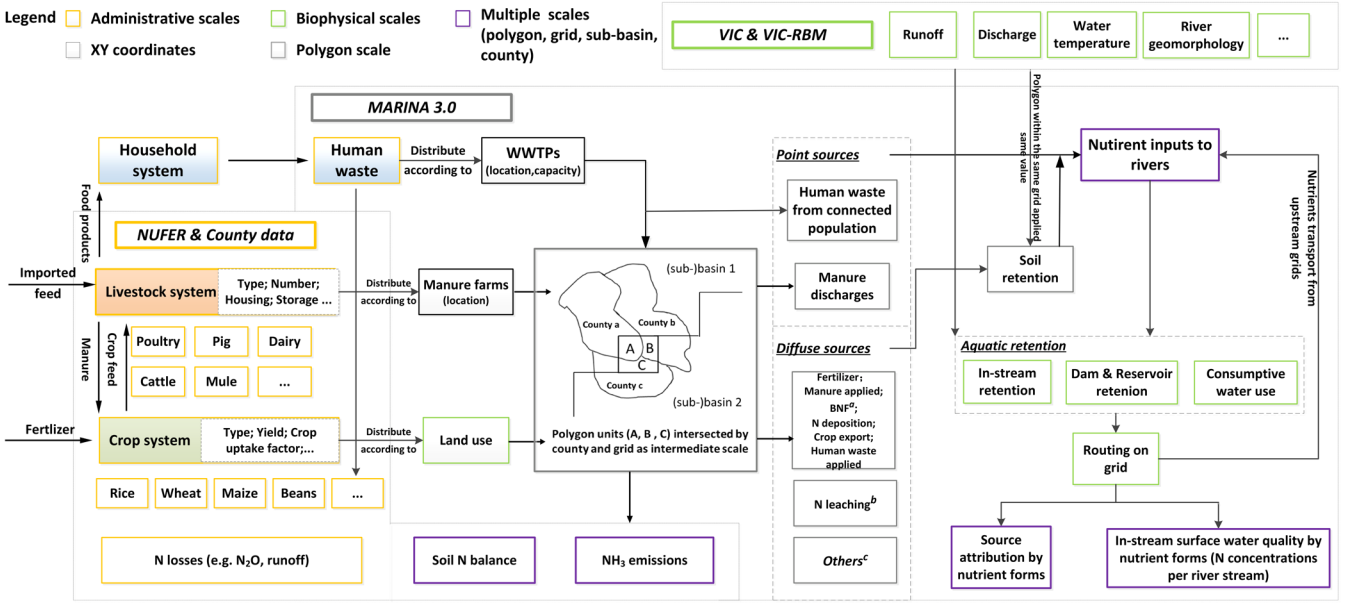


Figure 2. The overview of the multiscale nutrient modeling system. Administrative scales refer to county or provincial scale; Biophysical scales refer to a grid of 0.5° × 0.5°, sub-basin and basin scales; A polygon unit is the intermediate scale of the biophysical and administrative scales, resulting from the intersection of a county and a 0.5° grid. The figure is adapted from Chen et al.[33] and Chen et al.[32] NUFER is short for NUtrient flows in Food chains, Environment and Resources use model.[4,41] VIC-RBM is short for Variable Infiltration Capacity-River Basin Model.[36−38] WWTP is short for wastewater treatment plant. 'Multiple scales' in the legend include polygon, 0.5° grid, (sub)basin, and county. Nutrient forms include dissolved inorganic (DIN, DIP) and dissolved organic (DON, DOP) nitrogen and phosphorus. This paper focuses on the N model outputs. a: This refers to biological N_2 fixation. b: This refers to N leaching of organic matter, which is not applicable for DIN and thus is equal to 0. c: Others include human waste from unconnected populations that is directly discharged to water bodies (without treatment).

MATERIALS AND METHODS

Configuration of the Multiscale Nutrient Modeling System

We constructed a multiscale nutrient modeling system (Figure 2) with three major models, including the NUFER (nutrient flows in food chains, environment, and resource use) model[4,14,15] at the county scale, the MARINA 3.0 (model to assess river inputs of nutrients to seas) model[28,32,33] at the polygon scale, and VIC-RBM (Variable Infiltration Capacity-River Basin Model) hydrological and water temperature models[36−40] on a 0.5 × 0.5° grid scale. The NUFER model depicts the N flows of the whole food chain in China and quantifies the associated NH_3 emissions and soil N balance for over 2300 counties covering over 95% of the total crop and livestock production. The model was developed based on statistical data, field surveys, and literature and was well evaluated at the county, provincial, and national scales. The MARINA 3.0 model simulates instream nutrient concentrations and the associated source attributions for over 13,000 polygons (see below), covering the whole mainland of China by quantifying annual flows of nutrients from land to streams (with agricultural systems linked with NUFER), followed by the retention of nutrients and their transport by the river network. The validation results show that the model results of MARINA 3.0 compare well against existing studies and measurements, both in the river mouths and across 155 monitoring river sections covering the whole of China. The VIC-RBM model is a macro-scale global hydrological and water temperature model that has been widely applied for river basins worldwide and provides the hydrological inputs for MARINA 3.0. A realistic representation of the observed conditions was found for VIC-modeled results, with a normalized bias in the simulated streamflow of <0.25 and a mean bias in water temperature of less than |1 °C| for half the stations worldwide for 1981−2010.[37,38]

The multiscale system employs the multiscale approach of Chen et al.,[32,33] taking polygons as the basic modeling unit and the bridge over different model scales. Polygons are the intermediate scale between the biophysical (0.5 × 0.5° grid) and administrative (county) scales (details in Chen et al.[33]). Chinese counties are at a lower administrative level than cities, and the 0.5° grid is a common scale for global hydrological models. Therefore, the delineated polygons could store and bridge the characteristics (including model inputs, processes, and outputs, e.g., discharge, animal numbers, crop production, and N concentrations) and scales (both biophysical, e.g., grid, and administrative scales, e.g., county) from the above models. For instance, the crop and livestock production inputs and outputs from NUFER at the county scale are downscaled to polygon units based on land use or locations of pollution sources, following the multiscale approach for the hard-linking with MARINA 3.0. The changes in model inputs (e.g., animal number) in SP scenarios resulting from modeled regional N boundaries based on surface water quality thresholds from MARINA 3.0 are quantified at the polygonal scale and converted to the county scale using the above multiscale approach for further quantifying the changes in NH_3 emissions and soil N balance in the NUFER model. The hydrologically modeled results from VIC-RBM for a certain grid are applied to polygons in the grid. The model scheme of the multiscale nutrient modeling system, with illustration of the linkage between the above models (particularly for how polygons bridge different scales), is presented in Figure 2. In this way, the multiscale nutrient modeling system is used to evaluate the environmental impacts (Section S1.2) of and mitigation strategies (Section S1.3) for the anthropogenic alteration of N cycles in China.

Regional N Boundaries Based on N-Related Environmental Thresholds

The spatially explicit regional N boundaries are derived as China's share in the PB using a bottom-up approach based on the N-related environmental thresholds for (1) NH_3 emission intensities of 31 kg NH_3−N ha^{-1} of agricultural land, (2) N concentrations in surface water of 1 mg L^{-1} (to limit eutrophication[2] and meet the surface water quality standard in China[31]), and (3) soil N balance, which is used in two ways: as a constraint (total N input ≥ crop N requirement) to ensure crop production,[15] and as an indicator of the soil N surplus (the ratio of the N applied as synthetic fertilizer and manure to the crop N requirement) to reflect the associated risks of N leaching to groundwater. The NH_3 threshold follows Bai et al.,[15] who set it at the emission intensity that scores 60 (out of 100) on the SDG indicator of NH_3 emissions from agriculture per hectare of agricultural land.[42,43] Zou et al.[30] adopted the

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same value and showed that it corresponds to the secondary $PM_{2.5}$ standard of China's ambient air quality standards.[44] The derived N boundaries are utilized to guide and regulate the SP of livestock production by deriving the required reduction of N inputs from agriculture (e.g., reallocation of livestock amount and reduction of fertilizer applied) to fulfill the associated N boundaries for meeting the N environmental thresholds.

The regional N boundaries for soil N balance and NH_3 emission thresholds and associated required reduction of agriculture-derived N inputs are quantified based on a bottom-up approach for each polygon as follows:

$$RB_{nh,i} = Th_{nh,i} \cdot Area_{agr,i} \quad (1)$$

$$\sigma Nh_i = \sum_{tp=1}^{N} n_{tp,i} \cdot C_{tp,i} - RB_{nh,i} \quad (2)$$

$$RB_{soil,i} = Ic_{N,requirement,i} \quad (3)$$

$$\sigma soil_i = Ic_{manuretofield,i} + Ic_{fertilizer,i} - Ic_{N,requirement,i} \quad (4)$$

where $RB_{nh,i}$ and $RB_{soil,i}$ are the regional boundaries of N for NH_3 emission and soil N balance per polygon (i) (kg yr^{-1}); $Th_{nh,i}$ is the threshold for NH_3 emission intensities of 31 kg NH_3–N ha^{-1} of agricultural land. $Ic_{N,requirement,I}$ is the N requirement for crop production (eq S2, Section S1.2); $Ic_{manure,to,field,i}$ and $Ic_{fertilizer,i}$ are the N in manure and in synthetic fertilizer applied to the land of polygon i (eq S1): the fertilizer N of the county and the manure N of the county that reaches the land after the losses during housing and storage and the direct discharge, both from NUFER and distributed to the polygons with the share of each polygon in the cropland of the county. σNh_i is the required reduction amount of ammonia per polygon in kilograms. When σNh_i is larger than 0, the area should move animals out, and vice versa. N represents the total types of livestock (6 types, which include pig, dairy, poultry, beef cattle, other cattle, and mule and donkey); tp represents the type of livestock (tp with different numbers representing the different animals, ranging from 1 to 6); n is the number of livestock ($n_{tp,i}$ represents the total number for each livestock type per polygon); $C_{tp,i}$ represents the ammonia emission rate in kilograms per capita. $\sigma Soil_i$ is the required reduction amount (or the receiving capacity) of fertilizer and manure applied to land in kilograms. Accordingly, the fertilizer applied will first be reduced and then followed by the manure applied. The changes in manure applied or NH_3 emissions will be converted back to animal numbers based on the quantification processes in the NUFER-county model (partitioning coefficients and emission factors) while keeping the original structure of livestock production of that area. For more details, we refer to Section S1 and Bai et al.[15]

We adapted the bottom-up approach developed by Chen et al.[28] to derive regional N boundaries for surface water quality, which improved the previous studies by accounting for complex responses of N concentration to N inputs to rivers and upstream-to-downstream impacts, i.e., the reductions in upstream parts could compensate for the required reduction of downstream parts. The steps are summarized as follows.

First, the gap of accumulated load (instream load) is quantified, which is the gap between the current instream N concentration per 0.5° grid cell (BAU) and the critical threshold per grid cell (1 mg L^{-1}) by multiplying it with the discharge per grid cell (Step 1). Next, the gap of the accumulated load is routed along the river network with retentions to correct the impact of upstream grid cell reduction on downstream grid cells (Step 2). In this way, we quantify the required reduction of the instream load from local grid cells. Third, we quantify the required reduction of N inputs to rivers of each grid cell by dividing the actual required reduction of instream load per grid cell by the fraction of river export of that grid cell, which incorporates the retention processes in river networks (Step 3). Finally, the current N inputs to rivers per grid cell minus the actual required reduction of N inputs to rivers per grid cell is the regional N boundary based on the surface water threshold for China (Step 4). The associated quantifications of Steps 1–4 are described in detail in Chen et al.[28] More details of the associated changes of model input between 2050 (this study) and 2012 (Chen et al.[28]) are presented in Tables S1–S4.

The associated N boundaries for surface water quality in 2050 using SP scenarios are derived based on the hydrological data (e.g., discharge and water temperature) under RCP 2.6. The differences in model inputs and outputs in RCPs 2.6 and 8.5 are presented in Figures S3–S5 and Section S2.1. In SP scenarios, the required reduction in N inputs to rivers is converted back to changes in fertilizer and manure applied in MARINA 3.0 and further converted back to changes in animal numbers in associated compartments in the NUFER-county model. All the processes are bridged by the developed multiscale nutrient system (polygons).

Scenario Analysis of 2050

BAU. The BAU scenario follows the studies conducted previously by Bai et al.[15] and Zhao et al.,[45] selecting the SSP2 storyline toward 2050, which represents the continuation of current socioeconomic development trends.[46,47] China's total demand for agricultural products such as food and feed is projected to increase by 25% in per-capita calorie demand in 2050 relative to that in 2012, as reported by Zhao et al.[45] The per-capita demand of animal-sourced calories is projected to increase by 45% compared to that in 2012. The increase in food production by 2050 was evenly allocated to each county and polygon according to their share of the total in 2012.[15] The emission of human waste from wastewater treatment plants (WWTPs) is projected to 2050 based on the data from 2012[33] and the associated planning of the Chinese central government.[48] For more details, refer to Section S1.3.

SP of Livestock Production. This section introduces principles following all the SP scenarios, including integrated technology improvement and the multicriterion SP approach. The scenarios are as follows: the recoupling of crop and livestock production (SP-CL), the mitigation of unequal NH_3 emissions (SP-NH_3), the reduction in the N concentration in surface water (SP-WT) to safeguard the interests of most of the population, and the comprehensive SP of livestock production aiming to simultaneously reduce the exposure of most populations to the above N-related pollution (SP-INT). For details on the full procedures in the SP of livestock production under the different aims of SP scenarios, refer to Section S1.3. The procedures of SP-NH_3 and SP-CL follow the rules of Bai et al.,[15] applied here in the multiscale model system; the multiscale model system, the three N-related impacts, and the regional N boundaries are derived bottom-up within one framework; SP-WT and SP-INT are new to this study. The differences from, and the advances relative to, Bai et al.[15] are summarized in Section S2.5.

Integrated Technology Improvement. All the SP scenarios were developed based on the BAU scenario but with significant technological improvements in nutrient management throughout the whole food system. The technologies were specific to three sectors, i.e., crop production, the livestock manure management chain, and food waste and human excreta. The technologies aimed at reducing ammonia emissions and increasing the recycling of manure and human excreta, and food waste. All livestock manure is assumed to be collected and applied to the cropland of the same county, so that the recurring transport of manure stays within the county (Section S1.3). These technologies are implemented in all the SP scenarios through coefficients that differ from those of BAU; details about the key technologies and their effects on N recycling and ammonia emission reduction are presented in Section S1.3, Table S13, and Section S2.4.

Multicriterion SP. We developed the multicriterion approach for SP of livestock production, including: (i) regional N boundaries for meeting N-related environmental thresholds (see above) and ecosystem vulnerability (manure N loading capacity defined as the ratio of manure N excretion to crop N uptake), (ii) sensitivity to socioeconomic indicators (self-sufficiency rates of livestock products defined as the ratio of protein production to protein consumption and shortest transportation distance); and (iii) respecting local situations (keeping the original livestock production structure which reflects the local dietary pattern and cultural religion). For details about the application of this multicriterion approach in each SP scenario, refer to Section S1.3.

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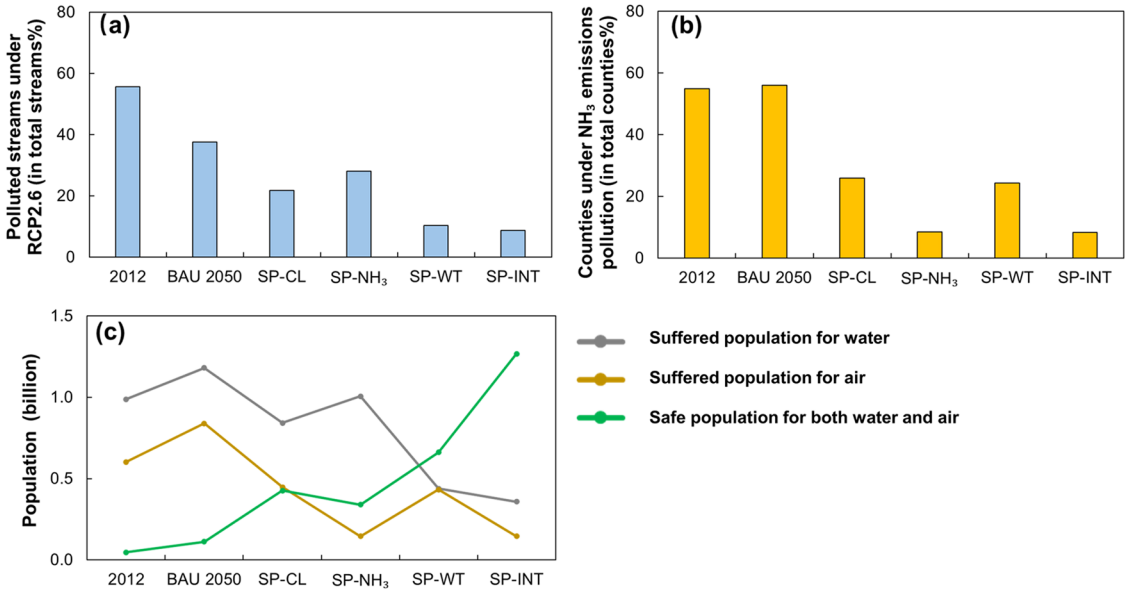


Figure 3. Percentage of polluted areas exceeding N-related thresholds for surface water quality and NH_3 emissions, and the associated affected population. (a) Number of streamlines (derived based on a DDM30 flow direction map[49] on a 0.5° × 0.5° grid) where DIN is >1 mg L^{-1} to the total number of streamlines [Polluted streams (%)]. (b) Counties with NH_3 emission intensity >31 kg NH_3−N ha^{-1} to the total counties [Counties under NH_3 emission pollution (%)]. (c) Population living in areas where water and air quality do not meet the thresholds [Suffered Population for water (billion) and Suffered Population for air (billion)] and population living in areas where water and air quality meet the thresholds [Safe population for water and air (billion)]. Panels (a−c) present results for 2012, 2050, and different spatial planning (SP) scenarios. The total population of China in 2050 is 1.41 billion (Shared Socioeconomic Pathway 2). BAU (Business As Usual) in 2050 follows the Shared Socioeconomic Pathway 2. All SP scenarios are developed based on BAU. SP-NH_3, SP-CL, and SP-WT refer to SP scenarios following regional N boundaries based on NH_3 emission intensity thresholds, the crop−livestock integration criterion, and surface water quality thresholds, respectively. SP-INT refers to the integrated SP based on all three of the above criteria. Results for surface water quality (instream N concentration) presented here are under the Shared Socioeconomic Pathway 2 in combination with RCP 2.6. The associated results for RCP 8.5 are presented in Figures S3−S5.

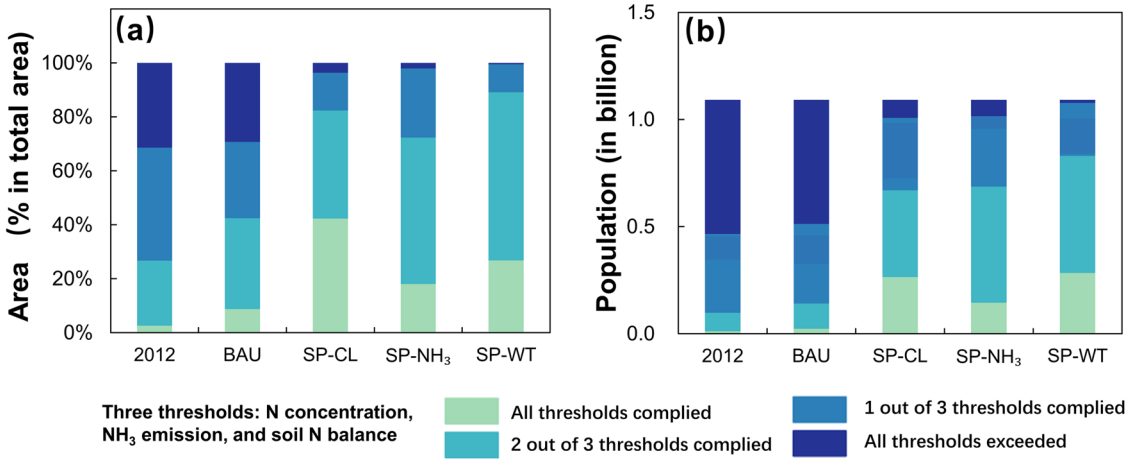


Figure 4. Synergies and trade-offs in environmental compliance with N-related thresholds under different scenarios. (a) The percentage of total area categorized by its compliance with specific nitrogen thresholds. (b) The associated exposed population (in billions). The three N-related thresholds are defined as N concentrations of 1 mg L^{-1}, NH_3 emission intensity of 31 kg NH_3−N ha^{-1}, and a ratio of the applied fertilizer and manure to the crop N requirement of 1. The color gradient represents the cumulative number of thresholds met, ranging from full compliance with all three thresholds (light green), through compliance with one or two thresholds, to the exceedance of all thresholds (dark blue). These intermediate categories can be further disaggregated by specific N thresholds, resulting in a total of eight combinations based on the compliance with or exceedance of each threshold (Figure S9). Results are presented for the 2012 baseline, 2050 Business As Usual (BAU), and single-purpose spatial planning (SP) scenarios. The modeled values of N concentrations, NH_3 emission intensities, and soil N balances are presented in Figures S5 and S6. *Note: For full scenario definitions, see* Figure 3.

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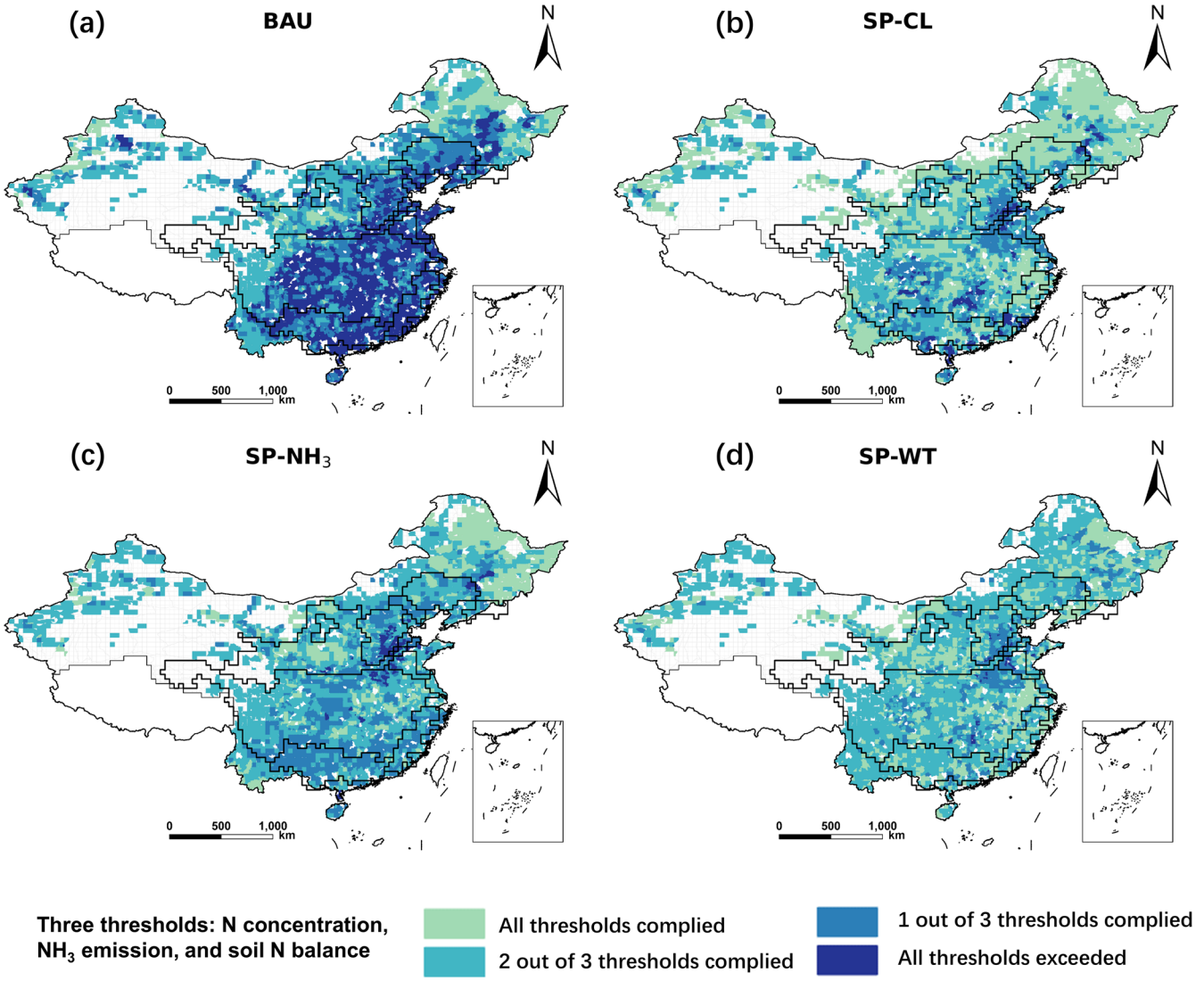


Figure 5. Spatial distribution of the synergies and trade-offs in environmental compliance with N-related thresholds under different scenarios. (a to d) The maps illustrate the spatial patterns of compliance across three N-related thresholds for the (a) Business As Usual (BAU), (b) SP-CL, (c) SP-NH_3, and (d) SP-WT scenarios at the polygon scale. The three N-related thresholds are defined as N concentrations of 1 mg L^{-1}, NH_3 emission intensity of 31 kg NH_3–N ha^{-1}, and a ratio of the applied fertilizer and manure to the crop N requirement of 1. The color gradient represents the cumulative number of thresholds met, ranging from full compliance with all three thresholds (light green), through compliance with one or two thresholds, to the exceedance of all thresholds (dark blue). These intermediate categories can be further disaggregated by specific N thresholds, resulting in a total of eight combinations based on the compliance with or exceedance of each threshold (Figure S10). The polygon is intersected by a 0.5° grid and Chinese counties. The modeled values of N concentrations, NH_3 emission intensities, and soil N balances are presented in Figures S5 and S6. Inset: the South China Sea islands (not modeled). Note: *for the full names of the scenarios, see* Figure 3.

RESULTS AND DISCUSSION

Modeling Spatially Explicit N Pollution and Changes between 2012 and 2050

We modeled multiple impacts of N-related pollution at the polygon level, considering instream dissolved inorganic nitrogen (DIN) concentrations for surface water quality control, NH_3 emission intensities for agricultural sustainability, and the match between regional N availability and requirement reflecting food security. This was done for 13,000 polygon units across China in 2012 and different scenarios projected for 2050 (Figure 3), following the N-related environmental thresholds defined in the Methods. Although Schulte-Uebbing et al.[2] have established a detailed PB for NH_3 emissions to safeguard biodiversity, the achievement of this critical NH_3-derived N deposition target in China presents significant challenges. As demonstrated by the study, maintaining current food production while remaining within the safe operating space suggests a drastic increase in nitrogen use efficiencies to a level that is considered technically infeasible.[2] Therefore, we stick to the SDG-based indicator. To ensure an adequate N supply for crop production, the ratios of the total N supply to the N requirements of crops were set at a minimum of 1.0 (Figure 3). Consequently, because of the priority of food security in China, all the areas complied with this threshold for the N requirements of crops and are thus not shown in Figure 3. Additionally, we employed the ratio of the amount of fertilizer and manure N applied to the N requirements of crops, which was set at a maximum of 1.0. Although other environmental impacts were not explicitly modeled, this ratio can indicate potential environmental impacts

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to prevent N from leaching into groundwater or excess N accumulation in soil (Figures 4 and 5).

The exceedance of N-related thresholds for surface water quality and NH_3 emissions is projected to decrease by ~30% (in the percentage of polluted streams, defined as the number of polluted streams divided by the total number of streams) and remain stable at ~55% (in the percentage of polluted counties, defined as the number of polluted counties divided by the total number of counties) in the Business As Usual (BAU) scenario of 2050 compared to 2012, respectively (Figure 3). Compared to the level of N-derived surface water pollution in 2012, the modestly lower levels in the BAU scenario are attributed to the combined effect of socioeconomic changes, including the effects of multiple policies, such as Zero Fertilizer Action,[50] a ban on the direct discharge of manure and the replacement of fertilizer N by manure N,[51,52] and climate change impacts, such as changes in river retentions (Figure S2). This finding concurs with those in other studies that predict approximately 11−30% declines in DIN river exports between 2012 and 2050.[53,54] The slight changes in NH_3 emissions are also related to the presumed effectiveness of these agricultural policies and measures.[15]

The population living in areas of both unpolluted air and surface water was less than 0.1 billion in China in 2012 (Figure 3). Between 2012 and 2050 (BAU), the areas (at the polygon scale) that meet at least two environmental N thresholds (i.e., areas with synergies) increase from 27 to 42% of the total area (Figure 4). However, the population living in these areas only accounts for 9−13% of the total population, implying that >85% of the total population still lives in areas with trade-offs (i.e., in compliance with, at most, one N-related threshold while others transgress the N-related thresholds) in BAU of 2050 (Figure 4). Even worse, among these 85% of the total population, more than 60% live in areas in compliance with none of the N-related thresholds.

Single-Purpose SP of Livestock toward Universal N Pollution Reduction

We used the BAU scenario to develop three distinct scenarios for mitigating the unequal distribution of N-derived pollution across all 13,000 polygon units by spatially reallocating livestock production following spatially explicit N boundaries. The scenarios are as follows: the recoupling of crop and livestock production (SP-CL), the mitigation of unequal NH_3 emissions (SP-NH_3), and a reduction in the N concentration in surface water (SP-WT) to safeguard the interests of most of the population. To prevent pollution transfer between regions and alleviate the reluctance of regions that would need to increase their livestock production, a consistent and relatively high standard of nutrient management was maintained through technology integration for the crop−livestock production system across all polygon units. This ensured reduced N losses and increased recycling of manure N in agricultural fields. Furthermore, because food security is a top priority for China's central government,[55,56] an adequate N supply was ensured to meet crop requirements in all the developed scenarios.

All the SP scenarios reduced the number of polluted surface water areas, excess NH_3 emissions, and associated exposed populations (Figure 3). Correspondingly, the best performances in reducing the N concentration in surface water and NH_3 emission intensity aligned with the main aims of SP-WT and SP-NH_3. Specifically, SP-WT lowered the number of polluted streams by 73%, and SP-NH_3 lowered the number of counties polluted by excess NH_3 emissions by 85%. SP-CL showed moderate effects on reducing both the N concentrations in surface water and NH_3 emission intensity. In SP-WT, the remaining areas of polluted surface water were highly population-dense, with 10% of the streams accounting for 33% of the total population (Figure S7). On the other hand, in SP-NH_3, the remaining areas polluted by excess NH_3 emissions were attributed to intensive crop production, with 8% of the counties accounting for 20% of the total crop production (Figure S7).

Compared to SP-CL and SP-NH_3, SP-WT was evidently more effective in reducing both water pollution and excess NH_3 emissions; i.e., the safe population under clean water and low NH_3 emission conditions increased by seven times compared to those in the BAU scenario (up to 0.7 billion). However, even in the best-performing single-purpose scenario (SP-WT), ~50% of the total population is expected to live in areas with either high NH_3 emissions or high N concentration levels in surface water. This is because of substantial trade-offs in the control of N losses to water and air among all the single-purpose SP scenarios, with one N-related indicator improving and the other declining by ~65% (in terms of increasing the number of polluted areas) compared to those of the best-performing SP scenarios (e.g., areas of SP-NH_3 polluted streams compared to those of SP-WT polluted streams).

Synergies and Trade-Offs in Reducing N-Related Pollution in Different SP Scenarios

These findings necessitate an improved spatially explicit understanding of synergies and trade-offs (at the polygon scale) among different N-related environmental impacts (Figures 4 and 5). In the BAU scenario, the areas in compliance with at least two environmental N thresholds (i.e., synergies) account for 42% of the total area (i.e., the associated area of the polygons dividing the total area), where 13% of the total population lives. Compared to the BAU scenario, SP-WT and SP-NH_3 could double the number of synergistic areas (>80% of the areas) and approximately quintuple the population living in these areas (approximately 61−76% of the total population) (Figure 4). In the single-purpose SP scenarios, the common synergistic areas are concentrated in Heilongjiang, along the Liao and Yellow Rivers, and upstream and at the delta of the Yangtze River (Figure 5). Correspondingly, in all the single-purpose SP scenarios, the areas where at least two N thresholds were exceeded (i.e., trade-off) accounted for 11% (SP-WT) to 28% (SP-NH_3) of the total area, with 24% (SP-WT) to 39% (SP-CL) of the total population living in these areas. Although SP-CL shows intermediate areas of trade-offs, these areas are relatively population-dense, located in urbanized coastal cities in the southern part of China (Figure 5). In all the single-purpose SP scenarios, common trade-off areas are observed (only the soil N balance could be improved, while the high levels of N concentrations in surface water and NH_3 emissions could not be avoided). Those areas are in the Hai, Huai, and downstream of the Yangtze Basins, with most of the polygons being in Hebei and Shandong Provinces, where intensive crop production is situated. The fulfillment of the N requirements for crop production fails to meet the N reduction required for meeting the critical N value for losses to water and air.

The substantial spatial differences among the synergies and trade-offs of different N-related environmental impacts (Figure 5) lie in the differences in livestock reallocation patterns and the associated transfer number among the different aims of the single-purpose SP scenarios (Figure 6). Such differences are

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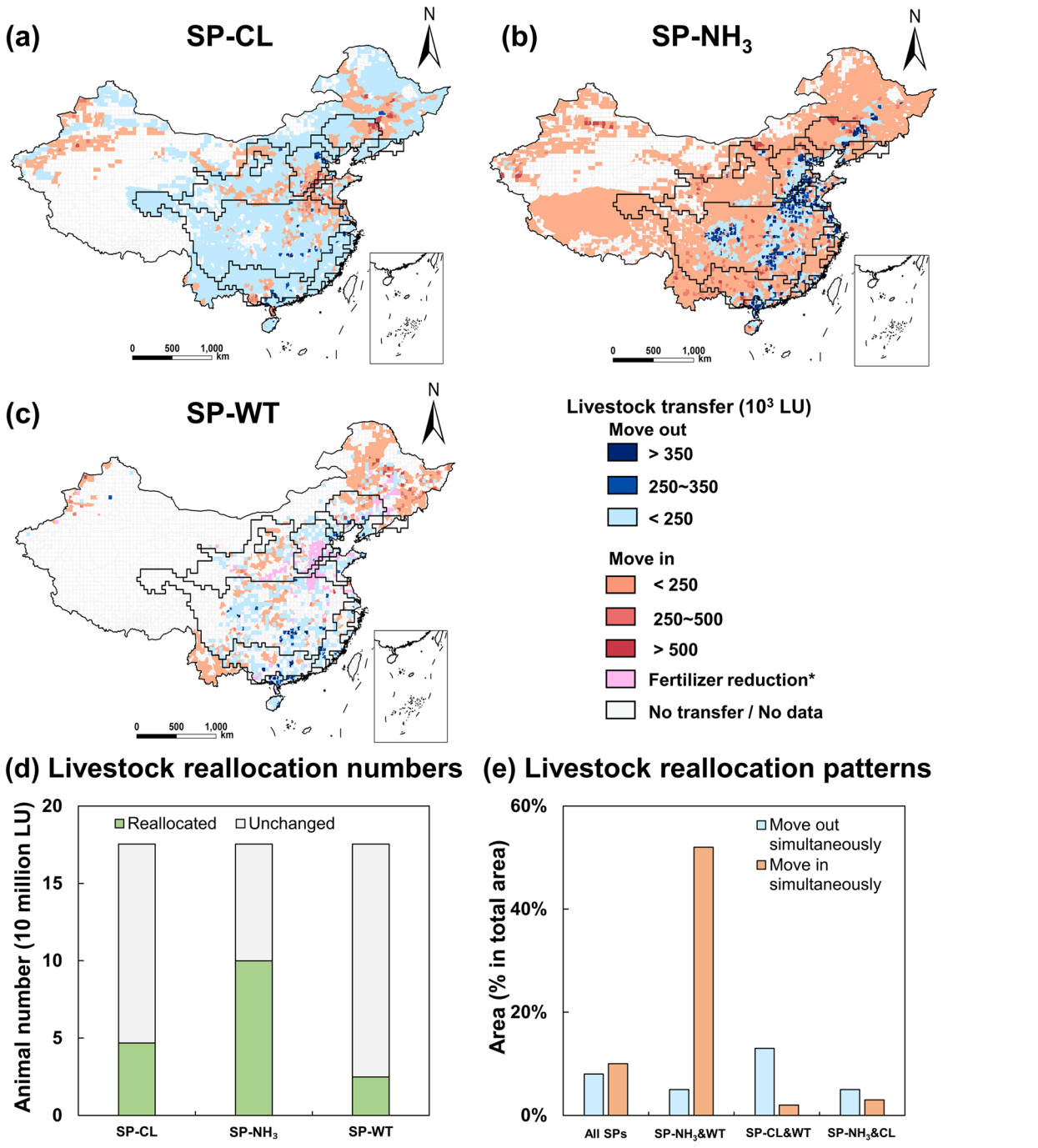


Figure 6. Magnitudes and cross-scenario alignment of livestock reallocation under single-purpose spatial planning (SP) scenarios. (a to c) Spatial distribution of livestock transfer numbers for SP-CL (a), SP-NH_3 (b), and SP-WT (c) in standard livestock units (LU). (d) National-scale livestock reallocation number for each SP scenario. The number of livestock moved out equals the number moved in at the national scale, so that the total livestock stock is conserved in the single-purpose scenarios (Table S12). (e) Synergies and trade-offs in livestock reallocation patterns among different aims of SP scenarios, expressed as the percentage of the total reallocated area. *Synergies* occur in areas with consistent reallocation patterns (i.e., all scenarios necessitate moving livestock in, or all necessitate moving livestock out). *Trade-offs* indicate spatial conflicts where reallocation directions diverge across scenarios (e.g., moving livestock in under one scenario vs moving them out under another). These interscenario alignments resulted in eight mutually exclusive combinations (eight bars). For example, the category "SP-NH_3 and SP-WT move out simultaneously" designates areas where both the SP-NH_3 and SP-WT scenarios require moving-out livestock, whereas the SP-CL scenario requires receiving livestock. This classification logic applies to all eight legend categories. *The pink color denotes areas where compliance with thresholds is achieved solely via fertilizer reduction, thereby requiring no livestock reallocation. Inset: the South China Sea islands (not modeled). Note: *for the full names of scenarios, see* Figure 3.

determined by the gaps in the current livestock-sector-derived N inputs (driven by local factors, such as animal protein demand,[45] dietary preference, and management practices[14]) and the associated regional N boundaries (driven by local factors, such as the river flow direction[28] and crops' N requirements[15]).

The synergistic areas of the livestock reallocation pattern (i.e., livestock production needed to move in or out simultaneously

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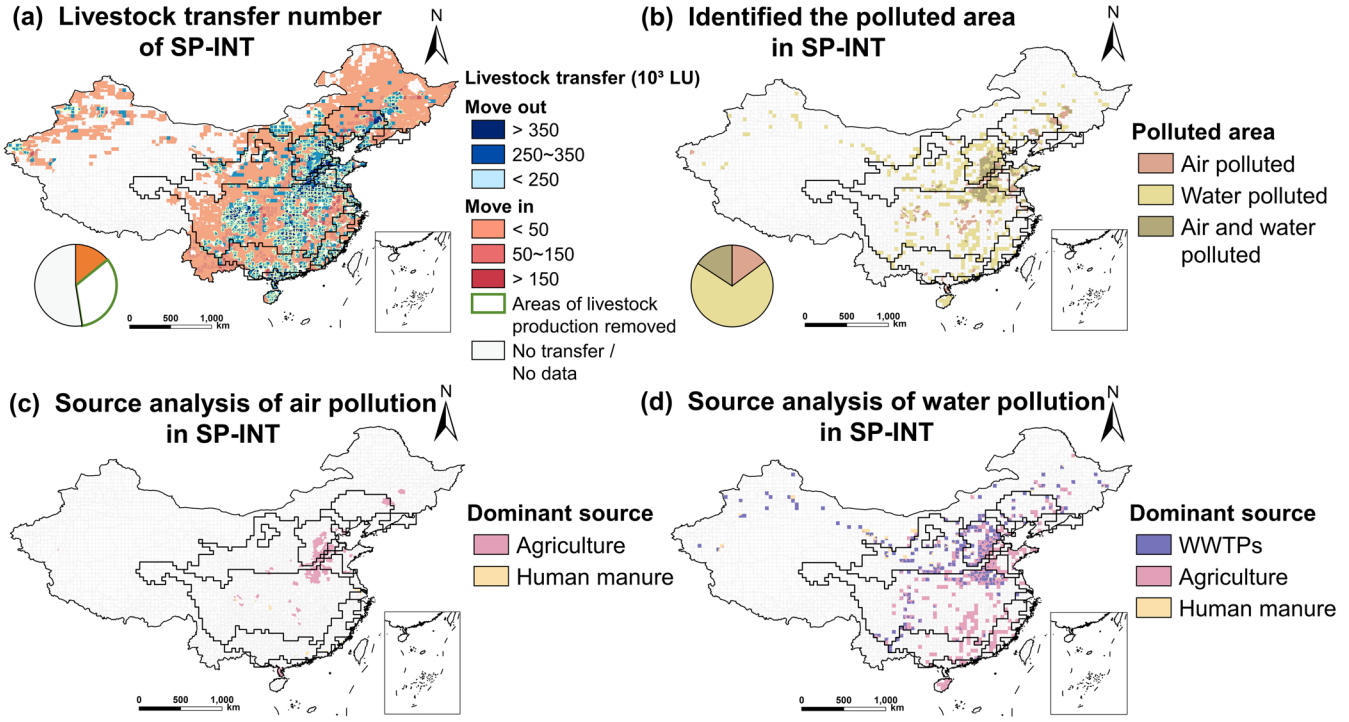


Figure 7. Livestock transfer number, polluted areas, and associated dominant pollution sources in SP-INT. (a) Spatial distribution of livestock transfers (in 10^3 standard livestock units, LU). The inset pie chart shows the proportions of unchanged (52.5%), relocated (14.2%), and removed (33.3%) livestock relative to the total population (Table S12). (b) Distribution of areas experiencing air pollution (NH_3 emission intensity >31 kg NH_3−N ha^{-1}), surface water pollution (instream N concentration >1 mg L^{-1}), or a combination of both. The inset pie chart illustrates the relative shares of each category within the total polluted area. (c, d) The dominant pollution sources contributing to the areas affected by air and water pollution, respectively. SP-INT refers to the integrated spatial planning complied with the regional boundaries of N based on three N thresholds, including NH_3 emission intensity thresholds (31 kg NH_3−N ha^{-1}), surface water quality thresholds (instream N concentrations of 1 mg L^{-1}), and soil N balance thresholds (ratio of the total N input and crop N requirement of 1). Inset: the South China Sea islands (not modeled).

for SP-WT, SP-NH_3, and SP-CL) only account for 18% of the total areas and vary significantly among watersheds (Figure 6). For instance, 11% of the areas in the Yellow River could receive more livestock production (move in) in all the SP scenarios, while in the Yangtze Basin, such areas account for only 2% (Figure S8). On the other hand, in all the single-purpose SP scenarios, more areas in the vicinity of the Yangtze River must move out livestock production than those in the vicinity of the Yellow River (14 vs 2%, respectively), implying that the potential toward a universal reduction in N-related pollution by livestock reallocation varies considerably for each watershed. Among the single-purpose scenarios, substantial areas (~80%) show contradictory livestock movements (Figure 6) and, thus, contradictory impacts (complied with or exceeded) on three N-related thresholds (Figures 4 and 5). For instance, more than 50% of the livestock move-out areas in SP-WT that in SP-NH_3 were identified as livestock move-in areas. This particularly holds for the Hai Basin, where areas showing contradictory movements (in and out) between SP-WT and SP-NH_3 are ~15% higher than the national average (Figure S8). This leads to further exceedance of the N threshold for surface water quality in these areas in SP-NH_3 or further exceedance of the NH_3 emission intensity threshold in SP-WT.

Additionally, the associated required livestock transfer number varies among the single-purpose SP scenarios. The spatially explicit livestock transfer number indicates that the reallocation of livestock required in SP-WT is much lower than that required in SP-NH_3, i.e., the achievement of 90% of the areas possessing acceptable NH_3 emission intensities in SP-NH_3 and acceptable N concentrations in surface water in SP-WT required the reallocation of 10 and 2.5 billion animals (mainly as broilers and layers) in China, respectively. This is because of the improved approach we used to derive spatially explicit N boundaries. Compared to other global studies using national or provincial inputs,[2] our study used localized county-scale input data and coefficients from the NUFER-county model[14,15] for regional NH_3 emission boundaries. For regional boundaries of N-derived surface water pollution, we used the bottom-up approach, which accounts for upstream-to-downstream impacts,[28] i.e., reductions in upstream pollution could compensate for required reductions in downstream pollution, thereby lowering the required reductions compared to those in other studies using a simplified approach neglecting the complex response of N concentrations to N inputs in rivers.[2,9] Additionally, in SP scenarios, wastewater treatment plants constructed using improved treatment technologies[33,53] could further reduce N inputs to rivers without affecting NH_3 emissions from agriculture.

Integrative SP to Reduce N-Related Problems for Most of the Population

In the single-purpose SP scenarios, significant population exposures remain to one or more N-related problems. This spatially explicit analysis necessitates integrated SP strategies that consider the combined effects of livestock reallocation patterns toward meeting all three N-related thresholds and the associated required livestock transfer number. We developed an integrative SP of livestock production combined with extra intensified state-of-the-art measures targeting dominant sources

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of hotspots of N pollution regions (SP-INT). SP-INT aims to maximize the synergies and minimize trade-offs in a spatially explicit way among the surface water quality of N, NH_3 emission intensities, and soil N balance to keep the majority of the population living in regions devoid of these problems (Figure 7). Under the condition that the soil N balance is ensured for all areas because of the priority of food production, the procedures of SP-INT are as follows: In areas where synergies exist in livestock reallocation patterns between controlling N losses to water and air (i.e., where livestock production must be moved in or out simultaneously), the associated reallocation strategies are designed to maximize the required number of livestock moved out while minimizing the capacity for receiving livestock. On the other hand, in the areas with trade-offs (i.e., where contradictory livestock movement occurs between controlling N losses to air and water), the required number of livestock must still be moved out, aiming to keep N losses to water and air within the limits, and ban these areas from receiving extra livestock production. This results in the excess of the required move-out livestock number over the capacity of receiving livestock number, suggesting the need to reduce livestock production (without reallocation) in China.

These results indicate that a 33% reduction in China's livestock (in LU) compared to BAU is needed to achieve 1.3 billion safe population in regions with surface water N concentrations and NH_3 emission intensity within the requirement, and no sacrifice of food security (Figures 3, 7a, and S11). This equals 197 million LU and ∼11 Tg of manure N excretions. The areas where livestock production must be reduced (without reallocation) are mostly distributed in Hebei, Shandong, Hunan, and Sichuan Provinces. The reallocation and reduction of livestock production still results in ∼10% of areas suffering either from too much N in water or emitted to the air (Figure 7b). With the dominant sources identified in the hotspot of N pollution regions, the source-specific extra measures targeting improved surface water quality are applied, including riparian buffer zones, filter strips for agriculture, and advanced wastewater treatment technologies for human waste (Table S7), to achieve a further increase of 0.3 billion population living in areas with clean water (thus, in total, 1.3 billion safe population). On the other hand, the areas characterized by high NH_3 emissions dominated by crop production continue to surpass environmental thresholds even after implementing the most advanced available abatement technologies in SP-INT. These areas account for 3% of the total area and contribute to 18% of total crop production. The innovative strategies, besides technology improvements, must be considered, including the reallocation of crop production in these areas (considering potential constraints such as water resources and climate conditions)[57] or changes toward a more sustainable diet with the selection of lower-emission food categories.[58]

Maintaining our core focus on resolving the cross-media asymmetry between water and air N pollution, N_2O (a global climate forcer), NO_x (driven largely by atmospheric chemistry), and N leaching to groundwater were not spatial optimization targets of SP-INT (justifications in Section S2.2), but we assessed the effects of SP-INT on them to verify that it does not create unintended cross-media trade-offs. Based on the source-based N flows of NUFER[14,15] and the associated emission factors (Tables S8−S10), SP-INT reduces the agricultural N_2O emissions by 20% and the NO_x emissions by 27% relative to BAU (Section S2.2, Table S11); the localized NO_x increases in livestock-receiving areas (median +15%) are buffered by their high environmental carrying capacity, as the reduced synthetic fertilizer offsets the additional manure (median change of the total N input − 4%; Figure S12). Groundwater N was not used as a regional boundary because its exceedance areas largely overlap with those of the stricter surface water boundary[2,30] and polygon-scale data for a groundwater boundary are not yet available (Section S2.2). Nevertheless, SP-INT does not shift N pollution to groundwater: the land area where the applied N exceeds the crop N requirement decreases from 77% in BAU to 58% and the N leaching by 26%, with an aggregate increase of 5% in part of the receiving areas (Section S2.2, Tables S14 and S15). Where groundwater is already severely polluted,[2,59] as in parts of Northeast China, the receiving capacity may be lower than the surface water boundary implies, and a groundwater boundary should be added when regional data and methods mature.[30,59]

Our findings concur with those of previous studies, which indicate that maintaining clean surface water, low NH_3 emissions, and sufficient food for most of China is only possible when strategies that increase N use efficiencies (NUEs) via integrated technologies, dietary shifts, and the spatial reallocation of food production are combined[2,9,28,29] (Section S2.1, Table S13). The national average NUEs must increase up to 68% for crop production in the SP-INT scenario, which is reasonable compared with the findings of other studies (NUEs from 60 to 90%).[2,9,29] A bridge of 75%−85% of the gap between the current and recommended diets, combined with 11% of reallocation of national total food production (with 14% for livestock production), was suggested to maintain food production within the regional N boundaries in China.[29] Our SP-INT modeled an ∼14% reallocation of national livestock production without reallocating crop production. The one-third reduction in livestock production in SP-INT also aligned with these findings, closing the gap between the current and recommended diets of animal products by ∼80%.[60] Complementary to previous studies on the SP of food production,[15,29,35] we presented the livestock transfer patterns on more detailed spatial levels where agriculture and policy operated (e.g., polygon vs province) while respecting the original livestock production structures, local diets (e.g., influenced by religion), and the spatially explicit N boundaries derived by an improved bottom-up approach.

Environmental Implications beyond N Management

The proposed N-focused integrated management scenario could produce both synergies and trade-offs related to other environmental impacts,[61] through the following three elements. (i) The technological improvements in nutrient management throughout the whole food system[14,15] have been reported to reduce agriculture-derived methane[62,63] and CO_2 emissions[29,64,65] by 6−55%, and phosphorus (P) losses from food production to the environment by up to 90%.[14,29] (ii) Reallocating livestock according to the regional N boundaries moves the sources rather than their total: global impacts that depend only on the total emissions (e.g., climate change) are essentially unchanged, whereas regional impacts that depend on the location of the emissions move with the livestock. Take P pollution as an example. Areas identified as receiving areas by the N thresholds could be move-out areas according to the associated P thresholds, implying the need for increased livestock relocation from these sensitive areas, coupled with a lower capacity of the receiving areas and ultimately a greater net decrease in the total livestock population. On the other hand, N

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and P pollution in aquatic systems largely share their dominant sources (e.g., agriculture and WWTPs) and the location of their hotspots,[4,32,66] so that reallocation strategies designed to meet both N and P thresholds would be synergistic across extensive areas. (iii) The one-third reduction in the number of livestock raised (without extra imports), which could be interpreted as a dietary change closing ~80% of the gap between the current and recommended diets of animal products,[60] would also reduce the associated GHG emissions by approximately 18−57%.[58] Although not explicitly included in our model system, this reduction would lower the livestock feed required and thus the arable land and the freshwater use, as the vast majority of the livestock-related freshwater use is for feed production, whereas only ~2% is for drinking and servicing.[67]

Our evaluation suggests that the proposed integrated management scenario presents a favorable balance of cobenefits beyond N reduction against its trade-offs. The latter implies a decrease in regions suitable for receiving livestock and an elevated need for moving-out livestock, reducing the net livestock population (without relocation); the explicit inclusion of the feedbacks (e.g., land-use and dietary changes) is recommended for future research (see Section S2.3 for extended discussions).

Policy Implications

The findings of this study reveal the importance of cross-media N management approaches that address the interconnection of N pollution in air and water while ensuring sufficient N input to soil for food production. Current policies in China largely focus on single media,[68−70] and our results suggest that such approaches risk unintended trade-offs. The south-to-north transfer of pig production,[71,72] for instance, can be read as a one-sided policy that reduced surface water pollution at the expense of population exposure to harmful NH_3 emissions.[15,30] Our results help avoid such trade-offs and contribute to existing environmental and spatial planning policies in two ways. To the single-medium environmental policies (the action plans for water, air, and soil[68−70,73]), our contribution is the cross-media perspective: the cross-media regional N boundaries are defined consistently within one framework, so that a measure for one medium could be checked against others, with technology improvement first and spatial planning second (Table S13). To the policy precedents of spatial planning,[71,74−76] our multiscale framework provides targets at the multiple scales at which they are implemented: the polygon-level capacities and reductions can be aggregated to the counties that implement livestock limits and pig-capacity targets,[75] and to the basins of the River Chief System,[77] whose river chiefs and county governments could set county targets in line with their share in the basin's N pollution.

The reallocation scenarios presented here should, however, be interpreted as the biophysical potential under the modeled agronomic and environmental constraints, rather than as a blueprint for immediate large-scale relocation. Closing the gap between this potential and implementable policy plans requires local validation, stakeholder involvement, sequenced instruments, and monitoring. China's large livestock concentrations and strong central governance favor such spatial planning,[15] on the condition that its criteria, principles and procedures are clear and consistent across the media. To translate this potential into feasible regional actions, we propose a three-phase portfolio of policy instruments (detailed in Section S2.6 of the SI). The first phase would prioritize the counties where our integrated scenario requires livestock to be moved out or removed (Figure 7), validate the county-level configuration with local data and stakeholders,[74,78] and lower the livestock density gradually through density caps, permitting and zoning, natural production turnover and compensated buy-outs,[79] rather than by directly relocating existing farms. The second phase would identify suitable receiving counties, first within the same province,[74] that meet the three N boundaries and the requirements of feed, water, labor, disease control, market access and economic viability,[74,80] equip them with manure treatment and nutrient recovery infrastructure,[14,81] and support them through subsidies, nutrient trading,[82] and ecological compensation linked to the quantified cross-media benefit,[18,80,83] with public participation;[82,84] interprovincial reallocation would be reserved for the residual capacity. The third phase would make the implementation adaptive: cross-media field studies, monitoring, and stakeholder surveys in the receiving and the moving-out areas, before and after the adjustment,[71,72,74] would be used to revalidate the boundaries, reset the priorities, and determine whether additional measures are needed.

Uncertainties, Limitations and Outlook

Our study entails the following uncertainties and limitations, which need future improvements (extended in Section S2.4). First, the uncertainties in the inputs and parameters of the three models, in the thresholds and in the scenario rules could propagate along the model chain to the key outputs (Table S16). Our uncertainty analysis suggests that the model and the main conclusions are robust: the elementary effects are below 1 in 43 of 48 cases, and of the 39 combinations of 13 factors and three outputs, 21 rank low, nine medium, and six high. The largest contributors are the NH_3 emission factors and the crop N uptake (NH_3 emission), the N uptake velocity in rivers and the hydrological bias (DIN concentration), and the livestock numbers and N excretion (reallocation), whereas the downscaling to polygons and the climate forcing rank low, although an inventory of industrialized farms with animal numbers and locations could further improve the spatially explicit reallocation.[85] The thresholds are the only source that ranks high for all three outputs. Across the 12 threshold combinations, the population safe from both water and air N pollution ranges from 0.47 to 1.34 billion under SP-INT (1.0 billion reported). The thresholds are, however, choices of the environmental target rather than model errors,[1,2,30] and the trade-offs among the single-purpose scenarios (79−85% of the reallocated area with contradictory movements, 81% reported) and the need to both reallocate and reduce livestock (at least 23%) hold for all 12 threshold combinations. Additionally, the species composition of livestock could change with the relocation; if the species of the removed livestock were free within each county, the reduction would be 28−38% instead of 33% (Table S16).

Second, several processes are not included in our model system and should be addressed in future research (Section S2.4): industrial discharges (about 5% of the N discharged to water bodies in China[86]), which matter downstream of industrial clusters; the feedback of N concentrations and algal biomass on instream retention; the costs of the relocation of livestock and the farm-level logistics of manure recycling within counties; the domestic migration of the population; and the rule-based design of SP-INT, for which a formal multiobjective optimization with stakeholder-defined weights and constraints is recommended. Finally, the principle of this framework can be applied to other regions confronted with cross-media N pollution: modeling on intermediate units between the

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biophysical and the administrative scales, for which cross-media impacts and boundaries are derived together, so that the trade-offs can be located and quantified. The main challenge is the availability of subnational input data (e.g., crop and livestock production, hydrology and local emission factors) and local monitoring data, without which the trade-offs cannot be located at that scale, and the model cannot be evaluated.

While acknowledging the defined system boundaries, our study establishes a novel framework to simultaneously mitigate air and water pollution without compromising national food security. The key novelties (extensive discussions in Section S2.5) are that single-medium regional N boundaries are not additive and that their conflicts appear only at the scale at which the sources are managed; resolving the asymmetry therefore requires aligning the dominant sources with the multiple spatially explicit boundaries simultaneously, rather than optimizing one medium at a time.

■ ASSOCIATED CONTENT

Data Availability Statement

All data and code needed to evaluate and reproduce the results in the paper are present in the paper and/or the Supporting Information. This study did not produce new materials.

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.6c11284.

Descriptions of the multiscale nutrient modeling system (NUFER, MARINA 3.0 and VIC-RBM), the quantification of the three N-related environmental impacts and regional N boundaries, and the scenarios with their model inputs; supplementary discussion of N concentrations under RCP 2.6 and RCP 8.5 and of technology improvement versus spatial planning, effects of SP-INT on N_2O and NO_x emissions and N leaching to groundwater, synergies, and trade-offs with other environmental impacts, uncertainty and sensitivity analyses along the model chain, novelties relative to previous studies, and a three-phase portfolio of policy instruments; Figures S1−S12 (basins, model inputs and results) and Tables S1−S21 (model inputs and sources, scenario settings, emission factors, livestock balances, model results and uncertainty analysis, comparison with previous work) (PDF)

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Notes

The authors declare no competing financial interest.

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