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Potential Reductions in the Environmental Impacts of Agricultural Production in Hubei Province, China

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Abstract: Quantifying potential reductions in environmental impacts for multi-crop agricultural production is important for the development of environmentally friendly agricultural systems. To analyze the spatial differences in the potential reduction in nitrogen (N) use, we provided a framework that comprehensively assesses the potential of improving N use efficiency (NUE) and mitigating environmental impacts in Hubei Province, China, for multiple crops including rice, wheat, maize, tea, fruits, and vegetables, by considering N and its environmental indicators. This framework considers various sources such as organic N fertilizers and synthetic fertilizers, along with their respective environmental indicators. We designed different scenarios assuming varying degrees of improvement in the NUE for cities with a low NUE. By calculating the N rate, N surplus, N leaching, and greenhouse gas (GHG) emissions under different scenarios, we quantified the environmental mitigation potential of each crop during the production process. The results showed that when the NUE of each crop reached the average level in Hubei Province, the improvement in environmental emissions is favorable compared to other scenarios. The N rate, N surplus, N leaching, and GHG emissions of grain (cash) crops could be reduced by 25.87% (41.26%), 36.07% (38.90%), 49.47% (36.14%), and 51.52% (41.67%), respectively. Overall, improving the NUE in cash crops will result in a greater proportionate reduction in environmental impacts than that in grain crops, but grain crops will reduce the total amount of GHG emissions. Our method provides a robust measure to assess the reduction potential of N pollution and GHG emissions in multi-crop production systems.

Keywords: N rate; NUE; N surplus; GHG emissions; crop production

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1. Introduction

A growing population and increasing consumption are placing unprecedented demands on agriculture and natural resources [1]. With a growing middle class and increasing urbanization [2], there is a rising demand for higher-quality and diverse food products. This leads to increased pressure on agricultural production to meet the needs of the population, which in turn drives the use of N fertilizers to boost crop yields [3]. However, due to the limitations of farmers' education levels and technical equipment [4], a large amount of fertilizer is still applied irrationally in China. This not only fails to bring a corresponding increase in yield, but also puts a heavy burden on the natural environment.

The concern over reducing environmental pollution caused by excessive nitrogen (N) fertilizer application, while ensuring yield sustainability, has grown [5]. Previous studies have shown that more than half of the N input from agricultural fields enters the atmosphere and water bodies, leading to serious issues such as air pollution, water pollution, soil acidification, climate change, stratospheric ozone depletion, and biodiversity loss [6,7]. Studies estimate that improved N management (INM) on croplands could reduce cropland N discharge from the current level of 5.1 ± 0.3 Mt N yr^{-1} (2010–2014 average) to 2.8–3.0 Mt N yr^{-1} (this range encompasses both the controlled release and the broad application of fertilizer scenarios) [8]. It is estimated that about 6 Gt of N enters the river basins of the Yangtze River in the form of dissolved inorganic N (DIN), half of which comes from the production of monoculture rice, wheat, and vegetables, where synthetic fertilizers are widely used [9].

A lot of research and experimentation have been performed to put N fertilizer into the soil with precision, such as 4R management (right type of fertilizer, right amount of fertilizer, right place, and right time) [10]. In addition, field experiments [11,12] are widely used to determine reasonable N application rates for grain crops. However, these field assessments are time-consuming and labor-intensive and are not suitable for assessment work in large regions. Yin et al. conducted an optimization assessment of agricultural N use for the whole of China to estimate the optimal N rate for maize, rice, and wheat from 27,476 on-farm year-site trials [13]. While the above results provide macro-level trend guidance at the national level [14–16], further detailed studies are needed to address the specificities at the municipal or county scale. Although some scholars have used agricultural models such as Denitrification–Decomposition (DNDC) (Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, USA) and decision support systems for agrotechnology (DSSAT) (USA) to simulate N use in some grain crops, the spatial heterogeneity of the environmental impacts of cash crops has been neglected. We found that the total N applied to cash crops is increasing year by year, even though the area of cash crops is less than that of grain crops. Moreover, cash crops are often over-fertilized and this should be also taken into account [17].

Hubei Province is a major grain province in the Yangtze River Basin of China. It produces 4.2% of China's grain on only 3.9% of China's arable land and consumes 6.8% of China's total fertilizer [18]. Therefore, Hubei Province was selected as the study area to explore the potential of N emission reductions to reduce N pollution in the Yangtze River Basin in China [19]. In this study, we selected three grain crops and three cash crops, considered multiple sources of N (organic and synthetic fertilizers, etc.), and systematically assessed N use and the environmental impacts of different types of crops. Based on the current situation of agricultural production and N fertilizer utilization in each city in Hubei Province in 2020, we set up scenarios for cash crops and grain crops. By calculating the N rate, N surplus, N loss, and GHG emissions under different scenarios, we quantified the potential for improvement through increased N use efficiencies (NUEs) in Hubei Province, China. The aims of this study are (i) to evaluate the N utilization and the environmental impacts of six crops under different N utilization efficiency enhancement scenarios, and (ii) to assess the potential to mitigate N pollution and the environmental impacts of different crops under different NUE enhancement scenarios in the municipalities of Hubei Province. The assessment results can reflect the uniqueness of the local conditions in Hubei Province, providing a basis for agricultural decision making in the region. Moreover, as a representative area, Hubei can serve as a reference for other regions in China in terms of reducing N pollution and GHG emissions.

2. Materials and Methods

2.1. Study Area

Hubei Province (29°01′53″ N to 33°06′47″ N, 108°21′42″ E to 116°07′50″ E) is located in the central region of China (Figure 1a). The land area is 18.59 × 10^6 ha. The soil properties in Hubei Province are affected by its geographical location, climatic conditions, and topography, and are diverse. The main soil types include paddy fields and red, alluvial, yellow-brown, and yellow soil [20]. By the end of 2022, Hubei Province, with twelve prefecture-level cities and one autonomous prefecture (Figure 1b) and a diverse topography (Figure 1c), was an important grain crop production area in China. The total fertilizer application in 2020 was 267.32 Mt, ranking sixth in the country. The reduction in the fertilizer rate in Hubei Province compared to 2015 is ranked third in China. Although the proportion of cash crops is increasing year by year, the planting structure in Hubei Province is still dominated by grain crops.

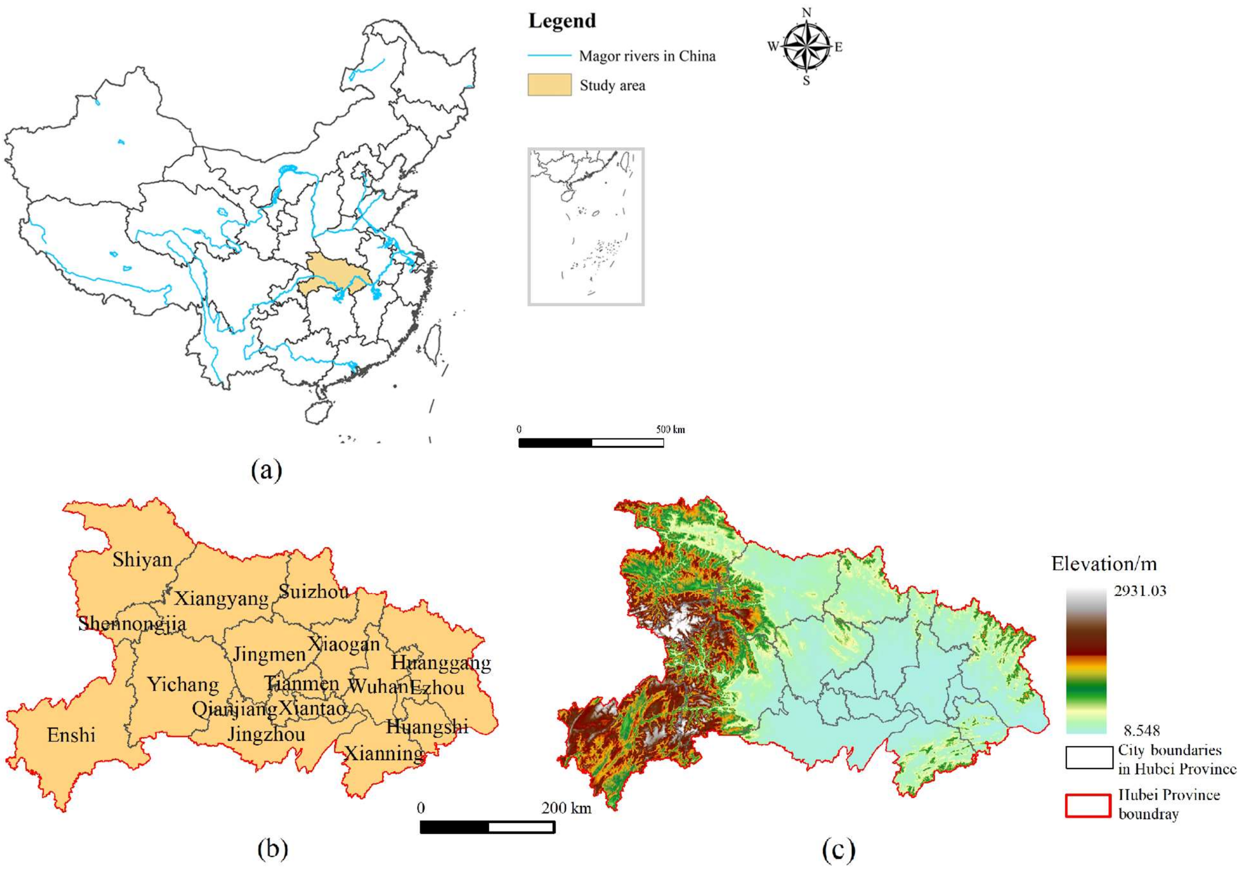

Figure 1. (**a**) Location of Hubei Province. (**b**) Distribution of municipalities in Hubei Province. (**c**) Elevation of Hubei Province.

2.2. Data Sources

In this study, the crop harvest area; the pig, sheep, poultry, and cattle stocks; and municipal rice, wheat, maize, tea, fruit, and vegetable production in Hubei Province were obtained from the Hubei Statistical Yearbook and the National Statistical Yearbook published in 2021 [21,22], where livestock data were used to calculate organic N fertilizer inputs for various crops. Spatial and temporal data of atmospheric N deposition in China were obtained from datasets of wet deposition of inorganic N in China (1996–2015) [23]. N application rates for rice, wheat, and maize were taken from Zuo et al. [24]. The N application rate for tea was obtained from Liang et al. [25], and the N application rates for fruits and vegetables were obtained from the 2015 National Compilation Information on the Cost and Benefit of Agricultural Products [26]. In addition, N fixation rates of various crops were obtained from Li and Smil et al. [27,28].

2.3. Methods

The use of N fertilizers and their environmental impacts were assessed on the basis of resource inputs, transformation processes, and outputs to the environment. Natural N inputs include atmospheric deposition and biological fixation, and anthropogenic N inputs are composed of both synthetic and organic fertilizers. The N outputs include N uptake by crops and GHG emissions (N_2O and CH_4 emissions). Among these, atmospheric deposition refers to the process by which N compounds from the atmosphere are deposited onto the Earth's surface, either through wet deposition (rain, snow, fog) or dry deposition (particulate matter settling out of the air) [29]. N deposition can come from both natural and anthropogenic sources. Therefore, it is applicable to all crops [30], and biological fixation is limited to some leguminous crops. In addition, N fertilizer utilization was evaluated in this study using NUE and N loss.

2.3.1. N Rate

The determination of excessive fertilizer inputs during crop growth relies heavily on the assessment of the N rate. In this research, it is assumed that the ratio of total N applied to crops at the city level is equivalent to that at the provincial level. The statistical values of N and composite fertilizer application data at the provincial level are used to scale the amounts applied at the city level. This scaling ensures that the total N and composite fertilizer applications across all cities match those at the provincial level. The municipal N fertilizer application rate is obtained by summing the adjusted N content of N fertilizer and compound fertilizer. To enhance the resolution of the data, the average N application to crops at the national level and the regional nutrient application rate for specific crops from a farmers' survey are utilized. The municipal N fertilizer application amount for each crop is calculated by scaling the average application rate of that crop by the sum of its harvested area. The specific formula is provided below:

$$F_{i.N} = \frac{\left(\sum_i N_{i,fact} \times A_{i,pro}\right) \times N_{j,total} \times N_{i,fact}}{\left(\sum_i N_{i,fact} \times A_{i,city}\right) \times N_{p,total}} \quad (1)$$

$$N_{total} = F_N + 0.29 \times F_{COMP} \quad (2)$$

where $F_{i.N}$ represents the N rate of crop i (kg ha^{-1}); $N_{i,fact}$ represents the reference N rate to crop i (kg ha^{-1}); $A_{i,pro}$ represents the provincial area of crop i (ha); $N_{j,total}$ represents the total amount of chemical fertilizer N input (kg); $A_{i,city}$ represents the municipal area of crop i (ha); F_N represents N fertilizer inputs (kg); F_{COMP} represents composite fertilizer inputs (kg); and j and p represent different cities and provinces.

2.3.2. NUE

NUE is the ratio of N uptake to N input [31]. We calculated the NUE of each crop as follows:

$$NUE_i = \frac{Yield_i \times NC_i}{N_{i,input}} \times 100\% \quad (3)$$

$$N_{i,input} = N_{i,fer} + N_{i,org} + N_{i,fix} + N_{i,dep} \quad (4)$$

$$N_{i,fer} = F_{i.N} \times Area_i \quad (5)$$

$$N_{i,org} = Num_k \times N_{k,exc} \times N_{k,rec}(1 - N_{k,vol}) \quad (6)$$

where NUE_i represents the NUE of crop i; $Yield_i$ represents the yield of crop i (kg); NC_i is the N content in different crops (%); $N_{i,input}$ represents the N input to crop i during the production process (kg); $N_{i,fer}$ represents chemical N input of crop i (kg); $Area_i$ represents the area of crop i (ha); $N_{i,org}$ represents the organic fertilizer N input of crop i (kg ha^{-1}); $N_{i,fix}$ represents the N fixation of crop i (kg ha^{-1}); $N_{i,dep}$ represents the atmospheric N deposition of crop i (kg ha^{-1}) [27,28]. Num_k represents the number of livestock k at the end of the year (head); $N_{k,exc}$ represents the N discharge rate of livestock k (kg $head^{-1}$ yr^{-1}); $N_{k,rec}$ represents the N recovery rate of livestock k (%); $N_{k,vol}$ represents the N volatilization rate of livestock k (%) [32]; and Area is the crop harvest area (ha).

2.3.3. N Surplus

N surplus is a reasonable indicator of N loss. It represents the portion of N inputs not absorbed by the crops [31]. The N surplus is calculated as follows:

$$N_{i,surplus} = N_{i,input} - Yield_i \times NC_i \tag{7}$$

where $N_{i,surplus}$ is N surplus from different crops (kg ha^{-1}); $Yield_i$ represents the yield of crop i (kg ha^{-1}); and NC_i is the N content in different crops (%).

2.3.4. N Leaching

For N leaching from rice, wheat, and maize, the study used the results of Chen et al. [32]. For N leaching from fruits and tea, Zhang et al. determined that the crop N leaching rate was 12.9% in drylands based on data from 259 dryland samples in China [33]. For N leaching from vegetables, Ti et al. derived that the N leaching rate was 19.4% for vegetables by estimating the N balance of greenhouse and open-air vegetables [34]. N leaching is calculated using the following equation:

$$N_{i,Leaching} = \begin{cases} 6.03 \times e^{0.0048 * N_{i,surplus}}, & \text{rice} \\ 13.59 \times e^{0.009 * N_{i,surplus}}, & \text{wheat} \\ 25.31 \times e^{0.0095 * N_{i,surplus}}, & \text{maize} \\ 0.098 \times N_{i,fer}, & \text{fruits, tea} \\ 0.249 \times N_{i,fer}, & \text{vegetables} \end{cases} \tag{8}$$

where $N_{i,Leaching}$ is N leaching from different crops (kg ha^{-1}); $N_{i,surplus}$ is N surplus from different crops (kg ha^{-1}); and $N_{i,fer}$ represents the N rate of crop i (kg ha^{-1}).

2.3.5. GHG Emissions

Crop GHG emissions include N_2O and CH_4, where N_2O emissions from N fertilizers include two components: direct and indirect emissions. CH_4 emissions are mainly from rice cultivation [24]:

$$GE_{i,CHG} = GE_{i,CH_4} \times 27 + GE_{i,N_2O} \times \frac{44}{28} \times 273 \tag{9}$$

where $GE_{i,CHG}$ represents the GHG emissions of crop i (kg CO_2 eq); GE_{i,CH_4} represents the CH_4 emissions of crop i (kg CH_4 C); GE_{i,N_2O} represents the N_2O emissions of crop i (kg N_2O N); $\frac{44}{28}$ is the molecular conversion factor from N_2 to N_2O; and 27 and 273 are global warming potentials (GWPs) [35]

(1) CH_4 emissions

The CH_4 calculation equation was from IPCC 2006 [36], where the parameter reference values were taken from the study results of Zuo et al. [24]. The CH4 emissions from rice fields were calculated as follows:

$$GE_{i,CH_4} = \sum\nolimits_{i,j,k} (SF_{i,j,k} \times t_{i,j,k} \times A_{i,j,k} \times 10^{-6}) \tag{10}$$

$$SF_i = SF_c \times SF_w \times SF_p \times (1 + \sum\nolimits_i ROA_i \times CFOA_i)^{0.59} \tag{11}$$

where $SF_{i,j,k}$ represents the CH_4 emission factor (kg CH_4 ha^{-1} day^{-1}); $t_{i,j,k}$ represents the rice planting period (day); $A_{i,j,k}$ represents the rice planting area (ha); i, j, k represent different ecosystems, water environments, and types and amounts of organic amendments, because CH_4 emissions from rice may vary under other conditions; SF_i represents the adjusted daily emissions factor of a particular harvest area, which is the baseline emission factor of continuously flooded fields without organic amendments; SF_w represents the scaling factor that considers the difference in the water regime across the cultivation period;

SF_p represents the scaling factor that considers the difference in the water regime across the preseason before the cultivation period; i is the different types of organic amendments; ROA_i is the application rate (kg ha^{-1}) of organic amendments (for rice straw, this is the dry weight); and $CFOA_i$ represents the conversion factor of the organic amendment i [37].

(2) N_2O emissions

Based on the experimental results of Chen et al. [38], we determined the relevant parameters regarding direct N_2O emissions from rice, wheat, and maize; for direct N_2O emissions from vegetables, we used the N_2O fluxes proposed by Mei et al. [32]. For fruits and tea, we used the results of Wang et al. and used the following equations [33]:

$$E_{i,N_2O\_dir} = \begin{cases} 0.74 \times e^{0.011 \times N_{i,surplus}}, & \text{rice} \\ 0.54 \times e^{0.0063 \times N_{i,surplus}}, & \text{wheat} \\ 1.13 \times e^{0.0071 \times N_{i,surplus}}, & \text{maize} \\ 0.0272 \times N_{i,fer}, & \text{fruits, tea} \\ 0.0228 \times N_{i,fer}, & \text{vegetables} \end{cases} \quad (12)$$

where E_{i,N_2O_dir} represents the direct N_2O emissions of crop i (kg ha^{-1}); $N_{i,surplus}$ represents the N surplus of crop i (kg ha^{-1}); and $N_{i,fer}$ represents N rate of crop i (kg ha^{-1}).

We consider indirect N_2O emissions as consisting of three components, calculated as follows:

$$E_{i,N_2O\_ind} = \left(E_{i,NH_3\_vol} + E_{i,NO_x\_vol}\right) \times 0.01 + N_{i,Leaching} \times 0.0075 \quad (13)$$

where E_{i,N_2O_ind} represents the indirect N_2O emissions of crop i (kg ha^{-1}); E_{i,NH_3_vol} represents the NH_3 volatilization of crop i (kg ha^{-1}); E_{i,NO_x_vol} represents the NO_x emissions of crop i (kg ha^{-1}); and $N_{i,Leaching}$ represents the N leaching amount of crop i (kg ha^{-1}).

The NH_3 volatilization of rice, wheat, and maize was calculated by citing Chen et al. [38] and for the NH_3 volatilization of fruits and tea, we used a N volatilization rate of 12.9% for dry land crops, derived by Zhang et al. [34]. For the NH_3 volatilization of vegetables, Ti et al. derived a N volatilization rate of 19.4% for vegetables by assessing the N balance of greenhouse and open-air vegetables [39], calculated as follows:

$$E_{i,NH_3\_vol} = \begin{cases} 2.97 + 0.16 \times N_{i,fer}, & \text{rice} \\ -4.95 + 0.17 \times N_{i,fer}, & \text{wheat} \\ 1.45 + 0.24 \times N_{i,fer}, & \text{maize} \\ 0.129 \times N_{i,fer}, & \text{fruits, tea} \\ 0.194 \times N_{i,fer}, & \text{vegetables} \end{cases} \quad (14)$$

where E_{i,NH_3_vol} represents the NH_3 volatilization of crop i (kg ha^{-1}) and $N_{i,fer}$ represents N rate of crop i (kg ha^{-1}).

NO_x emissions are calculated using the following equation [38]:

$$E_{i,NO_x\_vol} = 0.57 + 0.0066 \times N_{i,fer} \quad (15)$$

where E_{i,NO_x_vol} represents the NO_x emissions of crop i (kg ha^{-1}) and $N_{i,fer}$ represents the N rate of crop i (kg ha^{-1}).

2.3.6. Scenarios Analysis

Combining the agricultural production and N fertilizer use in Hubei Province in 2020, we calculated the average NUE level of each crop in Hubei Province and the NUE of different crops in each city so as to screen out the cities with lower NUEs for each crop. Under the premise of keeping the crop yield unchanged, based on the current situation, using the average NUE level in Hubei Province and the distribution of NUE values in each city as the baseline, we designed different scenarios for cities with low NUEs, assuming that there are different degrees of improvement in NUE. Since rice and wheat are the two most dominant crops in Hubei Province and they exhibit significant value disparities across different cities, four scenarios were established to delineate the enhancement levels for these crops, while three enhancement scenarios were devised for other crops. Scenarios 1–3 for rice assumed that cities with the lowest 20%, 30%, and 40% NUEs increased this level by 15%, 10%, and 8%, respectively, on the basis of the original level. Scenario 4 assumes that cities with a low NUE in Hubei Province reached the Hubei Province level. The simulation of other crop scenarios was similar to that of rice, and the specific details are shown in Table 1.

Table 1. Multi-crop scenario simulation.

Crop	Scenario	Range of Improvements	NUE Enhancement Magnitude
Rice	S1	Cities in the bottom 20%	15%
	S2	Cities in the bottom 30%	10%
	S3	Cities in the bottom 40%	8%
	S4	Cities below the average NUE in Hubei Province	The average NUE of Hubei Province
Wheat	S1	Cities in the bottom 30%	15%
	S2	Cities in the bottom 40%	12%
	S3	Cities in the bottom 50%	11%
	S4	Cities below the average NUE in Hubei Province	The average NUE of Hubei Province
Maize	S1	Cities in the bottom 20%	10%
	S2	Cities in the bottom 30%	8%
	S3	Cities below the average NUE in Hubei Province	The average NUE of Hubei Province
Tea	S1	Cities in the bottom 40%	2%
	S2	Cities in the bottom 50%	1%
	S3	Cities below the average NUE in Hubei Province	The average NUE of Hubei Province
Fruit	S1	Cities in the bottom 40%	2%
	S2	Cities in the bottom 50%	1%
	S3	Cities below the average NUE in Hubei Province	The average NUE of Hubei Province
Vegetable	S1	Cities in the bottom 20%	5%
	S2	Cities in the bottom 30%	4%
	S3	Cities below the average NUE in Hubei Province	The average NUE of Hubei Province

3. Results

3.1. Scenario Analysis to Mitigate the Environmental Impact Potential of Rice

In the simulations conducted for rice cultivation, it was observed that the enhancement in the effective NUE can lead to substantial reductions in GHG emissions and N rates resulting from N inputs. Reducing the N rate in rice reduces GHG emissions more than other crops (Figure 2a,b). The findings reveal that there is a potential to decrease GHG emissions per unit area by over 50% in all four scenarios analyzed. However, it was noted that the mitigation potentials of both N rate and N surplus were not significantly impacted. With the implementation of Scenario 1 (S1), there was a gradual decrease in the N rate, N surplus, N leaching, and GHG emissions per unit area in Hubei Province. Specifically, the N rate of rice decreased by 18.68%, the N surplus per unit area decreased by 22.99%, the N leaching per unit area decreased by 51.53%, and the GHG emissions per unit area decreased by 56.78%. The improvement areas in S1 were predominantly concentrated in the western part of Hubei Province, particularly in Ezhou City. Although S1 showed the smallest improvement in NUE, it showed the greatest improvement in environmental indicators in three cities, Ezhou, Enshi, and Shennongjia, all of which improved by more than 50%. In Scenario 2 (S2), the N rate of rice in Hubei Province was reduced by 21.85%, the N surplus per unit area decreased by 26.88%, N leaching per unit area decreased by 63.08%, and the GHG emissions per unit area decreased by 67.74%. The main improvement area encompassed the western part of Hubei Province, optimizing N fertilizer rates in areas with high N inputs and outputs. Although the reduction in the N rate was not as high as that in S1 in the western part of Hubei Province, the overall optimization effect was better. Scenario 3 (S3) further expanded the improvement area, which encompassed the east and west of Hubei Province. The total N rate was reduced by 21.93%, the N surplus per unit area decreased by 26.99%, and N leaching decreased by 61.99%. However, the improvement potential of S3 in terms of N leaching and GHG emissions per unit area was not as good as that of S2. In scenario 4 (S4), the N fertilizer optimization area was consistent with S3, but the adjustment magnitude was larger (Figure 3a,g). Per unit area, the respective reductions were 28.58% for N rate, 35.17% for N surplus, 69.26% for N leaching, and 71.64% for GHG emissions (Figure 3m). This indicates a significant gap between cities with a low NUE and cities exhibiting the provincial average for rice in Hubei Province. Additionally, the area with a high N rate but low N fertilizer utilization in grain crops in northwest Hubei Province could be associated with the fact that grain crops are not the primary product in that region.

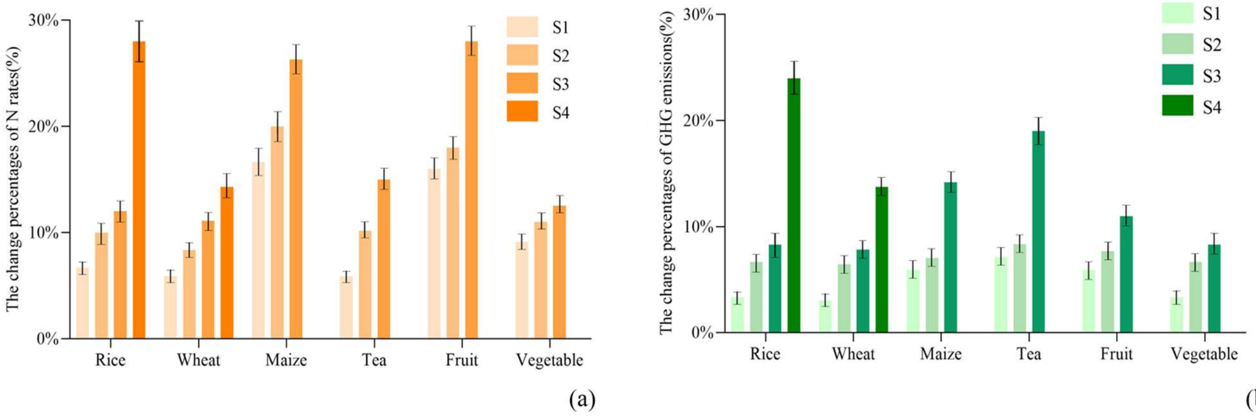

Figure 2. The percentages of change in N rates (**a**) and GHG emissions (**b**) after improving NUEs in different scenarios. The columns for each indicator are the average percentages of change in different indicators when the NUEs in the cities with the lowest NUEs (from light orange or green to dark orange or green) increased by different percentages. The error bars are the standard deviations in different NUE increasing groups from 1% to 7% with 2% intervals.

3.2. Scenario Analysis to Mitigate the Environmental Impact Potential of Wheat

In the scenario modeling analysis for wheat cultivation, it was observed that enhancing the NUE had the greatest potential to mitigate N leaching in wheat. Additionally, it showed a higher potential for reducing both N surplus and GHG emissions. Conversely, the potential for mitigation through the N rate was found to be relatively lower. Nevertheless, four scenarios were simulated for wheat to control the N rate within 250 kg ha^{-1}. In S1, the N rate of wheat decreased by 6.78%, the N surplus per unit area decreased by 24.3%, N leaching per unit area decreased by 35.59%, and the GHG emissions per unit area decreased by 31.49%. This scenario aimed to improve areas in Hubei Province with a high N input but a low wheat yield. The largest reduction was observed in Enshi City, as well as Ezhou City. S2 primarily focused on high-value areas in the western and eastern parts of Hubei Province. The N rate of wheat decreased by 7.02%, the N surplus per unit area decreased by 25.18%, N leaching per unit area decreased by 35.66%, and the GHG emissions per unit area decreased by 31.86%. Compared to S1, the gap between low- and high-value areas decreased. In S3, the total N rate of wheat in Hubei Province decreased by 7.48%, the N surplus per unit area decreased by 26.84%, N leaching per unit area decreased by 36.26%, and the GHG emissions per unit area decreased by 32.84%. Improvement efforts were mainly focused in the vicinity of the Wuhan city circle in the east of Hubei Province, except for the high-value area with a high N rate. However, the reductions in the eastern part of Hubei Province were weaker, resulting in an increased proportion of low-value areas in the province. S4 led to a decrease in the total N rate of wheat in Hubei Province by 10.28%. Per unit area, the respective reductions were 36.87% for N surplus, 44.35% for N leaching, and 41.63% for GHG emissions. The optimization range was further expanded (Figure 3b,h).

Due to the polarization of N fertilizer use for wheat in Hubei Province, the improvement range was larger, resulting in an overall maximum reduction among the four scenarios.

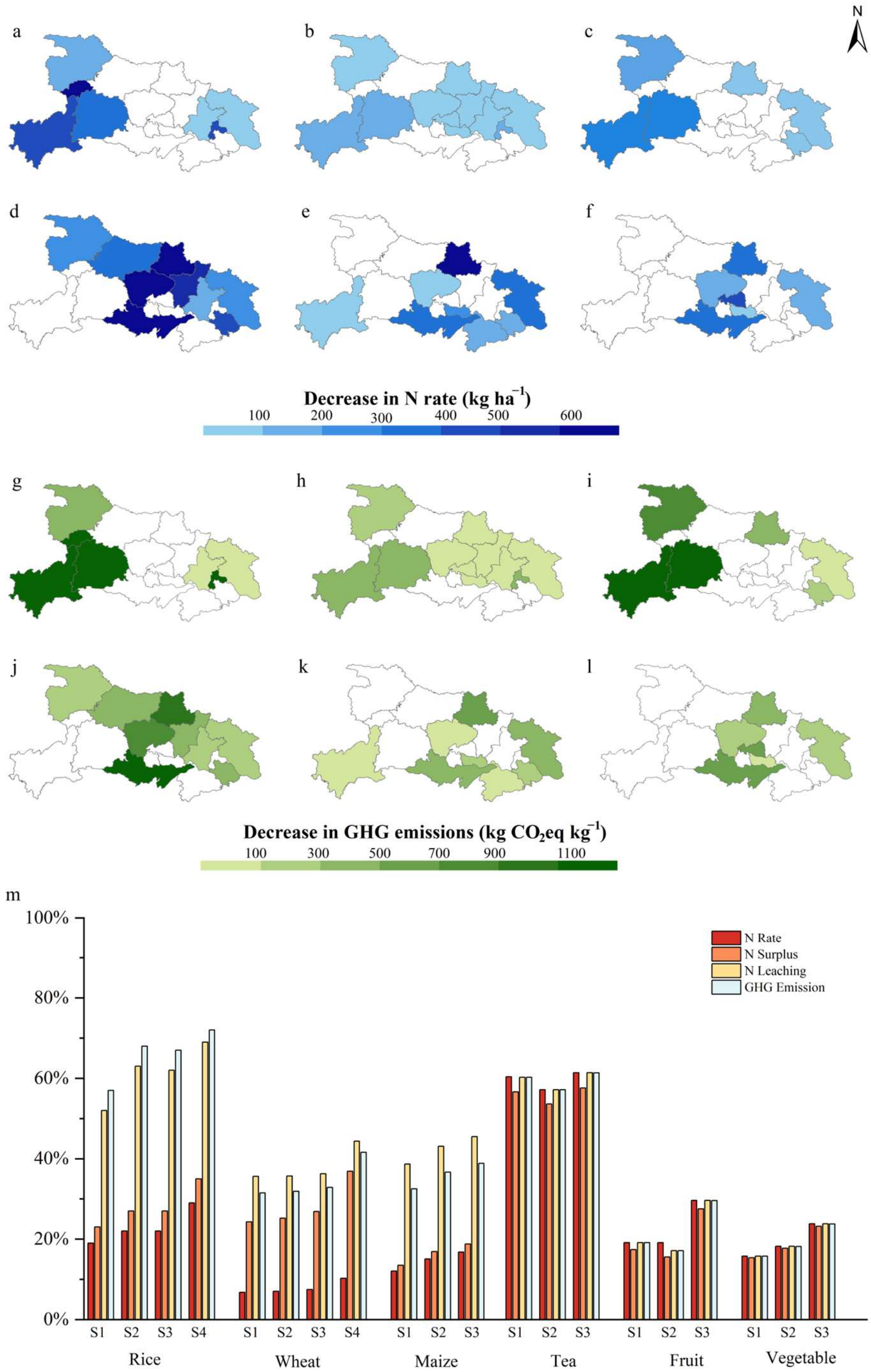

Figure 3. N rate (**a**–**f**) and GHG emission (**g**–**l**) reductions and regions of influence for rice (**a**,**g**), wheat (**b**,**h**), maize (**c**,**i**), tea (**d**,**j**), fruit (**e**,**k**), and vegetables (**f**,**l**) in the optimal scenario. (**m**) is the degree of improvement in the environmental impact indicators for different crops under different scenarios compared to the status quo in 2020.

3.3. Scenario Analysis to Mitigate the Environmental Impact Potential of Maize

Among the three grain crops, there are similarities in the trends in the indicators in the scenarios for wheat and maize, with higher mitigation potentials for N leaching and GHG emissions, unlike maize, which shows lower mitigation potentials for N surplus. In S1 for maize, the total N rate is reduced by 12.04%, the N surplus per unit area is reduced by

13.5%, N leaching per unit area is reduced by 38.63%, and the GHG emissions per unit area are reduced by 32.49% for the three improved cities. The southwest area of Hubei Province in the improved area is characterized by a high N input and a high output for maize. However, Huangshi City is a low-N and low-yield area with a low NUE. As a result, the environmental improvement effect in Huangshi City is not significant. In S2, the study area expands to include Shiyan City and Suizhou City. Per unit area, the respective reductions were 15.07% for N rate, 16.89% for N surplus, 43.12% for N leaching, and 36.63% for GHG emissions. With a constant yield, the reduction in the N rate for maize in the western region of Hubei Province is larger, indicating excessive N rates in that area. S3 results in a reduction of 16.76% in the total N rate per unit area of maize, an 18.78% reduction in the N surplus per unit area, a 45.5% reduction in N leaching per unit area, and a 38.83% reduction in GHG emissions per unit area. The largest reduction in N surplus is observed in the western region of Hubei Province among the three scenarios (Figure 3c,i). Notably, the improvement effect on Huanggang City is minimal, and the overall improvement in the northern part of Hubei Province does not significantly differ from the first two scenarios.

3.4. Scenario Analysis to Mitigate the Environmental Impact Potential of Tea

When comparing cash crops to grain crops, it becomes evident that they exhibit distinct characteristics in terms of mitigation potential across the four indicators. In the simulations conducted for three cash crops, namely tea, fruits, and vegetables, the mitigation potentials of N rate, N surplus, N leaching, and GHG emissions were found to be more synchronized. Specifically, tea demonstrated a higher mitigation potential of 50% across all four indicators, whereas fruits and vegetables exhibited a lower potential of 15–20% compared to tea. Although cash crops showed a relatively greater mitigation potential, it is important to note that grain crops have the ability to reduce GHG emissions by a larger amount when considering the overall magnitude of total mitigated GHG emissions. In S1, improvements are made in the central and northern areas of Hubei Province, resulting in a reduction in the N rate of 60.38%. Furthermore, the overall N surplus decreased by 56.64%, N leaching decreased by 60.28%, and GHG emissions per unit area decreased by 60.26%. It is worth noting that the improvement areas in Jingzhou and Jingmen City, which are characterized by a high N but a low yield, exhibited a higher reduction in environmental impacts. S2 results in overall reductions of 57.17% in the N rate, 53.63% in N surplus, 57.17% in N leaching, and 57.15% in GHG emissions per unit area. The environmental impacts of N fertilizer are reduced by 40–82% in the nine cities within the improvement area. However, there are significant variations in the magnitude of improvement and significant practical challenges. In S3, there were remarkable reductions of 61.38% in the N rate, 57.58% in yjr N surplus, 61.39% in N leaching, and 61.36% in GHG emissions per unit area (Figure 3d,j). This scenario achieved the most optimal effect among the three scenarios. Interestingly, it was found that improving the low-use areas of tea crops also led to a more desirable improvement effect across all three scenarios.

3.5. Scenario Analysis to Mitigate the Environmental Impact Potential of Fruit

The improvement in N management for fruit crops in Hubei Province encompasses a wide range of areas. In S1, the focus is primarily on the central and eastern regions of the province, resulting in a reduction of 19.14% in the N rate, a 17.39% decrease in the N surplus, a 19.14% reduction in N leaching, and a 19.13% decrease in GHG emissions per unit area. S2 expands to include the southern region of Hubei Province. In this scenario, the N rate per unit area decreased by 19.11%, the N surplus decreased by 15.54%, N leaching decreased by 17.11%, and GHG emissions per unit area were reduced by 17.10%. Compared to S1, there is a slight increase in the improvement potential, but the overall effect in Hubei Province tends to be balanced, with no significant disparities between regions. In S3, the N rate decreased by 29.59%, the N surplus decreased by 27.52%, N leaching decreased by 29.59%, and GHG emissions decreased by 29.58%. This scenario achieves the most optimal effect among the three scenarios, reflecting significant improvements in N management for fruit in Hubei Province (Figure 3e,k).

3.6. Scenario Analysis to Mitigate the Environmental Impact Potential of Vegetable

The improvement areas for vegetable crops in Hubei Province are more widely distributed, with the exception of the western part of the province. In S1, the focus was on improving Jingzhou, Suizhou, and Tianmen City. This results in a reduction of 15.76% in the N rate, a 15.36% decrease in the N surplus, a 15.76% reduction in N leaching, and a 15.75% decrease in GHG emissions per unit area for vegetables in Hubei Province. Notably, in the improved areas of S1, the application of N fertilizer in vegetables was more concentrated, with some regions exceeding 700 kg ha^{-1}. S2 expanded to include the central and eastern regions. In this scenario, the N rate decreased by 18.19%, the N surplus decreased by 17.72%, N leaching decreased by 18.19%, and GHG emissions per unit area decreased by 18.17% compared to S1. While the overall improvement in Hubei Province is enhanced compared to S1, the improvement in individual cities is reduced, resulting in improvement ranges of 22–28%. In S3, Xiantao City is added to the improvement area. According to our scenarios, the overall N rate is controlled within 530 kg ha^{-1}, leading to a reduction of 23.78% in the N rate, a 23.17% decrease in N surplus, a 23.78% reduction in N leaching, and a 23.76% decrease in GHG emissions per unit area (Figure 3f,l).

3.7. NUE Enhancement Effect

The NUE of different crops calculated in simulations is shown (Figure 4). For the grain crops, the NUE of rice improved from 9.72% to 16.42%; the NUE of wheat improved from 9.56% to 14.37%; and the NUE of maize improved from 22.72 to 44.23%. For the cash crops, the NUE of tea increased from the current 2.05% to 5%; the fruit NUE increased from the current 3.04% to 6%; and the NUE of vegetables increased from the current 16.18% to 22%. The NUE enhancement is smaller for cash crops and larger for grain crops. However, the reduction in the environmental impact indicators as a whole displays the opposite trend. This phenomenon suggests that cash crops have greater mitigation potential for the environment than grain crops. In S1, both tea and fruit crops had a NUE of 4.5%. However, the GHG emission reduction from tea cultivation was 2.03 times higher than that from fruit cultivation (Figure 3m). Among the six crops, tea showed a significant potential to mitigate environmental impacts, as its NUE increased to only 5%, but N rates were reduced by nearly 60%. In the wheat scenario, the NUE can reach more than 50%, but the environmental impact indicators do not exhibit large reductions. This indicates that N fertilizer for wheat in Hubei Province is managed in a more sustainable way than tea, which could be improved.

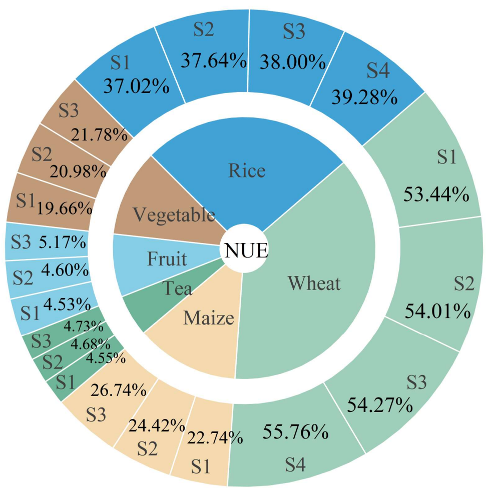

Figure 4. NUE in different scenarios for different crops.

4. Discussion

4.1. Influence Factors of Multi-Crop N Fertilizer Management

The NUE of crops can be influenced by various factors, including the N rate applied to the crops. There is typically a correlation between the NUE of crops and the N rate. At lower N rates, crops may exhibit a higher NUE as they are able to efficiently utilize the limited N available to them. This is because plants have mechanisms to optimize N uptake and use when N is scarce [40]. However, as the N rate increases, the NUE of crops may decrease, as the plants may not be able to efficiently utilize the excess N [41]. This can result in N losses through leaching, volatilization, and denitrification [42], leading to environmental pollution and a reduced economic efficiency.

It is important for farmers to optimize N rates to achieve a balance between maximizing crop yields and maintaining a high NUE. This can be achieved through precision agriculture techniques, such as soil testing [43], plant tissue analysis [44], and using N management practices like split applications, timing of fertilizer application, and use of N inhibitors [45]. By carefully managing N rates, farmers can improve the NUE of their crops, reduce environmental impacts, and enhance the sustainability of agricultural production.

Government policies can have a significant impact on multi-crop N fertilizer management in agriculture. Comparing the data on agricultural fertilizer use in Hubei Province for the last 10 years [46], we found that the implementation of the zero growth in fertilizer use policy effectively reduced the amount of fertilizer applied and reduced fertilizer non-point source pollution and carbon emissions, which improved the ecological efficiency of food production [47]. This phenomenon indicates that the policy also played a role in the reduction in N fertilizer application. The crop structure in Hubei Province is dominated by grain crops, so there are far more N fertilizer optimization decisions for grain crops than for cash crops. The increased use of optimized decision making has led to initial awareness of N fertilizer management for grain crops among farmers and a gradual reduction in N application [48]. In the future, corresponding policies can be issued for cash crops to effectively control N fertilization. It is recommended that the relevant fertilizer quotas for various cash crops in different regions should be implemented and improved as soon as possible so as to promote the use of economic means, such as incentives and cost control, to enhance the incentive to reduce the amount of chemical fertilizer used in cash crops. Government programmers can provide agricultural management training to managers of farms [49]. These policies have been widely adopted in developed countries such as the United States [50]. However, even though there is strong evidence of economic gains from changing practices [51], there is greater resistance to acquiring up-to-date agricultural skills due to China's predominantly smallholder agriculture, where farmers are predominantly elderly [52]. This may lead to higher costs for adopting mitigation measures, thus complicating the question of how to promote environmental and productive win–win situations through policy.

4.2. Environmental Impacts of Multiple Crops

The improvement potential was higher for cash crops than for grain crops. In terms of crop production, the percentage of cash crops is gradually increasing, while at the same time, the N surplus it generates is increasing at a rapid pace. For example, Xia et al. [53] noted that chemical fertilizer inputs to fruit crops were high in China and GHG emissions were also very high, which was consistent with the results of our study.

Cash crops have a lower root density and nutrient uptake capacity, and they usually require more fertilizer inputs to supply the N requirements compared to grain crops. In addition, smallholder producers in China often apply excessive amounts of N fertilizer to increase crop yields [54]. Therefore, effectively lowering the N surplus is significant for improving the N management of crop production systems. In this study, tea demonstrated a great potential to ameliorate N surplus, with reductions in the N surplus in tea accounting for about half of the total improvement potential of cash crops in the optimal scenario. In the multi-crop scenario, tea required the least improvements in N fertilizer utilization when N application was reduced by an equal amount, which is worthy of attention.

As one of the world's largest agricultural producers, many scholars have used different indicators to assess and predict the environmental impacts of China's agricultural systems and predict mitigation potentials. For example, the integrated knowledge and products strategy (IKPS) has been used to decrease vegetables' N surplus by 65%, while GHG emissions were decreased by 28% through field experiments over many years [55]. This study is consistent with our results in terms of GHG emissions and shows better results in terms of N surplus. Thus, this confirms that reducing excessive N application is an effective measure to reduce the environmental impacts caused by farmland [56].

Ren et al. mentioned [57] that they decreased the N surplus by 15–19% for rice, wheat, and maize by optimizing N application. This is consistent with our findings. However, our study shows greater potential in terms of N, and the main reason for this discrepancy is that interactions between indicators after N fertilizer input, different perspectives, and different crop types require distinct agricultural management methods and fertilizer practices, which affect the estimation of N surplus [58]. Although Hubei Province has gradually modernized its agricultural management, especially in terms of agricultural waste utilization and irrigation management, compared with other regions in China, the technology is not mature enough and the management model is still in the exploratory stage [59], so the problem of excessive N input still exists. Therefore, Hubei Province has great potential to increase environmental benefits.

4.3. Limitations and Uncertainties

Our study results indicate that more effective N utilization could help to reduce environmental impacts. There are also some inevitable uncertainties in our method. First, we obtained N application data for various crops from other studies and statistical yearbooks. However, due to data gaps and differences in study years, we systematically adjusted the data based on previously available information. Second, we used reference values that were not specific to Hubei Province in our calculations. For example, N leaching data for soybeans, fruits, and tea were obtained from 259 upland samples. The N leaching data from upland samples are on the national scale. Although these data are not from Hubei Province, the natural conditions of its sample sites are similar to those of cash crops such as fruits and tea grown in Hubei Province, so the results are within the credible range.

Due to the complexity and diversity of crop rotation systems, they are not taken into account in our assessment framework. This has some implications for our results. Failure to include crop rotation systems in the assessment framework may lead to biases in the evaluation of agricultural production efficiency, soil fertility conservation, and ecological environment protection. Crop rotation systems play an important role in improving agricultural production efficiency. For example, by properly combining crops, soil resources can be fully utilized and crop yields can be increased [60]. Some studies have shown that the gain in subsequent crop yield due to rotation was much higher with a lower N fertilization rate ($\leq$120 kg ha^{-1}), indicating that fertilization can be reduced and an acceptable yield can be maintained with crop rotation. In conclusion, crop rotation largely increases agricultural production without extra inputs, although its design may require consideration of diverse climates, soils, crops, and management practices to maximize the agronomic and environmental benefits [61] Crop rotation systems primarily reduce N fertilizer input for subsequent crops by planting N-fixing crops. Their impact on crops is reflected in yield, and our assessment framework mainly determines the N fixation amount through the yield and sowing area. Therefore, although a crop rotation system may influence our calculation of biological N fixation, its impact on our results remains within a small range, making our findings robust. In the future, for the sake of more precise calculations, we will consider exploring the specific mechanism of crop rotation systems' influence on N fertilizer inputs. There is no doubt that obtaining more accurate parameters and understanding the mechanism of a crop rotation system's effect on increasing the NUE is crucial for future sustainable agricultural development. Future research could explore more precise data suitable for Hubei Province and integrate the economic situation of N fertilizer input to further analyze the relationship between input costs and yields and could explore the specific influence mechanism of crop rotation systems on N inputs, providing a basis for policy decisions.

5. Conclusions

Based on the agricultural status in Hubei Province in 2020, we calculated the average NUE level of each crop in Hubei Province (rice 37.74%; wheat 53.51%; maize 23.82%; tea 4.05%; fruits 4.34%; vegetables 19.18%). Based on this, we provided a framework for comprehensively assessing the potential to improve the environmental impacts of different N inputs for different crops in Hubei Province under different scenarios. The results suggest that improving the NUE can effectively mitigate environmental impacts. Overall, the best improvement effect will be achieved when NUE of crops reaches the average NUE in Hubei Province. In this scenario, cash crops showed a greater proportion of improvement than grain crops; different environmental indicators could be reduced by 25 to 52%. However, in areas with low NUEs, the results achieved by this scenario require more equipment and more knowledge on the part of the farmers. While S1 and S2 do not have the same potential for improvement as S3, they are more achievable due to the more generous targets they set, and they can still improve the indicators by 20%. In Hubei Province, there is a noticeable issue regarding excessive N fertilizer input for cash crops. Tea had the largest total reduction potential in the N rate among the six crops. Our findings suggest that Hubei Province does not manage N fertilization in the optimal way and that additional room for improvement exists.

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