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Article

Environmental Impacts of Crops Production Systems in Subtropical Plateau Regions: Case Study of Yunnan, China

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Abstract: Although agricultural crops production systems in subtropical plateau regions currently pose high environmental risks, especially in developing countries, their environmental impacts and emission-reduction potentials remain unclear, and the development potential of such systems is likely huge. We conducted a case study in Yunnan Province, China, to quantify the environmental impacts from crop production during 2002–2021. The life cycle assessment method was employed to identify factors driving the environmental impacts, and potential mitigation strategies were proposed. The yield and total nutrient input of grain crops in Yunnan Province increased over the 20-year period, and environmental footprint of crops production in Yunnan Province was higher than that of other regions. Average annual mean greenhouse gas (GHG) emissions and soil acidification potentials (AP) and water eutrophication potentials (EP) of crops production during 2002–2021 were 732 kg CO₂-eq·Mg⁻¹, 15.8 kg SO₂-eq·Mg⁻¹, and 2.7 kg PO₄-eq Mg⁻¹, respectively. GHG emissions from crops mainly originated from applying agricultural materials during the crop life cycle. There was a significant correlation between surplus nitrogen and environmental impacts. Scenario testing showed that through crop sowing, nutrient regulation, and crop management, the crop yield could be increased and environmental costs could be reduced. The greatest reductions were found in wheat production: 53.1%, 67.9%, and 67.7% for GHG emissions, AP, and EP, respectively. Adopting comprehensive agricultural management measures could reduce the negative impact of crops production on the environment in subtropical plateau areas and achieve sustainable agricultural development.

Keywords: subtropics; plateau region; environmental impact; life cycle assessment;

1. Introduction

The challenges associated with rapid population growth and limited arable land pose considerable problems to global food security, and it is necessary to increase crops production. However, agricultural production requires significant resource inputs (fertilisers, pesticides, irrigation and agricultural machinery) to achieve the required yields and productivity levels [1,2], and synthetic fertilisers, particularly nitrogen (N) fertilisers, are required [3,4]. In this respect, farmers on the North China Plain (NCP) often over-input N fertilisers to improve wheat yields [5], and farmers in North America typically overuse N fertilisers to avoid the risk of reduced production [6]. However, excessive investments in N fertilisers and unreasonable agricultural management methods do not improve the grain yield or agronomic efficiency; instead, they cause environmental problems, such as increased greenhouse gas emissions, soil acidification, groundwater eutrophication and soil salinisation [7–9]. According to reports, the average N application rate in China's agricultural

ecosystem is $305 \text{ kg N ha}^{-1} \text{ yr}^{-1}$, which is much higher than the global average N application rate ($74 \text{ kg N ha}^{-1} \text{ yr}^{-1}$). In addition, N utilisation efficiencies in China, in North America, and globally are 0.25, 0.65, and 0.42, respectively [10]. Therefore, there is an urgent need to optimise crop nutrient management in China, improve fertiliser utilisation efficiency, reduce environmental risks, and address the dual challenges of crop productivity and ecosystem sustainability.

Crops production increases social stability and national economic development, but it has a high environmental impact, and sustainable agricultural development has, therefore, become an inevitable trend. It is likely that crops production will need to double by 2050 to meet the requirements of the growing global population [11]. Research has shown that owing to a combination of specific location factors, 79% of rice, 56% of wheat, and 52% of maize produced in China has experienced yield stagnation, and some crops in certain countries or regions have even experienced yield reductions [1]. It is, therefore, necessary to determine whether and to what extent environmental costs should be reduced while ensuring food security and improving sustainable land productivity.

Many studies have shown that grain yields can be increased and environmental impacts can be reduced by improving nutrient management and optimising agricultural practices [10,12,13]. Compared with traditional agriculture, crops production can be maintained or increased using organic and protective agriculture practices, but the temporal stability of organic agriculture requires improvement [14]. In addition, Feng et al. [15] indicated that intelligent climate agricultural practices (such as intensive planting, deep tillage, manure improvement and N fertiliser optimisation) can be used to improve maize yields while reducing the carbon footprint.

In agricultural production, the extensive application of N fertiliser can cause the loss of reactive nitrogen (Nr) into the air, soil and water bodies, resulting in environmental pollution [16]. Several studies have shown that there is an enormous potential to increase grain yield and the N utilisation efficiency (NUE) by reducing N loss, and thus, environmental impacts [17,18]. Previous studies have also shown that in Europe [19], the Mediterranean region [20] and the North China Plain [21], optimising the amount of N fertiliser used for maize and wheat production (improving agronomic efficiency) reduces environmental impacts and improves ecological efficiency. However, previous research has a limited scope, and researchers have often only focused on a single aspect of environmental risk, such as the global warming potential (GWP), eutrophication potential (EP), and acidification potential (AP). Therefore, measures for optimising resource investments and reducing the negative environmental impacts and emissions from crops production on subtropical plateau areas are currently unclear. The climate and soil conditions in the subtropical plateau region of China are excellent, and they are suitable for planting various food crops (like rice, wheat, and maize); as such, the region is an important grain-producing area in China. Yunnan is located in the low-latitude subtropical plateau region; its grain yield lags behind that of other regions and the fertilisation efficiency is imbalanced due to improper nutrient management.

With increased public awareness of environmental damage and the associated government attention, it is necessary to comprehensively consider various impact indicators relating to ecosystem quality when analysing environmental costs and to provide accurate estimations of grain yield levels and environmental costs at a regional scale to enable the sustainable development of the crops production system. Life cycle assessments (LCAs) are often used to quantify and evaluate the resource inputs and environmental impacts of crops production systems [22]. Therefore, in this study, we conducted a LCA to analyse the environmental impacts from producing crops in Yunnan Province from 2002 to 2021. The aim of this study was as follows: to (1) quantify the yield, nutrient input, and N fertiliser utilisation of the major grain crops in Yunnan Province; (2) assess greenhouse gas (GHG) emissions and AP and EP of crops production in the region; and (3) propose potential emission reduction strategies to reduce environmental costs in China's subtropical plateau areas.

2. Materials and Methods

2.1. Study Area

Our case study was conducted in Yunnan province ($21^{\circ}08'N$ to $29^{\circ}15'N$, $97^{\circ}31'E$ to $106^{\circ}11'E$) and based on data from 2002 to 2021 [23] (Figure 1). Yunnan is located within a typical subtropical plateau

monsoon climate zone and the average annual precipitation and temperature are 1064 mm and 17.4 °C, respectively [24] (Figure 2). The terrain is extremely complex and high in the northwest and low in the southeast, and the climate characteristics and main soil characteristics of different regions vary significantly (Table 1). Approximately 5.40 million hectares of land are cultivated in Yunnan Province, and the total area of sown crops reached 4.19 million hectares in 2022. The main crops grown throughout the year are rice, wheat, and maize, and the planting area and yield structure of the three crops follow the order of maize>rice>wheat.

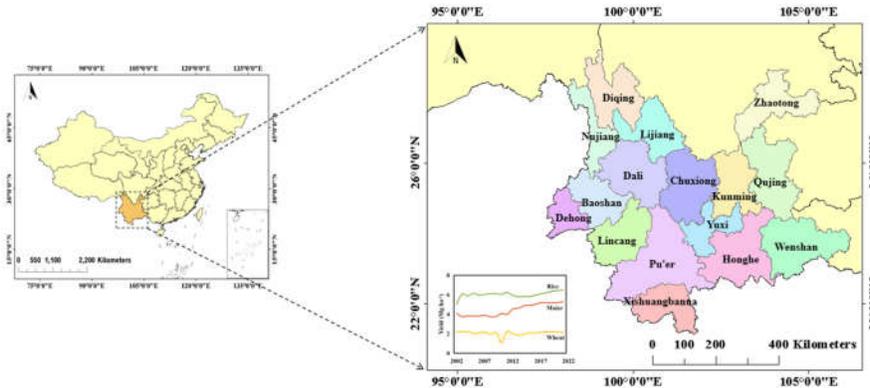


Figure 1. Crop planting region and sub-regions in Yunnan, including Kunming, Qujing, Yuxi, Zhaotong, Chuxiong, Honghe, Wenshan, Pu'er, Xishuangbanna, Dali, Baoshan, Dehong, Lijiang, Nujiang, Lincang, and Diqing city. The green, yellow, and red bars represent the average production (10^4 Mg) of rice, wheat, and maize in Yunnan province from 2002 to 2021, respectively. Data for crops production were obtained from the NBS (2018) from 2002 to 2021.

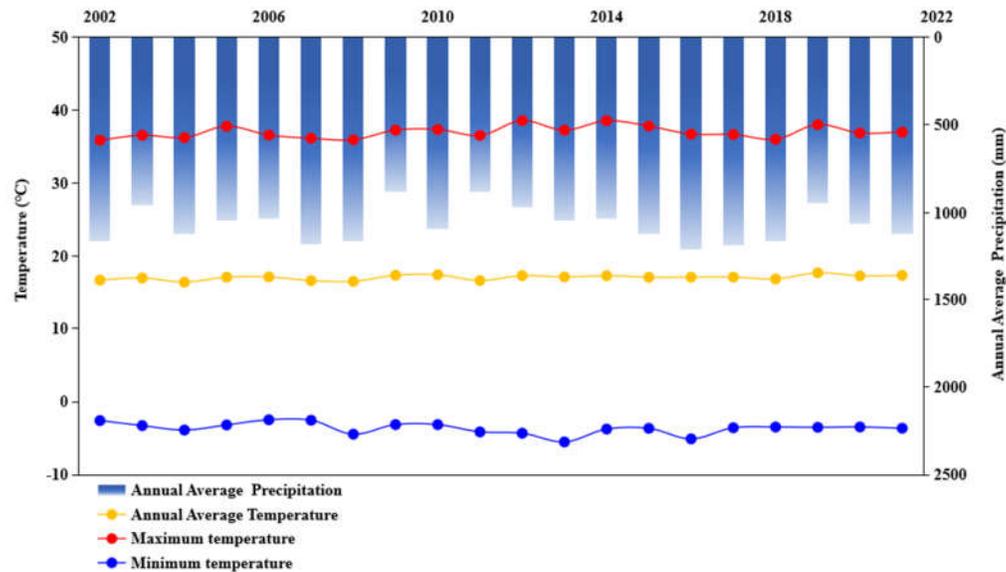


Figure 2. Precipitation and mean temperature for each year 2002–2021. Changes in annual temperature (maximum temperature, minimum temperature and average temperature) and annual precipitation in Yunnan Province from 2002 to 2021. The blue bars represent total precipitation in each year during 2002–2021; the red, yellow and blue dots represent the maximum temperature, average temperature and minimum temperature, respectively, in each year during 2002–2021.

Table 1. The climatic characteristics of in Yunnan in recent 20 years, and their major soil characteristics. Data for annual precipitation, annual temperature and annual illumination hours were collected from the China Meteorological Data Service Center (CMDSC). The major soil textures and soil pH were according to FAO and World Reference Base for Soil Resources (2018).

	Annual precipitation(mm)	Annual air temperature(°C)	Annual illumination hours (h)	Major soil textures	Soil pH
Kunming	917±131	16.7±1.6	2181±212	Loam to clay	5.8–6.7
Qujing	1012±147	15.6±1.9	1908±107	Loam to clay	5.7–7.0
Yuxi	893±131	20.5±0.8	2159±177	Loam to clay	5.6–6.6
Zhaotong	885±128	14.6±2.0	1456±96	Loam to clay	5.5–6.5
Chuxiong	949±123	18.9±1.2	2343±153	Loam to clay	5.5–7.5
Honghe	1106±122	19.9±0.1	1997±129	Sandy loam to	5.5–6.8
Wenshan	1082±158	18.8±1.2	1733±131	Loam to clay	5.3–6.3
Pu'er	1351±154	20.3±0.8	2197±144	Sandy loam to	5.3–6.4
Xishuangbanna	1492±208	22.1±0.5	2175±153	Loam to clay	4.9–6.2
Dali	983±126	16.8±1.6	2248±134	Loam to clay	5.4–7.4
Baoshan	1123±157	17.5±1.4	2325±134	Loam to clay	5.3–6.5
Dehong	1247±171	18.7±1.2	2317±135	Loam to clay	5.0–6.4
Lijiang	916±98	15.0±2.0	2400±121	Sandy loam to	5.5–6.8
Nujiang	1097±170	13.6±2.3	1817±134	Sandy loam to	5.4–6.9
Lincang	1157±163	19.3±1.0	2316±149	Sandy loam to	5.3–6.3
Diqing	820±123	10.7±2.9	1990±143	Loam to sandy	5.5–6.9

2.2. Data Collection

In this study, datasets of the sowing area, yield, nutrient inputs (N, P, and K), pesticide inputs and agricultural film usage during the production of rice, wheat, and maize from 2002 to 2021 were obtained from the China Statistical Yearbook [25], the China Agricultural Yearbook [26] and a Compilation of Cost and Income of Agricultural Products in China [27]. Meteorological data were obtained from the China Meteorological Data Service Center [24]. All statistical yearbooks, including national, provincial, and prefecture levels, are available in the China Statistical Yearbook Database (CAJ), and the yearbook series set for the years 2002–2021. We divided the 20 years of data into four stages: 2002–2006, 2007–2011, 2012–2016 and 2017–2021, to reduce the impacts of inter-annual climate variation.

2.3. Statistical Analysis

All primary data were processed using Excel 2019. IBM SPSS Statistics (IBM Corp. Armonk, NY, USA) was used to conduct the linear regression. The graphical plots were constructed using OriginPro 2021 and ArcGIS 10.8. The one-way analysis of variance (ANOVA) was used to test the interactive and main impacts of subregions or time periods on the grain yield, partial factor productivity of nitrogen (PFP-N), fertiliser rate, GHG emissions, AP, EP, and CF via SAS 9.3 statistical software. Where treatment impacts were significant, means were compared using least significant difference (LSD) tests at $P < 0.05$.

2.4. Functional Units and System Boundary

To accurately reflect food security and the overall environmental sustainability of the system, we evaluated the impact based on two functional units: per hectare and per million grams of crop.

The system boundary used in this study is defined as “the cradle-to-gate of the field” [28], and it includes all GHG emissions, AP, and EP from sowing to harvesting in relation to two stages: the Material Stage (MS), which includes the application of fertilisers and the use of pesticides and other agricultural materials (such as agricultural film), and the Farming Stage (FS), which includes the emissions generated by the cropland ecosystem processes [29]. The infrastructure of the irrigation system and the production of crop seeds were not included because of a lack of reliable data. Due to the waste of straw in the planting system, this study did not consider the environmental impact of crop straw production [21].

2.5. Impact Assessment

The most widely used index for representing NUE is the PFP-N (kg kg^{-1}), which is the yield produced per unit of N applied [30]. The PFP-N is defined as follows,

$$\text{PFP-N} = Y/N \quad (1)$$

where Y is the crops yield (Mg ha^{-1}) and N is the rate of N application (kg N ha^{-1}).

For the environmental assessment, we calculated the N balance (N_{surplus} , kg N ha^{-1}) from the difference between the amount of N input and that up taken, where it was absorbed by the aboveground biomass of crops [31],

$$N_{\text{surplus}} = N_{\text{input}} - N_{\text{uptake}} \quad (2)$$

where N_{input} (kg N ha^{-1}) represents the sum of N fertiliser applied, and N_{uptake} (kg N ha^{-1}) represents the total N uptake of the crop. Considering the rice, wheat, and maize yields of Yunnan over the past 20 years, the amount of N used to produce per million grams (Mg) of rice, wheat, and maize was 21.0 kg, 27.1 kg, and 19.8 kg, respectively [32,33].

2.6. Estimation of Greenhouse Gas Emissions, Acidification Potential and Eutrophication Potential

According to the system boundaries defined above in Section 2.4, the environmental impacts of crops production comprised emissions from fertilisers (N, P, and K), pesticides and plastic films in the MS and FS stages. The calculation formulas for the environmental impacts (GHG emissions, AP, and EP) of rice, wheat, and maize production systems were constructed as follows,

(1) GHG emissions

GHG emissions were calculated using the following equation and IPCC method [34,35],

$$\text{GHG}_T = \text{GHG}_{\text{MS}} + \text{GHG}_{\text{FS}} \quad (3)$$

where GHG_T ($\text{kg CO}_2\text{-eq Mg}^{-1}$) is the total GHG emissions per hectare per year from crops production. Furthermore, GHG_{MS} and GHG_{FS} ($\text{kg CO}_2\text{-eq Mg}^{-1}$) are the GHG emissions per hectare per year of crops planting area from MS and FS, respectively, which are obtained as follows,

$$\text{GHG}_{\text{MS}} = \sum (AI_i \times EF_i) \quad (4)$$

where AI_i (kg ha^{-1}) represents the application rate for the i^{th} agricultural input comprising fertilisers (N, P, and K), pesticides and plastic film; EF_i ($\text{kg CO}_2\text{-eq kg}^{-1}$) represents the GHG emissions factor associated with the i^{th} agricultural input [36], and

$$\text{GHG}_{\text{FS}} = \text{Total N}_2\text{O} \times 44/28 \times 298 \quad (5)$$

$$\text{Total N}_2\text{O} = \text{N}_2\text{O}_{\text{direct}} + 1.0\% \times \text{NH}_3 + 2.5\% \times \text{NO}_3^- \text{ leaching} \quad (6)$$

where total N_2O is the N_2O emissions at the FS divided into direct and indirect N_2O emissions from crops production. Furthermore, $\text{N}_2\text{O}_{\text{direct}}$ is the N_2O emissions from N fertiliser application [10], 44/28 is the conversion coefficient of $\text{N}_2\text{O-N}$ to N_2O , 298 is the conversion coefficient of N_2O to CO_2 , 1.0% and 2.5% are the indirect N_2O emission factors associated with NH_3 volatilisation and nitrate leaching, respectively [37].

(2) Acidification Potential (AP)

The AP of the entire life cycle of crop production systems mainly comprises emissions during the production and transportation of fertilisers and pesticides as well as NH₃ emissions directly related to the application of N fertilisers in agricultural systems. The AP was calculated as follows,

$$AP = \sum_{n=1}^m MS_{SO_2} + 1.88 \times NH_3 \times 17/14 \quad (7)$$

where AP (kg SO₂-eq Mg⁻¹) is the acidification impact produced by the crops input by the production unit; MS_{SO₂} is the SO₂ emissions from the production and transportation of various inputs during the MS, including fertilisers (N, P, and K), pesticides and plastic film; NH₃ is the volatilisation of NH₃ during the FS; 17/14 is the conversion coefficient of N to NH₃, and 1.88 is the conversion coefficient of SO₂ acidification gas emission with 1 kg NH₃.

(3) Eutrophication Potential (EP)

The substances that cause EP include NH₃, NO_x, NO₃⁻, NH₄-N, COD, and P_{tot}, the EP was calculated as follows,

$$EP = \sum_{n=1}^m MS_{PO_4} + 0.33 \times NH_3 \times 17/14 + 0.42 \times NO_3^- \text{ leaching} + 0.2\% \times P_{input} \quad (8)$$

where EP (kg PO₄-eq Mg⁻¹) is the eutrophication impact produced by the crops input by the production unit; MS_{PO₄} is the PO₄ emissions from the production and transportation of various inputs during the MS, including fertilisers (N, P, and K), pesticides and plastic film; NH₃ and NO₃⁻ leaching represent the previously calculated NH₃ volatilisation and NO₃⁻ leaching losses, respectively, 17/14 is the conversion coefficient of N to NH₃; 0.33 and 0.42 are the conversion coefficients of PO₄ with 1 kg NH₃ and 1 kg NO₃⁻ leaching, and P_{input} is the total amount of P fertiliser input [38].

2.7. Emission-Mitigation Scenarios for Greenhouse Gas Emissions, Acidification Potential and eutrophication Potential

Enormous energy inputs from fertilisers and pesticides occur throughout the life cycle of rice, wheat, and maize, and it is therefore necessary to increase the energy efficiency of crops production farms by reducing the fertiliser rate while increasing yield. To explore the potential for mitigating environmental impacts from crop production in the representative subtropical plateau region in China during 2002–2021, and to project this forward 20 years to 2041, specific efficient strategies and optimal scenarios were developed. In this respect, the baseline scenario (S1) projected the GHG emissions, AP, and EP for 2041 using the same average yield from 2002 to 2021 and the same fertiliser input in 2021, and the second scenario (S2) assumed that by applying the recommended fertilisers rate (all other inputs for crops production were the same as those used during 2002–2021), the yield of rice, wheat, and maize would increase by 15% and reach 6.99 Mg ha⁻¹, 2.42 Mg ha⁻¹, and 5.09 Mg ha⁻¹, respectively [39]. Through the new fertilisation-optimised scenario (S3), the crop yield would be increased by 5.3% and NUE by 24.1%, while N₂O emissions, N leaching, and NH₃ volatilisation from crop production would be decreased by 23.8%, 27.1%, and 39.4%, respectively, when using a recommended innovative N fertiliser (controlled release urea) [40]. The integrated scenario (S4) adopted the Integrated Crop Management System (ISSM is a redesigned crop planting system based on crop ecological and physiological models and regional soil climate conditions), which was previously employed and achieved 75% of the regional yield potential with optimised N application and management practices (optimising varieties, densities and sowing dates, and realising the efficient use of nutrients through rhizosphere nutrient regulation) [41].

3. Results

3.1. Crop Yield, Nutrient Input, and PFP–N

Over the 20-year period, the average yields of rice, wheat, and maize were 6.03 Mg ha⁻¹, 2.05 Mg ha⁻¹, and 4.43 Mg ha⁻¹, respectively, and the overall yield showed an upward trend over the four periods (2002–2021) (Figure 3a–c). The average PFP–N of rice and maize increased by 17.2% and 40%,

while that of wheat declined by 16.0% from 2002–2006 to 2017–2021 (Figure 3d–f). The average PFP–N of rice, wheat, and maize was 29.0 kg kg⁻¹, 15.9 kg kg⁻¹, and 16.2 kg kg⁻¹ during 2002–2021, respectively.

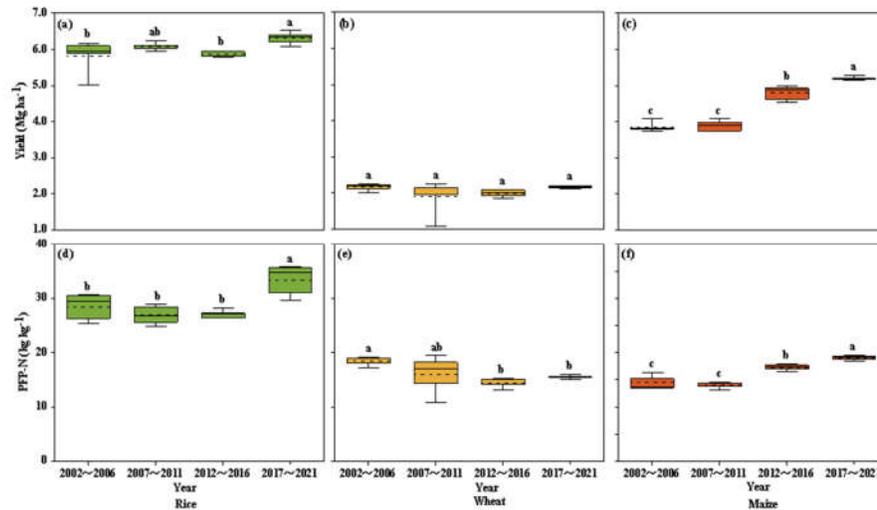


Figure 3. Grain yield and partial productivity of nitrogen fertiliser (PFP–N) for rice, wheat, and maize production from 2002 to 2021 in Yunnan Province (20 samples). The (a) rice grain yield, (b) wheat grain yield, (c) maize grain yield, (d) PFP–N of rice, (e) PFP–N of wheat, and (f) PFP–N of maize were compared across five-year intervals. Different lowercase letters represent significant differences among the year intervals ($P < 0.05$).

There were significant differences between the nutrient inputs of the four different crop periods. The total fertilisation rates for rice, wheat, and maize were the highest during 2017–2021, at 350 kg ha⁻¹, 190 kg ha⁻¹, and 398 kg ha⁻¹, respectively, showing an upward trend. There were no significant differences in the application rates of N fertiliser for maize or of P fertiliser for wheat between 2002 and 2021. However, the N fertiliser rate for maize was higher than that for rice and wheat, whereas the P and K fertiliser rates for rice were higher than those for wheat and maize (Figure 4).

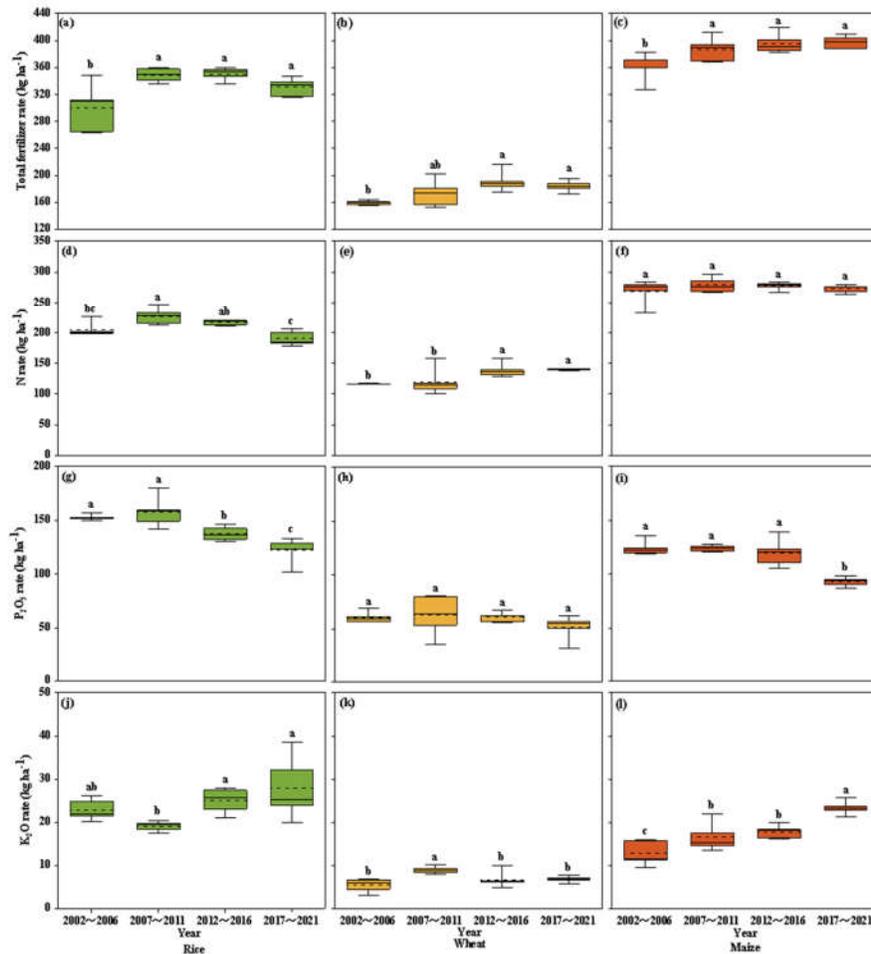


Figure 4. Fertiliser input for crop (rice, wheat, and maize) production systems from 2002 to 2021 in Yunnan Province (20 samples). The (a) rice total fertiliser rate, (b) wheat total fertiliser rate, and (c) maize total fertiliser rates were compared across the five-year intervals. (d–l) Different nutrient inputs (d–f, nitrogen (N) fertiliser rate; (g–i) phosphorus (P_2O_5) fertiliser rate; (j–l) potassium (K_2O) fertiliser rate) for crop (rice, wheat, and maize) production systems were compared across five-year intervals. Different lowercase letters represent significant differences among the year intervals ($P < 0.05$).

3.2. Greenhouse Gas Emissions, Acidification potential and Eutrophication Potential

There were wide variations in the environmental impacts from crop production in Yunnan. During 2002–2021, the average GHG emissions from rice, wheat, and maize production in Yunnan were 545 kg CO_2 -eq Mg^{-1} , 808 kg CO_2 -eq Mg^{-1} , and 825 kg CO_2 -eq Mg^{-1} , respectively, the average AP of the three crop types was 10.3 kg SO_2 -eq Mg^{-1} , 18.2 kg SO_2 -eq Mg^{-1} , and 18.5 kg SO_2 -eq Mg^{-1} , respectively, and the average EP was 1.79 kg PO_4 -eq Mg^{-1} , 3.14 kg PO_4 -eq Mg^{-1} , and 3.20 kg PO_4 -eq Mg^{-1} , respectively (Figure 5). Over the 20-year period, the GHG emissions, AP, and EP from the rice and maize production systems showed a downward trend, whereas the related impacts of the wheat production system showed an upward trend. The application of agricultural materials in the MS stage was the largest contributor to GHG emissions in the rice, wheat, and maize production systems, whereas agricultural input in the FS stage contributed the most to AP and EP. For the same food crops, GHG emissions and the trends of AP and EP were the same in the four stages during 2002–2021 (Figure 5a–c, d–f, and g–i).

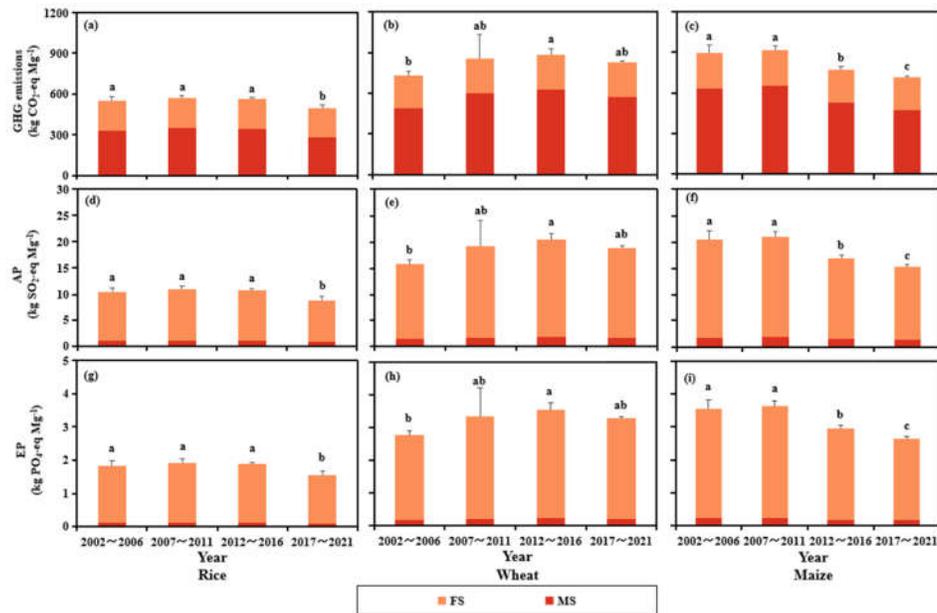


Figure 5. Environment impacts (global warming potential; acidification potential; eutrophication potential) of crop production from 2002 to 2021 across five-year intervals in Yunnan Province (20 samples). (a) Rice GHG emissions, (b) wheat GHG emissions, (c) maize GHG emissions, (d) AP of rice, (e) AP of wheat, (f) AP of maize, (g) EP of rice, (h) EP of wheat, (i) EP of maize were compared across five-year intervals. MS-Fertiliser, production and transportation of fertiliser at agricultural materials stage (MS); FS-Fertiliser, application of fertiliser at arable farming stage (FS). Different lowercase letters represent significant differences among year intervals ($P < 0.05$); means followed by the same small letter represent no significant difference between five-year intervals among different years at $P < 0.05$ according to LSD. Vertical bars represent \pm S.E. of the mean.

3.3. Correlations between Environmental Impacts and Influencing Factors

To analyse the factors influencing the environmental impacts, a correlation analysis was conducted between the environmental factors and the N surplus of the three crops with GHG emissions, AP, and EP. The N surplus affected the growth of rice, wheat, and maize (Figure 6). Notably, the environmental costs of rice production were greatly affected by the annual temperature (Figure 7). However, with changes in annual precipitation and temperature, the environmental impacts of wheat and maize showed no significant changes at the 0.05 level (Figures S1–S3). The environmental impacts of the rice, wheat, and maize production systems were positively correlated with N surplus, while the environmental impact of rice production was negatively correlated with temperature.

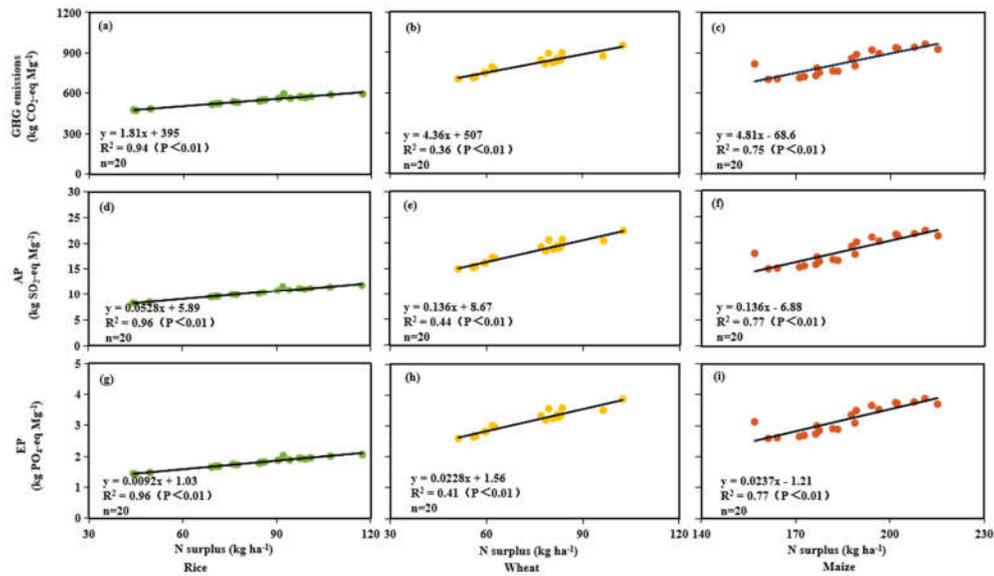


Figure 6. Correlations between N surplus and (a, b, c) GHG emissions, (d, e, f) the acidification potential, and (g, h, i) the eutrophication potential. The black solid line represents the linear correlation; green, yellow and orange dots represent mean GHG emissions, AP, and EP for rice, wheat, and maize production during 2002–2021 in Yunnan Province, respectively. $P < 0.01$ indicates the significance of the regression.

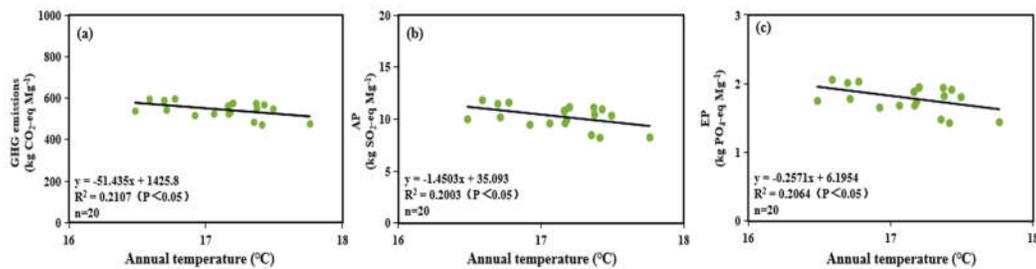


Figure 7. Correlations between environmental impacts of rice and annual temperature. The black solid line represents the linear correlation; green dots represent the average annual GHG emissions, AP, and EP of rice in Yunnan Province from 2002 to 2021. $P < 0.05$ indicates the significance of the regression.

3.4. Environmental Impacts and Mitigation Potential of Crop Production

The environmental risks from the grain crop production system in the plateau lake basin are significant, but there is great potential to reduce such risks. If the yield and N fertiliser input of crops maintained the average trend of the 20-year period studied, the environmental impacts of the three crops under the designed S1 scenario would undergo an upward trend. In the S2 scenario, the crops yield in the region with the amount of fertiliser used in S1 would be increased by 15%, but the AP and EP of the rice, wheat, and maize production systems would decrease by 13%. In S3 scenario, by applying innovative fertilisers, crop production would increase by 5.3%, while reducing the N fertiliser input by 24%. In addition, the AP and EP of rice, wheat, and maize would significantly decrease by 37%, and the GHG emissions would decrease by 22%, 29%, and 28%, respectively. Compared to S1, the comprehensive scenario (S4) combines crop sowing, nutrient regulation, crop management, and other aspects to achieve 75% of the regional yield potential. The greatest reduction in environmental risks would be associated with growing wheat, with reductions in GHG emissions, AP, and EP of 53%, 68%, and 68%, respectively. (Figure 8).

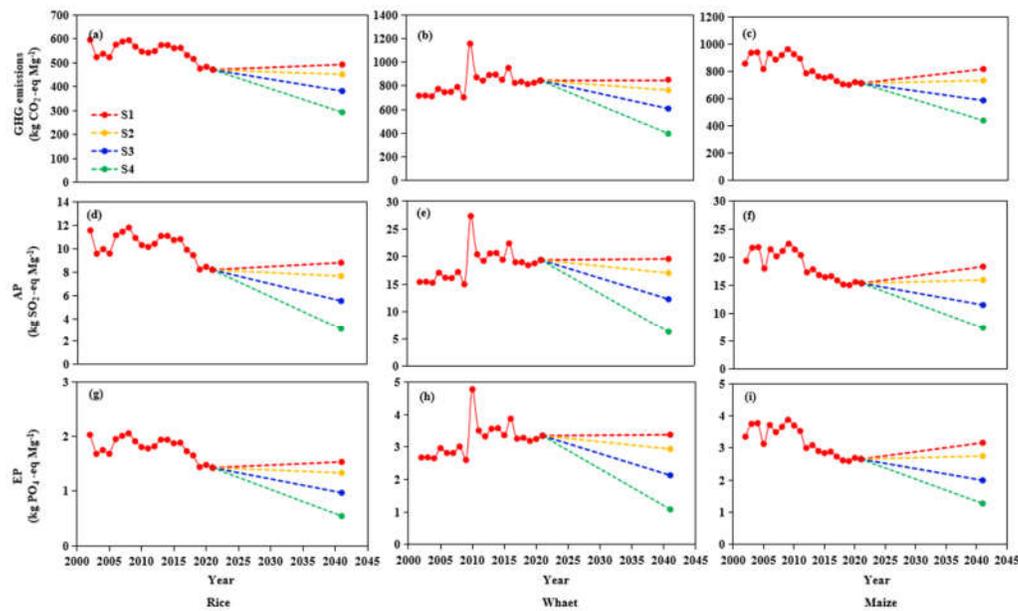


Figure 8. Projected greenhouse gas emissions, acidification, and eutrophication mitigation potential of rice, wheat, and maize production for 2041 in Yunnan, China. Red dots represent greenhouse gas emissions, acidification, and eutrophication from 2002 to 2021. Red dashed line (S1): projected greenhouse gas emissions, acidification, and eutrophication mitigation potential for 2041 following the trend observed from 2002 to 2021; orange dashed line (S2): increased yields of rice, wheat, and maize to 6.99 Mg ha^{-1} , 2.42 Mg ha^{-1} , and 5.09 Mg ha^{-1} , respectively, with the regional recommended fertiliser rate; blue dashed line (S3), replacing N fertiliser with controlled-release urea representing a yield increase of 5.3%, N input saving by 24.1% and decreases in reactive N losses after field application compared with S2 scenario; green dashed line (S4), grain yield reaches 75% of the global yield potential (8.10 Mg ha^{-1} , 6.70 Mg ha^{-1} , and 11.20 Mg ha^{-1} , respectively) with the same N fertiliser rate and resource as in scenario S3.

4. Discussion

4.1. Differences in Yield, Nutrient Input, and PFP-N

Crop production plays an important strategic role in sustainable development, stability, and regional security [42]. Owing to the agricultural sector adopting various modern technologies, the grain yield has significantly increased over the past few years [43]; however, the current most effective way of improving grain yield is to increase the amount of fertiliser applied [44,45]. In the present study, the average grain crop yields in Yunnan Province over the 20-year period studied were relatively low at 6.03 Mg ha^{-1} , 2.05 Mg ha^{-1} , and 4.3 Mg ha^{-1} for rice, wheat, and maize (Figure 3), respectively. These values were lower than the national average yields (rice: 7.0 Mg ha^{-1} , wheat: 5.7 Mg ha^{-1} , and maize: 7.6 Mg ha^{-1}) by 13.9%, 64.0%, and 41.7%, respectively [3,46,47], and considerably lower than yields of rice in southern China, wheat in Germany, and maize in the United States [48]. We found that in the past, the amount of N fertiliser input for rice and maize was higher than the national average amount [3], while the average PFP-N of grain crops production (28.95 kg kg^{-1} , 15.93 kg kg^{-1} , and 16.18 kg kg^{-1} , respectively) was lower than the 35.7%, 51.7%, and 62.4% of the national average PFP-N level of crop production (45 kg kg^{-1} , 33 kg kg^{-1} , and 43 kg kg^{-1} , respectively) (Figure 4) [3,49]. These results show that crop production in Yunnan is inefficient and the yields and economic benefits are low. Previous studies have shown that excessive N fertiliser application can lead to a decrease in the crop N absorption and utilisation efficiency, as well as to associated problems such as reduced crop production efficiency, increased resource consumption and environmental risks [50]. In this respect, the crop NUE is related to changes in the soil type, climate, crop rotation strategy, and variety of crop employed. Dobermann suggested that the target NUE of grain crops lie within

the range of 40–70 kg kg⁻¹, which is associated with the PFP–N of nitrogen fertiliser [51]. To meet the grain demand in the subtropical plateau region, improvements in the NUE are necessary to optimise the crop production efficiency in the region within the coming decades. When optimised fertiliser management techniques and agricultural management methods are applied to these good soil conditions and a reasonable planting density is adhered to, yield disparities can be reduced and the fertiliser utilisation efficiency can be improved [52–54]. Zhou et al. reported that optimising fertilisation can improve the NUE while increasing the yield by 13% to 15% [55]. To improve the yield and resource utilisation efficiency in subtropical plateau areas, it is necessary to comprehensively consider the climate, species and varieties grown, the cultivation measures employed, and the management practices employed in the soil crop system.

4.2. Characteristics of Environmental Impacts from Crop Production

It is important to study the environmental footprint of crop production to achieve sustainable development, efficient resource management, address climate change, and guide policymaking. In this study, the GHG emissions, AP, and EP of rice and maize production showed downward trends, whereas the environmental footprint of wheat production showed an upward trend, which was opposite to the change trend in the PFP–N of crops (Figure 5). Improvements in the NUE within crop production would reduce the environmental impacts. In this respect, a study found that optimising N fertiliser management reduced environmental risks and improved the ecological efficiency of crop production [20]. The GHG emissions, AP, and EP of European wheat are much lower than those of wheat produced in Yunnan, because the yield level of European wheat is much higher than that of Yunnan wheat [56,57]. And the input of N fertiliser and P₂O₅ fertiliser in maize production in the Yunnan Province is higher than that in the United States, resulting in a higher environmental impact on maize production in Yunnan compared to the United States [58] (Table 2). The GHG emissions of the main grain crops in this study area range from 471–962 kg CO₂-eq Mg⁻¹ (Figure 6), while the weighted average GHG emissions of vegetables produced in China are 116 kg CO₂-eq Mg⁻¹ [36]; this difference could be due to the fact that compared with vegetable crops, grain crops are more dependent on agricultural machinery [59]. However, these differences are not fixed and the GHG emissions of different types of vegetables and food crops in different regions and under different cultivation management practices may vary significantly. In this study area, the GHG emissions from the rice system are lower than those from the wheat and maize systems, while Chen et al. (2014) found that the total GHG emissions from rice in China are the highest [3]. The difference may depend on specific local conditions and other management practices, such as environmental conditions, soil types, agricultural management, variety characteristics, and nitrogen supply [60].

Table 2. Comparison of the Scope of environmental impacts between Yunnan Province and other regions.

	Unit	Rice		Wheat		Maize	
		Yunnan Province	Northeast China	Yunnan Province	Europe	Yunnan Province	America
Greenhouse gas emissions	kg CO ₂ -eq Mg ⁻¹	471–596	987–1486	702–951	610–650	700–962	254–824
Acidification potential	kg SO ₂ -eq Mg ⁻¹	8.2–11.8	–	15.3–22.4	4.9–6.5	15.0–22.4	2.7–7.8
Eutrophication potential	kg PO ₄ -eq Mg ⁻¹	1.4–2.1	–	2.6–3.9	5.0–7.6	2.6–3.9	0.7–2.3

Previous studies have shown that N surpluses generally increase with increasing N application [61–63]. This results in the loss of Nr to the air, water, and soil, thereby increasing the risk of

environmental pollution. For example, N leaching can lead to increased nitrate concentrations in water, resulting in soil acidification and water pollution. In addition, N emissions may lead to an increase in GHGs [62,64–67]. This study found a significant positive correlation between N surplus and the environmental footprint of grain crops in Yunnan Province, China (Figure 6).

In agricultural systems, N fertiliser is the most critical factor for improving the environmental impacts of crops production [68,69]. Therefore, it is necessary to reduce the N application rate and optimise N fertiliser management to reduce the N surplus and environmental load. It is worth noting that controlling N application does not necessarily reduce crop yield or crop production efficiency, but rather leads to crop production or increased environmental risks, as previously confirmed by research [56,70].

4.3. Mitigating the Environmental Impacts of Crop Production in Subtropical Plateau Regions.

Reducing the environmental impacts from growing major crops in subtropical plateau areas is a major challenge to sustainable agricultural development. The results of this study indicate that emissions from crop production in subtropical plateau areas can be effectively alleviated. Environmental emissions can be reduced by optimising the amount of N input and increasing the crop yield based on the current production level and the amount of nutrients input in the research area. The results of this study show that the N surplus in crop production is linearly correlated with environmental impacts (Figure 6). Through long-term experimental observations, Hu et al. (2023) found that optimising the N rate for high yield crops provided a high NUE and low environmental risks [71]. Certain measures reduce NH_3 volatilisation, such as using controlled-release fertilisers, reducing the amount of N input, using urease inhibitors, or using deep N fertilisation [72–74]. The S3 scenario in this study showed that replacing N fertiliser with controlled-release urea resulted in a 5.3% increase in the yield, savings of 24.1% associated with the amount of N input, and a decrease in active N loss after field application (Figure 8). In addition, pesticides and irrigation are also important factors affecting environmental impacts [75]. In crop production, it is necessary to control the use of pesticides and optimize irrigation to reduce environmental risks. The results of scenario S4 in this study showed that selecting appropriate varieties, sowing dates, planting densities, and advanced nutrient management (ISSM) have the greatest potential to reduce emissions from crop production in high subtropical regions [3] (Figure 8). Therefore, comprehensive agricultural management practices should be adopted for crop production in subtropical plateau areas to promote the sustainable development of agriculture and reduce environmental impacts and pollution.

4.4. Uncertainty

This study used the LCA method to quantify the environmental performance of the main crops production systems in Yunnan Province, China, and there are certain limitations associated with using this method for this study. First, the data sources for the planting area, energy consumption, fertiliser and pesticide use, and crops yields were obtained from national statistical data [24,25,27], and there are differences between these data and data from specific regions or farmlands; as such, the accuracy of the results could have been affected. The second limitation is associated with the uncertainty and variability of the EFs. This study selects IPCC emission factors to evaluate the environmental impacts of crops production in subtropical plateau areas, and LCA of crops production typically needs to consider changes on temporal and spatial scales. The subtropical plateau region can lead to uncertainty in emission factors due to its unique climate characteristics, geographical environment, soil types, and agricultural management practices [36,76]. The third limitation is the accuracy of determining the system boundary. An LCA relies on the scope and boundaries employed to conduct an assessment. Crops production involves a series of links, such as soil management, agricultural material manufacturing, planting methods, product processing, and transportation [77]; therefore, selecting certain boundaries may cause a degree of uncertainty. Crops production research should focus on addressing these limitations to improve the reliability and applicability of conducting LCAs. Nevertheless, this study provides basic information for understanding the impacts of pollutant emissions on crops production in subtropical plateau areas.

5. Conclusions

The LCA method was used to evaluate the environmental impacts of major food crops in Yunnan Province based on statistical data on crops production from 2002 to 2021. To explore emission reduction strategies for food crops production, further analyses were conducted to determine the main factors driving environmental impacts. The results indicated that over the 20-year period, the yield of grain crops and the amount of fertiliser used in Yunnan Province showed an upward trend, and GHG emissions associated with grain crop production mainly originated from the application of agricultural materials in the MS stage. The environmental footprint of crop production in Yunnan Province was found to be higher than that of other regions, and there was a highly significant correlation between N surplus and environmental impacts. Temperature also influenced the environmental impacts associated with growing rice. The scenario analysis showed that through crop sowing, nutrient regulation, and crop management, increased food crops yields could be achieved, while reducing environmental risks; moreover, emissions, AP, and EP from wheat production could be reduced by 53.1%, 67.9%, and 67.7%, respectively. This study provides a basis for managing the sustainable development of the main crops planting systems in subtropical plateau regions.

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Abbreviations

N, nitrogen;	MS, agricultural materials stage;
NUE, N use efficiency;	FS, farming stage;
LCA, life cycle assessment;	Nr, reactive nitrogen;
GWP, global warming potential;	GHG, greenhouse gas;
AP, soil acidification potential;	EP, water eutrophication potential;
NCP, China's North China Plain;	FPF–N, partial factor productivity of nitrogen

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