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Crop Structure Changes Altered the Cropland Nitrogen Balance between 2005 and 2015 on the Sanjiang Plain, China

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Abstract: Nitrogen (N) budgets have been computed in many countries at various scales to improve understanding of N-balance characteristics and to assess the environmental pollution risks of applying chemical fertilizer N. However, dynamic characteristics, driving forces, and potential soil fertility consequences related to cropland N balance have seldom been discussed, especially in regions with highly fertile soils and low N-use intensities. This study investigated the temporal and spatial characteristics of N balance, and the impact of agricultural development on the agro-ecosystems of the Sanjiang Plain, one of the largest producers of commodity food grains in China. County-level agricultural statistics at five-year intervals were used to calculate agricultural N balances, N surplus intensity, and N-use efficiency between 2005 and 2015. Agricultural development has brought about continual increases in cultivated land area, consumption of chemical fertilizers, and nitrogen use efficiency (NUE). Nitrogen surplus intensity decreased from 65.0 kg/ha in 2005 to 43.5 kg/ha in 2010, and to 22.2 kg/ha in 2015. However, NUE was >90% in 13 counties in 2015, and in 11 counties in 2010. In contrast, only 5 counties had NUE above 90% in 2005, which indicates that N from the soil was used by crops and soil fertility was gradually decreasing. The percentage change of crop area, namely, the increase in maize area percentage, contributed significantly to the increases in NUE. A judicious management of fertilizers that meets the nutrient needs of the crops and ensures agricultural sustainability on the Sanjiang Plain is therefore essential. The findings of this study emphasize the importance of assessing the impact of crop structure adjustment on soil fertility and nitrogen balance during agricultural development.

Keywords: nitrogen balance; agro-ecosystem; crop structure changes; environmental risk; Sanjiang Plain

1. Introduction

Food security, environmental degradation and climate change are significant challenges facing humankind. Agriculture is at the heart of these challenges, since it must seek to ensure global food security by increasing yields while adverse environmental impacts need to be reduced [1,2]. Nitrogen (N) is a key element in agricultural systems if high yields are to be achieved. Nitrogen deficiency negatively affects plant growth, whereas an N surplus can substantially reduce environmental quality and human well-being [3–5]. As recently as the 1960s, N availability in most parts of the world was controlled by natural processes and N was deficient in cropland [6]. However, the rapid development of the fertilizer industry provided a reliable supply of fertilizer N and other nutrients essential for plant growth, which has allowed farmers to considerably increase crop production per unit of land over the past century [7,8]. China has a large population and limited arable land per capita [9]. Increasing fertilizer inputs, especially N, is a common approach used to produce sufficient food for the rising population in China. In 1990, China consumed 19.2 Tg of N in the form of chemical fertilizers, a quarter of the world's total, and 32.6 Tg in 2010, a third of the world's total [10]. Unfortunately, because it is difficult to predict N fertilizer requirements accurately, N is often applied in excess of what the crop requires, which has unintended adverse consequences for the environment, including the degradation of downstream water quality and eutrophication of coastal marine ecosystems [3,6,11,12].

Nutrient balances are useful indicators of environmental risk or potential land degradation, and can optimize nutrient use [13–16]. The N balance is defined as the difference between the total quantity of nitrogen inputs (such as inorganic fertilizers, livestock manure, biological nitrogen fixation, and atmospheric deposition) and the size of the outputs (such as uptakes by harvested food and fodder crops) from agricultural land [17]. Nitrogen deficiency, N surplus, and N-use efficiency (NUE) in agricultural production are estimated on the basis of agricultural N budgets [4].

Agricultural nutrient balances differ substantially depending on the economic development level of the local economy [3]. The N balances of many developed and rapidly growing economies are positive, which indicates that nutrients are apparently accumulating. Nitrogen budgets have been computed in many countries at various scales to understand the N balance characteristics, to assess the potential pollution incurred due to excessive fertilizer N input, and to quantify feasible improvements in N-use efficiency by crops [3,17–20]. Most Chinese studies have focused on the excess input of chemical fertilizer N and chosen the most densely populated and agriculturally productive regions in China, such as the Changjiang River basin [21–23], the Haihe basin [24], and the Bohai Rim region [10]. However, N balance characteristics of regions with fertile soil and low input of chemical fertilizer N has seldom been discussed [25], and few studies pay attention to the variation of crop type and its effect on N budgets. In parts of many developing countries, such as sub-Saharan Africa and some provinces in China, agricultural nutrient inputs are insufficient to maintain soil fertility, which causes soil nutrient mining and threatens long-term food production [3,13,26,27]. China is the world's largest developing country and had a net excess N supply of 2.65×10^6 t in 2000, However, 37.68% of China's counties have a nitrogen deficit. Cropland in these counties represents 43.1% of the national total [26], but the characteristics and potential risks related to the N balance in these regions is seldom discussed [25,28].

It is against this background that this study set out to: (1) examine the N balance, spatio-temporal changes, and their driving forces in terms of NUE andN surplus intensity (NSI); and, (2) to provide a scientific basis for the spatio-specific management of fertilizer N on the Sanjiang Plain, which is dominated by human activity with low N fertilization and high-intensity agricultural exploitation.

2. Materials and Methods

2.1. Study Area

The Sanjiang Plain (43°49′55′′–48°27′40′′ N, 129°11′20′′–135°05′26′′ E) lies in the north-eastern part of Heilongjiang Province, China. It comprises 23 counties or cities, and is spread over 10.89×10^6 ha (Figure 1). According to data collected from the Chinese Academy of Agricultural Sciences, the total population in 2015 was 6.31 million, of which 47% was engaged in farming on the Sanjiang Plain. The Sanjiang Plain is formed by alluvial deposits from three rivers, namely, the Heilong River, the Wusuli River, and the Songhua River, and the elevation is less than 200 m in most parts. The climate is a temperate humid to sub-humid continental monsoon type. The annual mean temperature is 1.4–4.3 °C and ranges from −18 °C in January to 21–22 °C in July. The annual mean precipitation is 500–650 mm [29].

Sanjiang Plain, which has the largest and most concentrated area of freshwater wetlands in China, is also one of the largest producers of commodity food grains (cereals and pulses). Due to large-scale agricultural development, nearly 80% of the freshwater wetlands on the Sanjiang Plain were reclaimed over past decades [30]. Given its fertile soils, inputs of N as a chemical fertilizer for croplands can be as low as 0.05 t/ha, which is well below the national average of 1.27 t/ha [26]. However, with the development of agriculture, the use of N fertilizers on the Sanjiang Plain has increased gradually, and the resulting environmental risks can no longer be ignored.

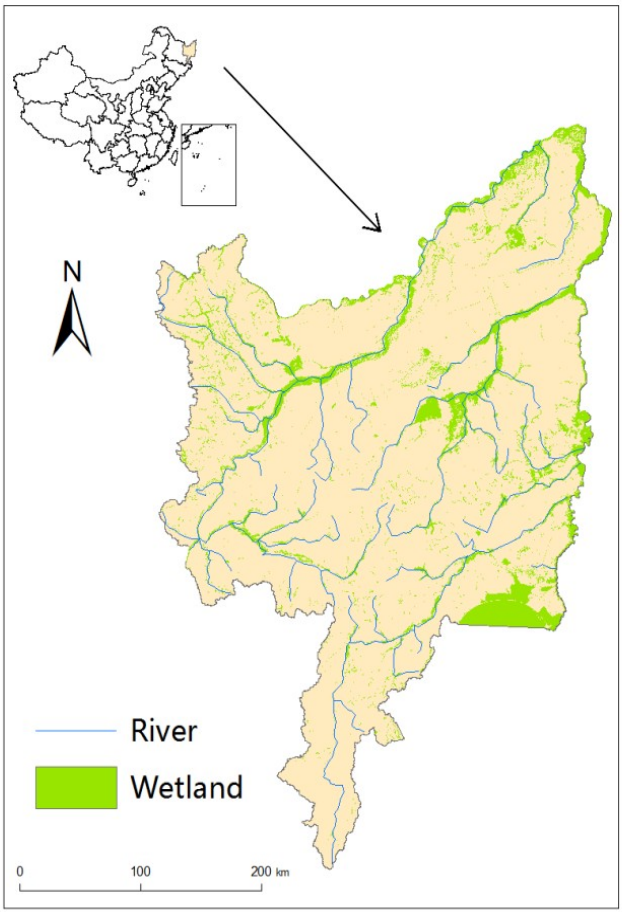

Figure 1. Location of the Sanjiang Plain, China.

2.2. County-Level Database

County-level agricultural statistics for 2005, 2010, and 2015 were used to calculate the N budgets for the Sanjiang Plain. The data, including the type and amount of fertilizers, crop yield and sowing area, and the extent of cultivated land, rice paddies, uplands, and livestock populations (numbers of pigs, sheep, cattle, etc.) were collected from the Chinese Academy of Agricultural Sciences. Data for irrigated land were collected from the China Statistical Yearbook for Regional Economy. The data were incomplete for Youyi County. Therefore, the regional average was used to replace the missing data. ArcGIS software developed by Environmental Systems Research Institute, Inc. (ESRI, CA, USA) was used to analyze spatial data. Finally, the N inputs and outputs were calculated at the county level.

2.3. Nitrogen Balance

Nitrogen balance was calculated as the difference between total N input and total N output. According to the Organization of Economic Cooperation and Development (OECD) methodology and other studies, chemical fertilizers, irrigation water, atmospheric deposition, human and livestock manure, and biological N fixation are counted as inputs, whereas uptake through the removal of harvested food and fodder crops are counted as outputs [21,22,31,32]. The flow diagram of the study for estimating the N balance is shown below (Figure 2).

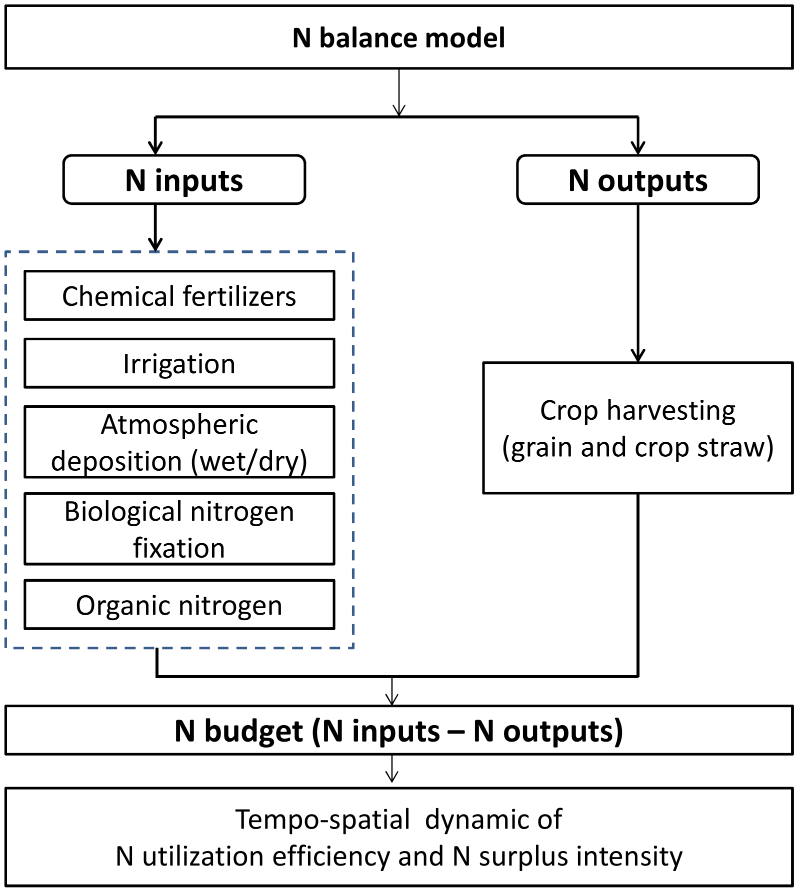

Figure 2. The conceptual diagram of the N balance model.

- Chemical fertilizers ($N_{chemical}$)

Chemical fertilizers are always considered the largest source of N in an agro-ecosystem, and chemical fertilizer N can come from both pure N fertilizers ($N_{nitrogen}$) and compound fertilizers ($N_{compound}$). Compound fertilizers in north-eastern China contain N, P, and K in a 1.0:2.0:0.2 ratio [33]. Therefore, the N content of the compound fertilizers is 31%.

$$N_{chemical} = N_{nitrogen} + 31\% N_{compound}$$

- Irrigation ($N_{irrigation}$)

Uplands accounted for 65% of the arable land on the Sanjiang Plain. Irrigation water always contains some N, mostly leached from fertilizers, and human and animal waste. Therefore, N concentrations are relatively high in all intensively cultivated regions [22,34]. The annual N input from irrigation ($N_{irrigation}$) was calculated by multiplying the irrigated area ($A_{irrigation}$) by 27.25 kg/ha of N, which is the midpoint of the range of 25.8–28.7 kg/ha, as given by Li and Jin [33].

$$N_{irrigation} = 27.25 \times A_{irrigation}$$

- Atmospheric deposition (wet/dry) ($N_{atmospheric}$)

Atmospheric deposition, whether wet or dry, is an important source of N. Wet deposition delivers nutrients that are dissolved in precipitation, and the amount of N was estimated by multiplying the concentration of inorganic N in precipitation (7.57 kg/ha) by the cultivated land area (A) [33,35]. Dry deposition amounts are significant, but difficult to measure. According to the commonly used method of Lovett and Lindberg [36], total (wet + dry) N deposition is two times the wet deposition.

$$N_{atmospheric} = 2 \times (7.57 \times A)$$

- Biological nitrogen fixation ($N_{biofixation}$)

Nitrogen is also introduced into agricultural systems in significant quantities by symbiotic and non-symbiotic N fixation. In this study, only soybean was taken into account as a symbiotic N-fixing crop because the planted area of other symbiotic N-fixation crops was very small. The annual N-fixation rate of soybean was taken as 139.25 kg/ha (midpoint of 128.5–150 kg/ha) on the Sanjiang Plain [33,37]. The cultivation of rice and other non-leguminous crops is an additional source of N fixation by microorganisms. As suggested by Li and Jin [33], the annual rate of non-symbiotic N fixation in rice paddies was taken as 44.8 kg/ha and, in uplands, it was 15 kg/ha. Nitrogen input from biological N fixation for each crop was the product of the sowing area ($A_{soybean}$, $A_{uplands}$ and A_{paddy}) and the N fixation rates for each crop.

$$N_{biofixation} = 139.25 \times A_{soybean} + 15 \times A_{uplands} + 44.8 \times A_{paddy}$$

- Organic nitrogen ($N_{organic}$)

Organic N includes inputs from human and livestock waste recycled as manure and straw, and used to fertilize the soil. Human and animal waste in rural areas of China is commonly used as manure. The annual N input from human (N_{human}) or livestock ($N_{livestock}$) manure is the product of the populations in rural areas of humans (P_{human}) and livestock ($P_{livestock}$) and the amount of N excreted by each individual (E). According to studies by Bao et al. [21], Smil [34] and Xing and Yan [38], the mean annual values for this source of N are 5, 8, 40, and 5 kg/capita for humans, pigs, cattle, and sheep, respectively. According to Xing and Zhu [12], 40% of human and animal waste is used as manure and applied to crops. A conversion factor of 0.85 should be used to estimate the total rural adult population proportion of the total rural population.

$$N_{human} = P_{human} \times 0.85 \times 5 \times 0.4$$

$$N_{livestock} = \sum_{i=1}^{n} 0.4 \times P_{livestock} \times E$$

The amount of N added to the land as manure in the form of straw (N_{straw}) was estimated based on the concentration of N in crop residues (E_i), the proportion of straw returned to the field (R_i), the straw to grain yield ratio (K_i), and crop yield (Y_i) of the four major crops (rice, wheat, maize and soybean) [21,33,38].

$$N_{straw} = \sum_{i=1}^{n} E_i \times R_i \times K_i \times Y_i$$

- Nitrogen output/crop harvesting ($N_{harvest}$)

Crop harvesting (both grain and crop straw were included) is the most important sink for N input and is the only output considered in this study. It was calculated by multiplying crop yield (Y_i) by the N requirement (R_i) of the crop per unit yield [33]. Ten major crops were taken into account and their R_i was suggested by Li and Jin [33], Zheng et al. [24].

$$N_{harvest} = Y_i \times R_i$$

2.4. Nitrogen Surplus Intensity, Nitrogen Use Efficiency

The N surplus intensity of a county is defined as the N balance value divided by the arable land area of that county. A positive value for NSI indicates that residual N in the soils may constitute a potential environmental risk. Nitrogen use efficiency is defined as the fraction of N input harvested as a product. A higher NUE indicates that more N was used by the agro-ecosystem. Nitrogen use efficiency has been proposed as an indicator of progress in achieving the Sustainable Development Goals recently accepted by 193 member-countries of the United Nations General Assembly [7,24]. The international recommended value for NUE is 50–90%, and improving it is one of the most effective means of increasing crop productivity while decreasing environmental degradation [7,39]. However, an NUE of greater than 90% implies mining of N from the soil, which is caused by an inadequate N input and can lead to land degradation [39].

2.5. Statisical Analysis

Regression analyses were conducted between primary NUE, N input intensity and change, cultivated area percentages, area changes for different crops, and changes in NUE of the cropland between 2005 and 2015 on the Sanjiang Plain. The analyses were used to reveal the factors driving NUE change caused by variation in N input intensity and crop area percentage. All analyses were conducted using the software Stata (version 14.0; Stata MP, College Station, TX, USA).

2.6. Uncertainty Analysis of N Budgets

Since the parameters used in the study originated from literatures and were extrapolated to the Sanjiang Plain (N deposition rate and soybean N fixation rates were excluded because they were parameters directly related to the Sanjiang Plain), a sensitivity analysis was performed by Monte Carlo simulations in Crystal Ball software (Decisioneering, Inc., Denver, CO, USA) run 20,000 times for 2005 to quantify the overall uncertainty in N balance. For N content of compound fertilizer, a coefficient of variation (CV) of 5% was assumed. For irrigation N factor, the CV was assumed to be 45%. The CVs for both uplands and paddy field N fixation were assumed to be 35%, and for N excreted by human and livestock, CVs of 30% were assumed [40,41].

3. Results

3.1. Agricultural Development and Crop Yield

Although the general population increased from 7.2×10^6 in 2005 to 7.4×10^6 in 2010 and then decreased to 6.3×10^6 in 2015, the rural population steadily decreased from 3.3×10^6 in 2005 to 3.2×10^6 in 2010, and 3.0×10^6 in 2015. A decrease of the rural population isn't usually beneficial to agricultural production. However, the cultivated land area and consumption of chemical fertilizers increased over the decade by 39.2% and 45.1%, respectively. The total production of major food grains, including maize, soybean, and rice, also increased from 7763.5×10^6 kg in 2005 to $18{,}464.8 \times 10^6$ kg in 2015 (Table 1), all of which indicated that agricultural activity on the Sanjiang Plain had substantially intensified.

On the Sanjiang Plain, the fertilizer N application rate increased from 82.6 kg/ha in 2005 to 86.2 kg/ha in 2015, a minor increase of 4.3%, in sharp contrast with the increase of chemical fertilizer N, which could be attributed to the reclamation of cultivated land. Correspondingly, the yields of major food grains (maize, soybean, and rice) increased from 4012.1 kg/ha in 2005 to 6616.5 kg/ha in 2015, an increase of 64.9% (Table 1).

Table 1. Population, cultivated land area, consumption of chemical fertilizers, and crop production in 2005, 2010, and 2015 on the Sanjiang Plain.

Parameter	2005	2010	2015	2015–2005 (%)
Population (10^6)	7.2	7.4	6.3	−12.7
Rural population (10^6)	3.3	3.2	3.0	−11.1
Livestock population (cattle, pigs, sheep) (10^6)	7.0	8.3	8.5	20.6
Cultivated land area (10^5 ha)	21.9	28.6	30.4	39.2
Chemical fertilizers (10^4 t N)	18.1	24.9	26.2	45.1
Total food grain production (10^6 kg)	7763.5	13,783.0	18,464.8	137.8
Productivity of food grains (kg/ha)	4012.1	5120.2	6616.5	64.9
N fertilizer rate (kg/ha)	82.6	86.9	86.2	4.3

Data was collected from the Chinese Academy of Agricultural Sciences.

3.2. Nitrogen Input, Output, and Agricultural Balance

Nitrogen input increased from 47.2 × 10^4 t in 2005 to 58.8 × 10^4 t in 2010, but then decreased to 51.5 × 10^4 t in 2015. Chemical fertilizers and biological fixation were the two major sources of N, which together accounted for 77.5% of the total input in 2005, 76.5% in 2010, and 71.6% in 2015. Both the amount and the percentage of chemical fertilizer N increased over the period, and it became the largest N input in 2015, contributing51.0% of the total. However, biological N fixation, the largest source of N input in 2005, decreased from 18.5 × 10^4 t in 2005 to 10.6 × 10^4 t in 2015, which was a decrease of 42.7%. The proportion of biologically fixed N to the total input correspondingly decreased from 39.2% in 2005 to 20.6% in 2015. Total N output increased from 33.0 × 10^4 t in 2005 to 44.8 × 10^4 t in 2015, and the largest harvested crop N was 46.4 × 10^4 t in 2010. Soybeans, maize, and rice were the three major N input sinks, accounting for 92.4% of the N in harvested crops in 2005, 94.8% in 2010, and 97.3% in 2015. Soybeans dominated total N output in 2005 and was displaced by maize in 2015.

Nitrogen budgets for croplands were constructed by calculating the difference between all N inputs and outputs. Although both N input and N output increased substantially between 2005 and 2015, the N budget decreased from 14.2 × 10^4 t in 2005 to 6.7 × 10^4 t in 2015, with N input exceeding N output by 43.0% in 2005 and by 15.0% in 2015. Correspondingly, NSI decreased continuously, from 65.0 kg/ha in 2005, to 43.5 kg/ha in 2010, and to 22.2 kg/ha in 2015. NUE increased continuously over the period, from 69.9% in 2005, to 78.8% in 2010, and to 86.9% in 2015 (Table 2). The region displayed a low surplus during the period.

Table 2. Estimated inputs and outputs for agricultural nitrogen on the Sanjiang Plain.

N Budget Term	2005		2010		2015	
	Amount (10^4 t N)	% of Input	Amount (10^4 t N)	% of Input	Amount (10^4 t N)	% of Input
Input						
Chemical fertilizers	**18.1**	**38.3**	**24.9**	**42.3**	**26.2**	**51.0**
Irrigation	**0.9**	**1.9**	**1.7**	**2.9**	**2.2**	**4.2**
Atmospheric deposition	**3.3**	**7.0**	**4.3**	**7.3**	**4.6**	**9.0**
Biological fixation	**18.5 (17.3–19.7)**	**39.2**	**20.11 (18.9–21.3)**	**34.2**	**10.6 (10.3–10. 9)**	**20.6**
Non-symbiotic	2.4		4.2		6.7	
Symbiotic	16.1 (14.8–17.3)		15.9 (14.7–17.2)		3.9 (3.6–4.2)	
Recycled N	**6.4**	**13.6**	**7.8**	**13.3**	**7.9**	**15.4**
Animal waste	3.8		4.1		4.0	
Human waste	0.6		0.6		0.2	
Crop residue	2.1		3.2		3.7	
Total input	**47.2 (46.0–48.4)**		**58.8 (57.6–60.1)**		**51.5 (51.2–51.8)**	
Output						
Harvested crops						
Wheat	0.3		0.02		0	
Maize	6.3		17.5		28.0	
Rice	4.2		6.8		10.2	
Soybeans	20.0		19.7		5.4	
Tuber crops	0.1		0.1		0.3	

Table 2. *Cont.*

N Budget Term	2005		2010		2015	
	Amount (10^4 t N)	% of Input	Amount (10^4 t N)	% of Input	Amount (10^4 t N)	% of Input
Oil crops	0.4		1.3		0.3	
Sugar beet	0.2		0.1		0	
Tobacco	0.1		0.2		0.1	
Vegetables	1.4		0.7		0.5	
Fruits	0.1		0.2		0.02	
Total output	**33.0**		**46.4**		**44.8**	
Budget (input–output)	**14.2**		**12.4**		**6.7**	
Nitrogen surplus intensity (kg/ha)	**65.0**		**43.5**		**22.2**	
Nitrogen use efficiency (%)	**69.9**		**78.8**		**86.9**	

Any data error is caused by rounding.

3.3. Spatial Patterns of Nitrogen Use Efficiency and Nitrogen Surplus Intensity

Although NUE increased between 2005 and 2015 on the Sanjiang Plain, it varied widely among the counties, with ranges of 35.2–99.7% in 2005, 42.6–155.0% in 2010, and 19.0–145.8% in 2015. The NUE for 13 counties, which accounted for 63.6% of the arable land, was higher than 90% in 2015, compared to 11 counties in 2010, and five in 2005.

There was also an uneven spatial distribution for NSI at the county level. The figures ranged from 0.4 kg/ha to 177.6 kg/ha in 2005, −52.9 kg/ha to 175.1 kg/ha in 2010, and −55.2 kg/ha to 166.5 kg/ha in 2015. The spatial distributions for NSI and NUE on a county scale are shown in Figure 3.

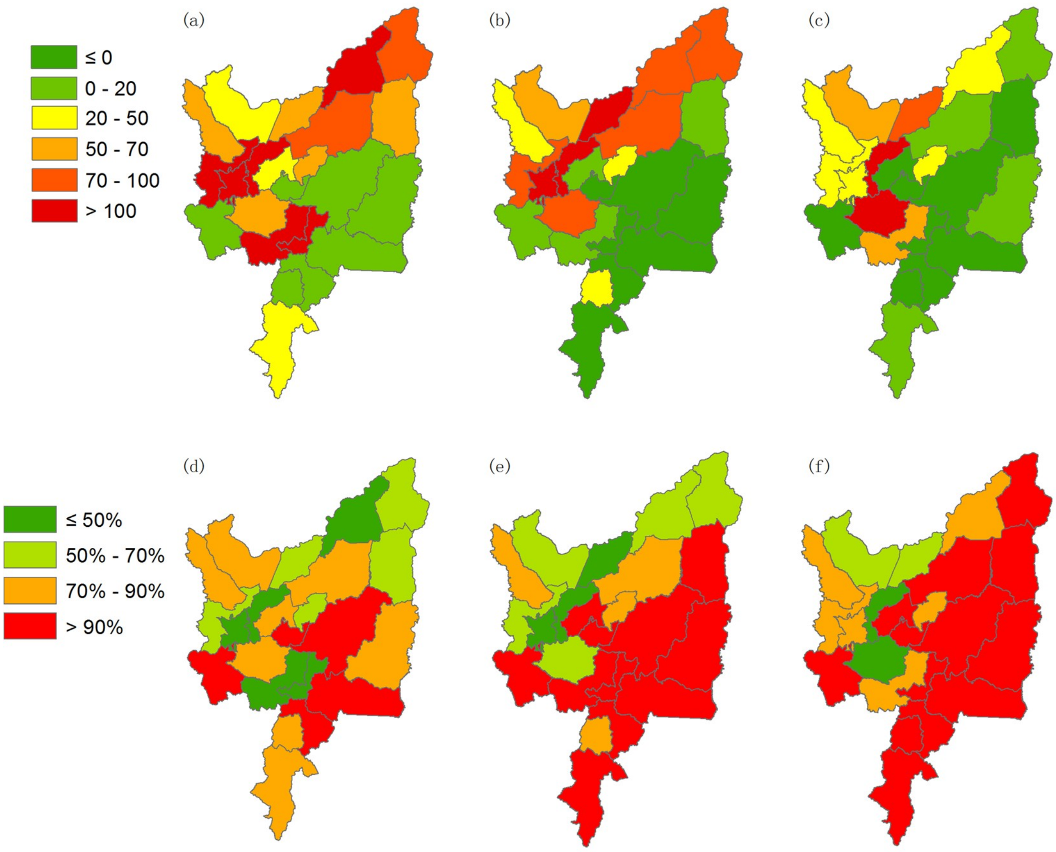

Figure 3. Nitrogen surplus intensity (NSI, kg/ha) (**a**) 2005, (**b**) 2010, (**c**) 2015, and nitrogen use efficiency (NUE) (**d**) 2005, (**e**) 2010, (**f**) 2015.

3.4. Impacts of Agricultural Development on NUE

Regression analysis illustrated that the changes in NUE between 2005 and 2015 were negatively correlated with NUE in 2005 ($p < 0.1$), N input per unit area in 2005 ($p < 0.1$), and changes in N input per unit area between 2005 and 2015 ($p < 0.01$), but positively correlated with changes in the area percentage for maize ($p < 0.1$) (Table 3).

Table 3. Factors associated with the NUE changes in cropland between 2005 and 2015 on the Sanjiang Plain.

	Coefficients	Standard Error
Constant	92.020	86.834
NUE in 2005	**−0.990** *	0.393
N input per unit area in 2005	**−0.372** *	0.161
Change in N input per unit area between 2005 and 2015	**−0.341** ***	0.081
Area percentage under soybean in 2005	0.552	1.138
Change in area percentage under soybean between 2005 and 2015	0.446	0.938
Area percentage under rice in 2005	0.416	0.699
Change in area percentage under rice between 2005 and 2015	0.164	0.543
Area percentage under maize in 2005	1.092	1.119
Change in area percentage under maize between 2005 and 2015	**0.781** †	0.424
R^2	0.554	-
N	**22**	-

Unit of analysis is the county. Dependent variable is NUE change between 2005 and 2015. Model results passed standard regression diagnostics. † $p < 0.1$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

3.5. Uncertainty Analysis of N Budgets

After running 20,000 Monte Carlo simulations, the average N budget was 14.2×10^4 t with a 90% certainty range of $11.3–15.7 \times 10^4$ t. Paddy field N-fixation rates and N excreted by each unit of cattle were two dominant variances, which accounted for 36.0% and 35.4% of the variability of the N budget, respectively (Figure 4).

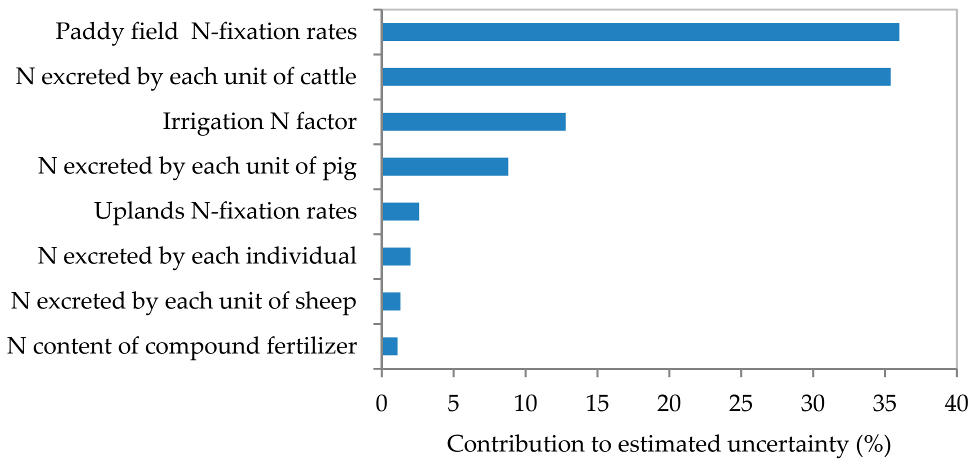

Figure 4. Contributions of parameters to variability of N budget of 2005.

4. Discussion

Although the N budget for farmland decreased between 2005 and 2015 on the Sanjiang Plain, it continued to be positive, which meant that excess N was lost to the environment. However, the N balance on the Sanjiang Plain was much less than that in the Changjiang and Haihe River basins [21,22,24]. The NSI for the Sanjiang Plain was much lower than that in the Haihe basin (158.8 kg N/ha in 2010), and the average NSIs for China (142.8 kg/ha in 2004 and 168.6 kg/ha in 2015) and the U.K. (51 kg/ha in 1995) [24,42,43]. It is also far below the standard limit (60 kg N/ha for sandy soils and 100 kg N/ha for clay soils) for nitrate leaching into groundwater and surface water on a regional or national scale [44]. Since N balance is positively related to chemical fertilizer input [31,45,46], the reduced NSI may be due to the low input of synthetic N fertilizers. The ratio of fertilizer N to total N input, which was 38.3–51.0% on the Sanjiang Plain, was much lower than in other Chinese provinces (except Tibet) [26]. Usually, about 70% of the N comes from chemical fertilizers in China [19,26]. Although the fertilizer N application rate increased by 4.3% over the ten years, it is markedly lower than the national average, and is also below the recommended rate for high yields [19].

Nitrogen use efficiency was 86.9% in 2015, which indicates that less than 15% of N input was lost in the agro-ecosystems. Previous studies revealed that NUE was 23% in the Changjiang River basin, and 42% in the Haihe basin [22,24], which were much less than NUE of the Sanjiang Plain. According to Smil [34], global NUE in crop biomass was 50% (46–56%) for all sources of N inputs. Research by Zhang et al. [7] showed that global average NUE in crop production needs to reach 70% by 2050 to meet the dual goals of food security and environmental stewardship. Alternatively, NUE only needs to rise to 60% in China due to large regional differences in crop production and China's development stage. Therefore, at least to some extent, fertilizer N can increase crop production on the Sanjiang Plain while still minimizing the adverse environmental and health impacts of N. Compared to the North China Plain, the Sanjiang Plain has less N fertilizer utilization, which could result from higher soil fertility and long-term fertilization practices in the region. Figure 3 suggests that the spatial differences in NUE and NSI mean that N deficiency in croplands was more serious in 2015 than 2005. The internationally recommended value for NUE is 50–90% [7,39] and NUE of greater than 90% implies mining of N from the soil, which is caused by inadequate N inputs [39]. However, the results showed that 56.5% of the counties had NUE of more than 90% in 2015, whereas this figure was 21.7% in 2005 for the Sanjiang Plain. Although the total N content in the soil on the Sanjiang Plain was greater than that in other Chinese districts, the soil inorganic N content was insufficient to satisfy plant nutrient needs [25]. Furthermore, following wetland and forest reclamation, the soil N content decreased substantially [47]. Also, prolonged cultivation may have further decreased the stock of soil nutrients [48,49]. Previous results have showed significant decreases in the soil organic carbon density in the black soils of northeast China [50]. High-intensity agriculture and the decrease in soil N content mean that if the negative nutrient balances and mining of soil N continue, soil degradation is inevitable and will threaten long-term food production [27]. A NUE value of higher than 100% may be explained by the assumption of no changes in soil nitrogen stock in the study [4].

Regression analysis was used to illustrate the main factors influencing the changes in NUE. It indicated that the changes in NUE between 2005 and 2015 were positively correlated with changes in the area percentage of maize ($p < 0.1$), which implies that the spatial variation in NUE may be related to the rapid expansion of agriculture and changes in planting structure while inputs of chemical fertilizer N are maintained. In the decade from 2005 to 2015, the area under the three main crops (soybean, maize, and rice) on the Sanjiang Plain increased from 19.3×10^5 ha to 27.9×10^5 ha (a 44.2% increase), and the soybean, maize, and rice share of the total cultivated area increased from 88.5% in 2005 to 91.7% in 2015. Furthermore, food grain production increased by 34.0% over the same period. However, the area under soybean decreased by 75.6% from 2005 to 2015. Therefore, the rise in cultivated land is due to the sharp increases in the maize and rice areas (332.3% and 128.7%, respectively). The corresponding changes in the production of these three crops were −72.4%, 342.3%, and 140.0%, respectively (Figure 5). It is generally known that soybean can support itself through biological N fixation, whereas maize produces higher yields. However, increasing the area planted with maize requires more N fertilizer. The shift from soybean to maize may lead to the mining of soil N since the utilization rate for N fertilizer has not improved.

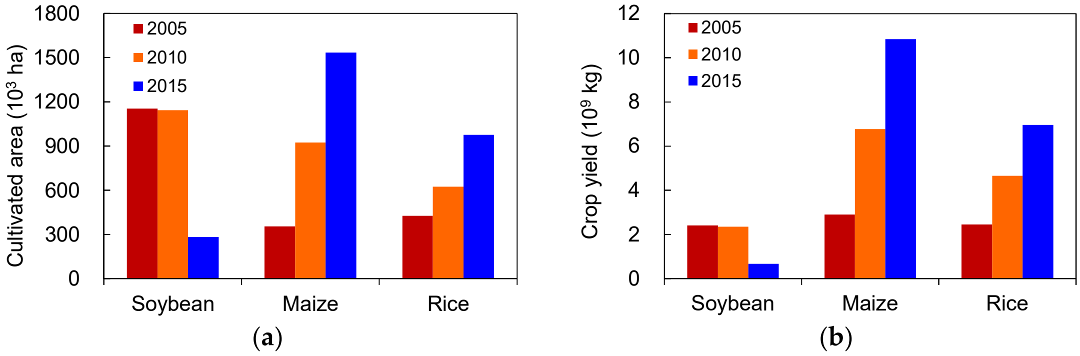

Figure 5. Cultivated area (**a**) and yield (**b**) of soybean, maize, and rice on the Sanjiang Plain in 2005, 2010, and 2015.

The driving forces behind this structural adjustment in planting were shifts in government policies. Since 2004, a series of policies were implemented in China to ensure stable grain production and to safeguard farmer interests, including food subsidies, abolishing agricultural taxes, and a minimum assured support price for food grains [51,52]. As a result, forest lands and wetlands were reclaimed and converted into cropland. Furthermore, since 1995, when China began importing soybean because of high production costs and the low oil yield of domestically produced soybean, the economic efficiency of soybean production has been lower than that of the major competing crops, such as maize and rice [53,54].

It is well known that accurate nutrient budgets for large regions are difficult to prepare. Firstly, it is difficult to measure N input from atmospheric deposition and biological N fixation, which explains why estimates were based on a number of parameters (Figure 4). However, parameter values were originally generated for different purposes. Furthermore, only the agro-ecosystem was taken into account, whereas forests, wetlands, and other ecosystems, which may also influence the N balance of an agro-ecosystem, were not included. However, to our knowledge, this study is the first attempt to quantify the N balance of the agro-ecosystem on the Sanjiang Plain and to analyze the impact of agricultural development on the N budget. The research suggests that high NUE and low NSI can threaten the sustainability of agriculture in the Sanjiang Plain due to degrading soil fertility and poor management caused by low fertilizer N inputs and high-intensity agriculture. The findings emphasize the importance of monitoring and assessing the impact of crop structure adjustment on N balance and soil fertility during agricultural development, which can help inform future efforts to support sustainable cropland management in similar areas of the world. Better management is urgently required to meet the nutrient needs of crops without adversely affecting the environment to ensure the sustainability of agriculture. There are many possible approaches to achieve this goal [24,33,47], such as the judicious application of chemical fertilizers targeted toward food productivity based on the characteristics of each crop; increasing applications of organic manure to replenish soil nutrients extracted during crop harvesting; and monitoring soil quality and nutrient losses. Attention should also be paid to other agricultural system outputs and their effects on factors such as air and water, biological diversity, and human health and well-being [4].

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