

## Article

# Targeting Hotspots to Achieve Sustainable Nitrogen Management in China's Smallholder-Dominated Cereal Production

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**Abstract:** Agriculture in China, which is dominated by millions of smallholders, consumes 30% of global nitrogen (N) fertilizers and results in a high surplus and vast spatial variability of N. Identifying the N-management practices of smallholder farmers is critical to pursuing sustainable agricultural productivity. However, at the national scale, N budgets and spatial distribution based on first-hand data from smallholder farmers are not well characterized. Here, using data collected from a national survey involving 7.3 million farmers from 2005 to 2014, we quantified N budgets, evaluated their spatial variation, and revealed “hotspots” of low N removal and high N surplus for wheat, maize, and rice systems at the county level. The N surplus for cereal crops was 122–140 kg N ha<sup>-1</sup>, which is equivalent to an annual N surplus of 11.3 megaton (Mt). Chemical N was the most important contributor to the N surplus, while farmers used manure N less than 10% of the total N input. N budgets exhibited vast spatial variation at the county level, and the hotspots contributed to 56% of the total N surplus in China. Targeted efforts for eliminating hotspots could increase N removal by 13–21%, increase N use efficiency to 0.55–0.70, and significantly reduce the N surplus for all counties and crops, by 42%. Based on farmer survey data, our results provide updated estimates of N budgets and highlight hotspots of N surplus for cereal crop systems in China. They provide a benchmark for the development of new agricultural N management policies and technologies in the country.

**Keywords:** agriculture; nitrogen surplus; nitrogen use efficiency; spatial variation; county level; smallholder



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## 1. Introduction

Feeding a growing population sustainably is essential for achieving the United Nations' Sustainable Development Goals [1]. As inefficient use of nitrogen (N) in agriculture poses serious challenges to food security and the environment, balancing N inputs/outputs, especially in intensive agriculture regions, is essential for simultaneously addressing productivity and sustainability [2–4]. Quantifying the variation in N budgets within and across regions is a prerequisite for balanced N management [5]. For example, only 10% of the world's croplands accounts for 32% of the global N surplus [6]. Thus, targeted policies and management in high N surplus regions could improve the balance between productivity and sustainability.

China accounts for 30% of the global chemical N fertilizer use, but only 9% of global agricultural land, and cereal crops account for nearly 70% of the total planting area, consuming more than half of total N fertilizers [7,8]. High N inputs and surpluses have been reported widely in various regions [4,9–11]. For example, it is common for farmers to apply  $\geq 300$  kg N ha<sup>-1</sup> of fertilizer to wheat fields in the North China Plain [12,13]. Several factors contributed to the high N surplus for the cereal crop systems in China. First, this is partly explained by the relatively low price of N fertilizers compared with the values of land,

labor, and crops [14]. Second, small farm sizes and high inter-farm variation deter farmers from adopting optimized N-management technologies. For example, a small farm size is associated with a low level of mechanization and inhibits the application of precision fertilization techniques. A household survey showed that a 1% increase in farm size in China reduces the use of fertilizer by 0.3% per hectare [15,16]. Third, most farmers are poorly educated and lack scientific guidance for optimizing N-management techniques, which leads them to apply excessive fertilizer to ensure high yields [17]. Fourth, the lack of agro-environmental policies may contribute to the N surplus in China. At present, China has no specific agro-environmental laws and regulations [18]. Moreover, China has become the largest producer of livestock and poultry in the world, with huge amounts of organic N excretion and great spatial variation reported [19,20]. With the separation of livestock and cultivation [21], it is also necessary to assess how much organic N is put into farmland and crops to plan for better use of organic nutrients.

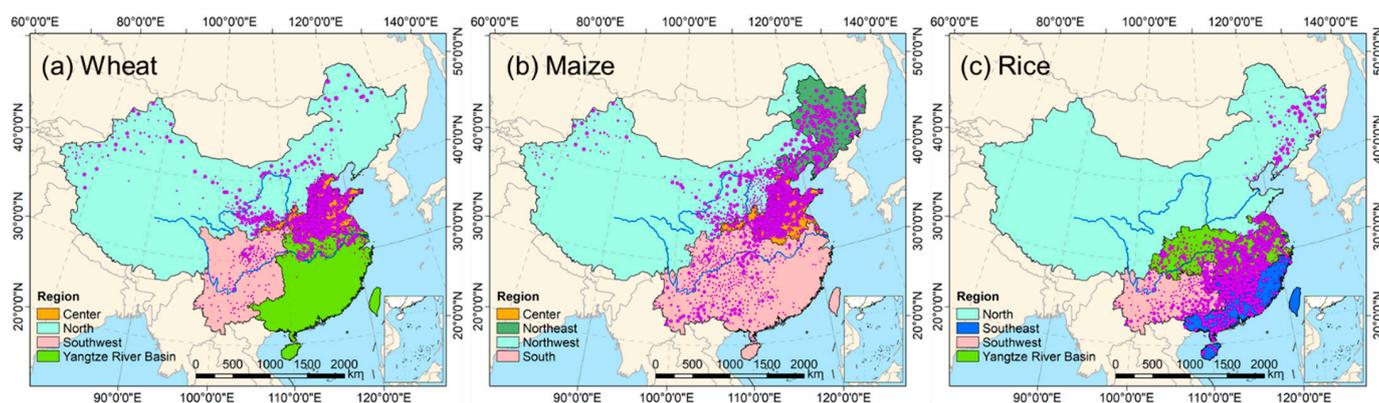
In China, there are 200–300 million households engaged in agriculture, and each typically farms only a few hectares, which leads to great variability among farmers and regions and difficulties in managing N [16,22,23]. Previous studies have reported regional and national agricultural N budgets based primarily on data from regional and national censuses (e.g., China's statistical data) or model simulations [24–26]. Nevertheless, Chinese statistics generally do not include details of chemical and organic N use for specific crops. Furthermore, for smallholder-dominated Chinese agriculture, it is critical to identify farmer practices in N management to pursue sustainable agricultural productivity [17,27]. However, at the national level, there are very few first-hand data from smallholder farmers pertaining to N management in cereal production.

To date, it has not been possible to perform a detailed analysis of the N budget in China due to the lack of a spatially explicit dataset based on smallholders across China; thus, policy-makers and industry lack the tools and information needed to identify optimal choices. To fill this knowledge gap, we first investigated field-level and county-level N budgets of the three main cereal crops (i.e., wheat, maize, and rice) in China based on a survey of 7.3 million farmers in 1747 counties conducted during the 2005–2014 period. Then, we diagnosed the N surplus status for each county with a N removal–surplus framework. This framework enabled the identification of “hotspots” with low N removal and high N surplus. Finally, pathways of targeted hotspots and partial hotspots were suggested, and their performance was assessed to address productivity and sustainability.

## 2. Materials and Methods

### 2.1. Data Collection

A nationwide survey of farmers was organized by the Ministry of Agriculture and Rural Affairs of China and carried out by various local agrotechnical extension departments from 2005 to 2014. We collected survey data from 31 provincial administrative regions of China. The spatial distribution of the survey data is depicted in Figure 1. We filtered the data and included a total of 1747 counties (916 counties for wheat, 1324 counties for maize, and 886 counties for rice) encompassing 7.3 million individual farmers. We collected data on grain yield, the chemical N application rate, manure varieties, and the manure application rate. Cereal crops are cultivated across China, from frigid to subtropical and from arid and semiarid to humid regions. On the basis of climatic conditions, geographical location, and cropping system (e.g., crop type, rotation, rainfed, or irrigation), we categorized the production systems into four agroecological zones for each crop [27].



**Figure 1.** Major regions and distribution of the survey data for each county of wheat (a), maize (b), and rice (c) in China from 2005 to 2014, respectively. The size of the points represents the number of farmers in each county.

## 2.2. Definitions and Parameters of N Budgets

For the purposes of this study, the N budgets consisted of input, removal, and surplus items. N input, removal, and surplus were defined as shown in Equations (1)–(3):

$$N_{in} = N_{fer} + N_{man} + N_{dep} + N_{fix}, \quad (1)$$

$$N_{rem} = N_{grain} + N_{sr}, \quad (2)$$

$$N_{sur} = N_{in} - N_{rem}, \quad (3)$$

where  $N_{in}$  is the total N input,  $N_{fer}$  is the chemical N fertilizer input,  $N_{man}$  is the manure N input,  $N_{dep}$  is the N input from wet and dry atmospheric deposition,  $N_{fix}$  is the N from biological fixation,  $N_{grain}$  is the N harvested in grain,  $N_{sr}$  is the N in crop straw removed from the field,  $N_{rem}$  is the N removal with  $N_{grain}$  and  $N_{sr}$ , and  $N_{sur}$  is the N surplus based on the difference between  $N_{in}$  and  $N_{rem}$ . We defined N use efficiency (NUE) as the ratio of  $N_{rem}$  to  $N_{in}$ .

$N_{fer}$  was taken directly from the farmer survey data.  $N_{man}$  was calculated by multiplying the manure rate of the different manure varieties (e.g., cattle slurry, pig slurry, mutton slurry) from the farmer survey data by the respective N content. Due to the lack of updated parameters, the N contents of different manure varieties were taken from the “Nutrient Content in Organic Fertilizer of China” report [28].  $N_{dep}$  was taken from Xu, et al. [29]. We matched the deposition value of each county with the corresponding region in Xu, et al. [29]. We adjusted the deposition values to approximate the growth periods of wheat, maize, and rice.  $N_{fix}$  was acquired from Smil [30]: 5 kg N ha<sup>-1</sup> for wheat and maize and 30 kg N ha<sup>-1</sup> for rice. There are few studies on N fixation by cereal crops, so it was very difficult to provide different parameters for crops in each region or county. Therefore, only one parameter was used for each crop in this study.  $N_{grain}$  and  $N_{sr}$  were calculated by multiplying the grain yield (Figure S1) by the grain N concentration and harvest index. Grain N concentration and harvest index parameters were based on the published literature (Table 1). Straw cycling ratios were taken from Zhang, et al. [31]: 0.74 for wheat, 0.30 for maize, and 0.42 for rice.

**Table 1.** N concentration in grain and N harvest index for wheat, maize, and rice.

| Crop         | Grain N Concentration (g kg <sup>-1</sup> ) | N Harvest Index | Data Source             |
|--------------|---|-----------------|-------------------------|
| Wheat        | 21.1  | 0.77            | Yue et al., 2012 [32]   |
| Spring maize | 11.6  | 0.61            | Zhang et al., 2012 [33] |
| Summer maize | 12.7  | 0.59            | Yan et al., 2016 [34]   |
| Rice         | 11.9  | 0.65            | Xu et al., 2015 [35]    |

### 2.3. Calculation of Gross N Budgets

We calculated the gross N surplus according to the farmer survey data combined with the crop planting area for each county and for all of China. At the county level, N budget items (unit:  $\text{kg N ha}^{-1}$ ) from the farmer survey were calculated based on a 10-year average. Meanwhile, we collected crop planting area data from 2005 to 2014 from the county statistical yearbook and other accessible materials. We used a 10-year average to calculate planting area. The totals of the surveyed counties accounted for 86%, 89%, and 72% of the gross planting areas for wheat, maize, and rice, respectively. Herein, N budgets at the regional (agroecological zones) and national scales were calculated by weighting the planting area according to the values for each county. We derived the gross N budgets (unit: megaton, Mt) at the regional and national scales based on the proportion of each county's planting area for each crop relative to the total planting area in China. The total planting area for each crop was the 10-year average obtained from the National Bureau of Statistics of China from 2005 to 2014.

### 2.4. Classification of Farmers and Definition of Hotspots

To delineate the N surplus at the field level further, we ranked the N surplus of all farmers in each county from high to low, screened out the farmers whose N surplus was ranked in the top 10%, and calculated the average value to obtain the N surplus of the top 10% in each county. We used the same method to arrange the N surplus ( $\text{kg N ha}^{-1}$ ) of each county across the whole of China, calculated the total N surplus and planting area in the top 10% to top 50% of counties, respectively, and then calculated the percentage of each level of the national total.

Management of N must meet the dual objectives of environmental protection and food security. In this study, we defined and distinguished hotspots of N budgets and then designed a strategy for the improvement of N management for cereal crops. First, the surveyed counties were divided into four types based on N removal and N surplus, namely, Win–Win (counties with high N removal and low N surplus), Win–Lose (counties with high N removal and high N surplus), Lose–Win (counties with low N removal and low N surplus), and Lose–Lose (counties with low N removal and high N surplus). Hotspots were defined as counties with low N removal and high N surplus (Lose–Lose). Based on previous research [36], the boundaries of N surplus and N removal were calculated based on the socially optimal N rate and grain yields of the three cereal crops in China.

### 2.5. Improvement Strategy Scenarios

Two scenarios were developed to explore improvement strategies for sustainable N management of the three cereal crops in China. Scenario 1 (S1) was established to eliminate hotspot counties (i.e., the Lose–Lose type) by improving N removal (basically, improving grain yield) and decreasing the N surplus (mainly, reducing N inputs) for hotspot counties until Win–Win thresholds are reached. The other three types remain with their N removal and N surplus rates unchanged. Scenario 2 (S2), built on S1, aimed to achieve sustainable N management of cereal crops in all regions of China fully. It was considered that the Win–Lose and Lose–Win types of farmers partly achieved sustainable N management. We assumed that N surplus and removal could be optimized further by adopting technologies for these two types. In this scenario, the N surplus of the Win–Lose types is reduced and the N removal of the Lose–Win types is increased until Win–Win thresholds are reached, and the N removal and surplus of Win–Win-type counties remains unchanged (Figure 5a). The calculation of total N budgets kept the planting area unchanged.

### 2.6. Data Processing and Analysis

Analysis of data was performed using Microsoft's SQL server 2012 (Microsoft Corp, Redmond, WA, USA). All map-related operations were performed with ArcGIS 10.2 software ([www.esri.com/en-us/arcgis](http://www.esri.com/en-us/arcgis) (accessed on 25 May 2020)). The N budget for each county was matched to the layers to depict the spatial variations, and the map was obtained

from the Resource and Environment Data Cloud Platform (<http://www.resdc.cn> (accessed on 25 May 2020)).

### 3. Results

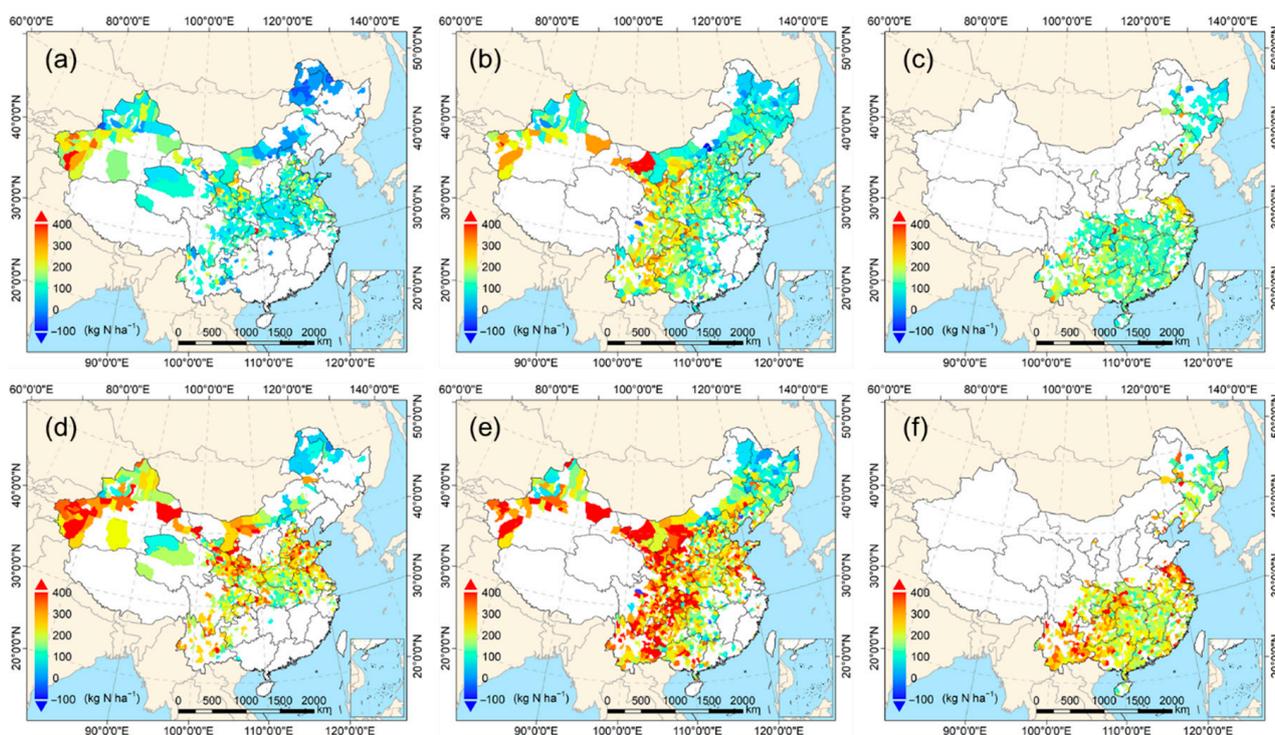
#### 3.1. N Budgets and Spatial Variation in Cereal Crops

Our estimate revealed a positive  $N_{sur}$  for the three cereal crops from 2005 to 2014 (Table 2). The county area-weighted average  $N_{sur}$  of wheat, maize, and rice was 122, 134, and 140 kg N ha<sup>-1</sup>, respectively (Figure 2a–c, Table 3), which is equivalent to 11.3 Mt N per year when calculated according to the total planting area of the three crops in China. The  $N_{sur}$  in all counties ranged from −18 to 505 kg N ha<sup>-1</sup> for wheat, −134 to 538 kg N ha<sup>-1</sup> for maize, and −97 to 562 kg N ha<sup>-1</sup> for rice. Spatial variation in N budgets was present across different regions (Figures 2 and S1–S3).

**Table 2.** N budgets for wheat, maize, and rice in agricultural production in China.

| N Budgets (Mt) | Wheat | Maize | Rice | Total |
|----------------|-------|-------|------|-------|
| $N_{fer}$      | 4.70  | 6.43  | 5.22 | 16.4  |
| $N_{man}$      | 0.33  | 0.63  | 0.32 | 1.28  |
| $N_{dep}$      | 0.48  | 0.64  | 0.59 | 1.71  |
| $N_{fix}$      | 0.12  | 0.16  | 0.89 | 1.17  |
| $N_{in}$       | 5.63  | 7.86  | 7.02 | 20.5  |
| $N_{rem}$      | 2.71  | 3.57  | 2.89 | 9.16  |
| $N_{sur}$      | 2.91  | 4.29  | 4.14 | 11.3  |

Abbr.  $N_{fer}$ , Chemical N input;  $N_{man}$ , Manure N input;  $N_{dep}$ , N deposition;  $N_{fix}$ , N biological fixation;  $N_{in}$ , Total N input;  $N_{rem}$ , N removal;  $N_{sur}$ , N surplus.



**Figure 2.** N surplus for wheat ( $n = 916$ ), maize ( $n = 1324$ ), and rice ( $n = 886$ ) in agricultural production in China. Average N surplus for wheat (a), maize (b), and rice (c); top 10% N surplus for wheat (d), maize (e), and rice (f).  $n$  indicates the number of counties.

**Table 3.** N budgets for wheat, maize, and rice in different regions of China. n indicates the number of counties.

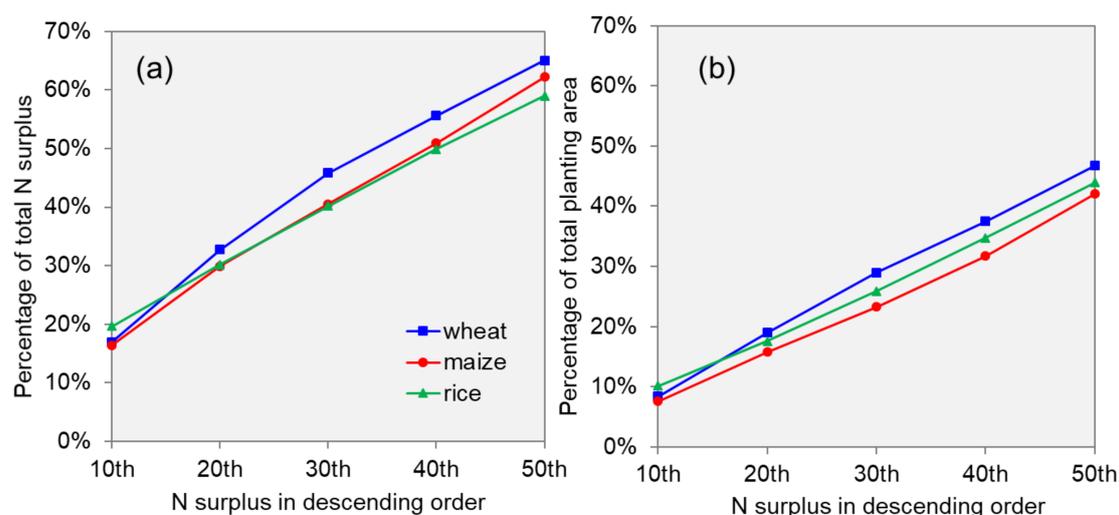
| Crop  | Region              | Planting Area | n    | $N_{in}$              | $N_{fer}$             | $N_{man}$             | $N_{rem}$             | $N_{sur}$             |
|-------|---------------------|---------------|------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
|       |                     | million ha    |      | kg N ha <sup>-1</sup> |
| Wheat | North               | 4.00          | 258  | 218                   | 158                   | 35                    | 89                    | 128                   |
|       | Yangtze River Basin | 3.55          | 145  | 223                   | 192                   | 6                     | 103                   | 120                   |
|       | Center              | 14.5          | 346  | 250                   | 217                   | 8                     | 128                   | 122                   |
|       | Southwest           | 1.90          | 167  | 184                   | 129                   | 31                    | 74                    | 110                   |
|       | Total               | 23.9          | 916  | 235                   | 197                   | 14                    | 113                   | 122                   |
| Maize | Northeast           | 11.3          | 164  | 217                   | 178                   | 14                    | 122                   | 95                    |
|       | Center              | 9.79          | 347  | 239                   | 211                   | 3                     | 105                   | 134                   |
|       | Northwest           | 5.51          | 310  | 282                   | 214                   | 43                    | 123                   | 159                   |
|       | South               | 5.39          | 503  | 280                   | 217                   | 38                    | 88                    | 192                   |
|       | Total               | 32.0          | 1324 | 246                   | 201                   | 20                    | 112                   | 134                   |
| Rice  | North               | 2.82          | 105  | 211                   | 157                   | 4                     | 107                   | 105                   |
|       | Yangtze River Basin | 13.6          | 352  | 252                   | 190                   | 11                    | 101                   | 151                   |
|       | Southeast           | 9.31          | 238  | 220                   | 163                   | 7                     | 91                    | 129                   |
|       | Southwest           | 3.89          | 191  | 245                   | 173                   | 22                    | 95                    | 150                   |
|       | Total               | 29.6          | 886  | 237                   | 176                   | 11                    | 97                    | 140                   |

Abbr.  $N_{in}$ , Total N input;  $N_{fer}$ , Chemical N input;  $N_{man}$ , Manure N input;  $N_{rem}$ , N removal;  $N_{sur}$ , N surplus.

The total  $N_{in}$  was 20.5 Mt, of which 74–84% came from  $N_{fer}$ , 5–8% from  $N_{man}$ , 8% from  $N_{dep}$ , and 2–13% from  $N_{fix}$ . The  $N_{in}$  values for wheat, maize, and rice were 235 (39–574), 246 (29–632), and 237 (50–655) kg N ha<sup>-1</sup>, respectively (Figure S2).  $N_{fer}$  was the largest input item. The average  $N_{fer}$  for wheat, maize, and rice was 197, 201, and 176 kg N ha<sup>-1</sup>, respectively.  $N_{man}$  was another major anthropogenic N input item of  $N_{in}$ , but it contributed only 11–20 kg N ha<sup>-1</sup> to the total N input (Table 3). Counties with  $N_{man}$  values > 40 kg N ha<sup>-1</sup> accounted for only 13–26% of all surveyed counties, and these were found mainly in southwest and northwest China (Figure S2). In comparison with  $N_{man}$  and other input items, fertilizer N input, to a considerable extent, contributed substantially to the N surplus across the whole of China (Figure S3). Most counties (93%, 94%, and 97% of the counties surveyed for wheat, maize, and rice, respectively) had  $N_{fer}$  surpassing  $N_{rem}$ . By contrast,  $N_{man}$  in exceedance of  $N_{rem}$  occurred in only a few counties (<5% of counties surveyed nationwide) in the northwest and southwest.

Total  $N_{rem}$  was 9.16 Mt, with values of 113 (8–237), 112 (7–241), and 97 (40–147) kg N ha<sup>-1</sup> for wheat, maize, and rice, respectively (Figure S1). The counties with  $N_{rem}$  values > 120 kg N ha<sup>-1</sup> comprised only 32%, 22%, and 7% of all counties for wheat, maize, and rice, respectively, at the national scale. The widespread  $N_{in}$ , which was far greater than  $N_{rem}$ , resulted in low NUE for cereal crops (Figure S4). The national average NUE was 0.45 (0.48, 0.45, and 0.41 for wheat, maize, and rice, respectively). Approximately 35–46% of the counties surveyed had an NUE below 0.4 for all three crops (Figure S4).

We further calculated the N surplus for the top 10% farmers of each county, which averaged 227–242 kg N ha<sup>-1</sup> for the three cereal crops (Figure 2d–f). When calculated according to the total planting area, these farmers accounted for 16–19% of the total N surplus of the three cereal crops. For counties with a higher N surplus than the national average, the N surplus of their top 10% farmers was even more problematic and conspicuous (Figure 2). The regions in central China for wheat, northwest and south China for maize, and the Yangtze River Basin for rice were typical regions with high N surplus at the county level, and N surplus values > 300 kg N ha<sup>-1</sup> for the top 10% farmers occurred mainly in these regions (Figure 2d–f). Especially for maize, the N surplus of the top 10% farmers in the south and northwest was more than 400 kg N ha<sup>-1</sup>. The cumulative change in N surplus with respect to the total amount and proportion of planting area showed that approximately one-third of the surveyed counties contributed ~50% of the N surplus with only 30% of the planting area (Figure 3).

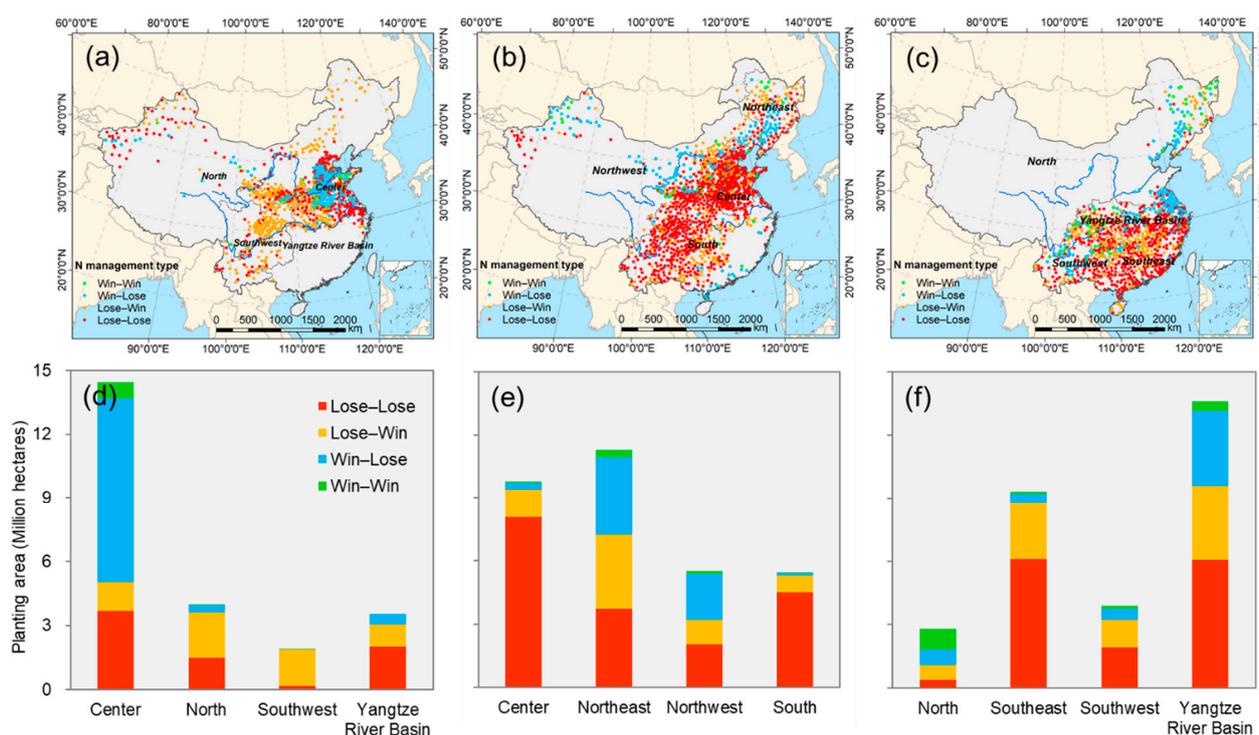


**Figure 3.** The cumulative percentage of the total N surplus (a) and total planting area (b) when the N surplus per unit area of each county is arranged in descending order.

### 3.2. Hotspot Counties in Terms of N Budgets

Here, we set limits on N removal and N surplus rates to define hotspot counties. All surveyed counties were divided into four types: Win (high N removal)–Win (low N surplus), Win–Lose, Lose–Win, and Lose–Lose (defined as hotspots) (Methods, Figure 4). The results showed that only 2–6% of the surveyed counties were Win–Win-type counties (Table 4). Of the surveyed counties, 33–63% were hotspots, accounting for 31%, 57%, and 49% of the total planting area for wheat, maize, and rice, respectively (Figure 4), and all hotspots contributed to 44% (4.03 Mt) of the total  $N_{rem}$  and up to 56% (6.37 Mt) of the total  $N_{sur}$  (Table 4). For wheat, central China and the Yangtze River Basin were the two major agroecological zones with concentrated hotspot counties, with hotspots in these two regions accounting for 77% of the total wheat hotspot areas. For maize, hotspot counties contributed to 70% (3.02 Mt) of its 4.29 Mt N surplus. Hotspot counties accounted for a substantial proportion (33–83%) of each maize agroecological zone, especially in central and southern China. In these two regions, hotspot counties accounted for 83% of the planting area in their respective agroecological zone. For rice, there were few hotspots (14% of the total planting area) in northern China, whereas hotspots in the other three agroecological zones covered approximately half of each planting area (65%, 49%, and 44% in the southeast, southwest, and Yangtze River Basin, respectively).

In addition to the hotspots, Win–Lose and Lose–Win counties were also worthy of attention. Win–Lose counties, with higher N removal, contributed to 31% (2.82 Mt) of total N removal with 25% of the total planting area (Figures 4 and S1, and Table 4). The central area for wheat, northeast region for maize, and Yangtze River Basin for rice were the main distribution areas of Win–Lose counties. The N removal values in these Win–Lose counties were 137, 143, and 115 kg N ha<sup>-1</sup>, respectively, which were 21%, 28%, and 19% higher than the national average. Lose–Win counties, with a low N surplus, had N surplus values for wheat, maize, and rice of 83, 62, and 98 kg N ha<sup>-1</sup>, respectively, which were 32%, 54%, and 30% lower than the national average (Table 4). Overall, Lose–Win counties contributed to only 15% (1.73 Mt) of the total N surplus with 25% of the total planting area.



**Figure 4.** Four types of N management counties for cereal crops in China. Spatial distribution of four types of N management counties for wheat ((a), n = 916), maize ((b), n = 1324), and rice ((c), n = 886). The total planting area of the four types of N management counties in each agroecological zones for wheat (d), maize (e), and rice (f). Win–Win, counties with high N removal & low N surplus; Win–Lose, counties with high N removal & high N surplus; Lose–Win, counties with low N removal & low N surplus; Lose–Lose, counties with low N removal & high N surplus. Each point represents a county in (a–c), n indicates the number of counties.

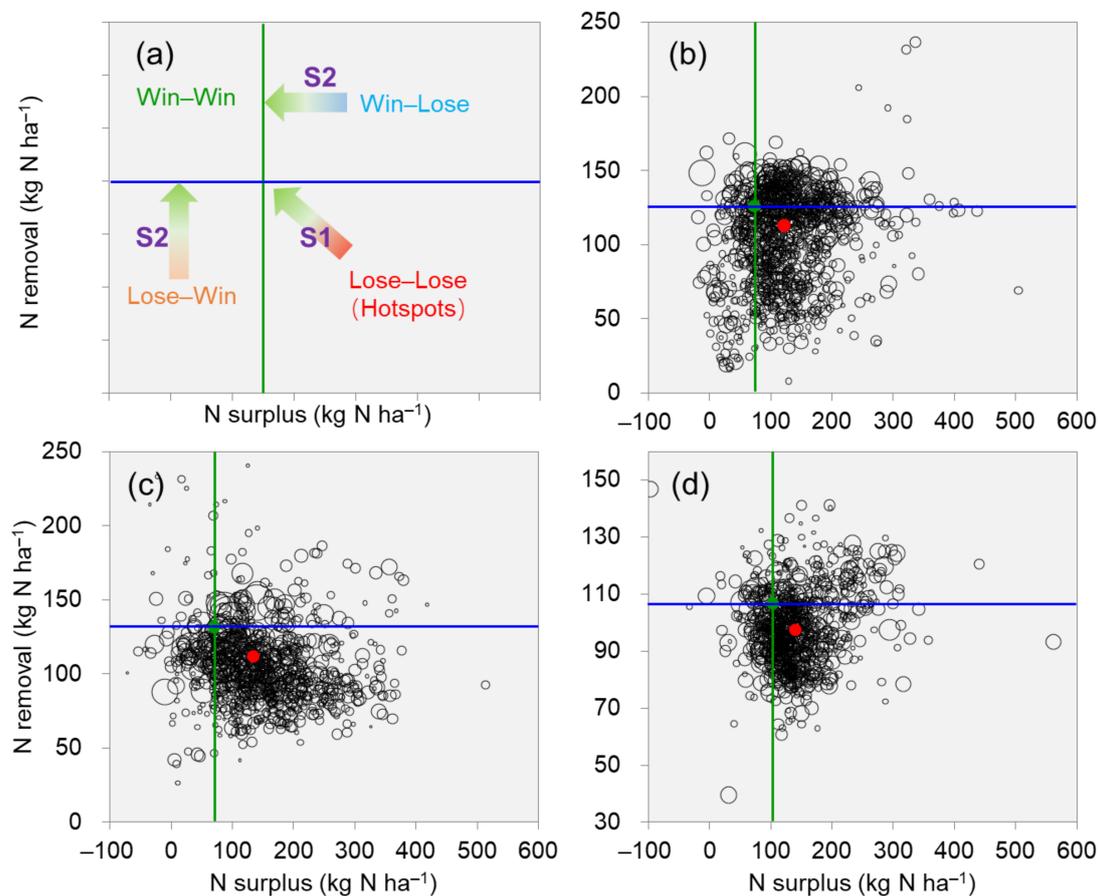
**Table 4.** Total N budgets of different N management types for wheat, maize, and rice in China. n indicates the number of counties.

| Crop  | Types     | Planting Area | n    | Total $N_{in}$ | Total $N_{rem}$ | Total $N_{sur}$ |
|-------|-----------|---------------|------|----------------|-----------------|-----------------|
|       |           | million ha    |      | (Mt)           | (Mt)            | (Mt)            |
| Wheat | Win–Win   | 0.8           | 21   | 0.14           | 0.11            | 0.03            |
|       | Win–Lose  | 9.5           | 222  | 2.58           | 1.30            | 1.27            |
|       | Lose–Win  | 6.2           | 368  | 1.00           | 0.49            | 0.51            |
|       | Lose–Lose | 7.4           | 305  | 1.91           | 0.81            | 1.10            |
|       | Total     | 23.9          | 916  | 5.63           | 2.71            | 2.92            |
| Maize | Win–Win   | 0.6           | 26   | 0.13           | 0.08            | 0.05            |
|       | Win–Lose  | 6.3           | 175  | 1.73           | 0.92            | 0.81            |
|       | Lose–Win  | 6.8           | 286  | 1.11           | 0.69            | 0.42            |
|       | Lose–Lose | 18.3          | 837  | 4.90           | 1.88            | 3.02            |
|       | Total     | 32.0          | 1324 | 7.86           | 3.57            | 4.29            |
| Rice  | Win–Win   | 1.7           | 52   | 0.31           | 0.20            | 0.12            |
|       | Win–Lose  | 5.2           | 177  | 1.57           | 0.60            | 0.97            |
|       | Lose–Win  | 8.2           | 219  | 1.55           | 0.75            | 0.80            |
|       | Lose–Lose | 14.5          | 438  | 3.59           | 1.34            | 2.25            |
|       | Total     | 29.6          | 886  | 7.02           | 2.89            | 4.14            |

Abbr.  $N_{in}$ , N input;  $N_{rem}$ , N removal;  $N_{sur}$ , N surplus.

### 3.3. Targeting Hotspot Regions for Sustainable N Management

Sustainable N management must meet the dual objectives of environmental protection and food security. Compared to the Win–Win types, surveyed counties of all other types, especially hotspot counties, were associated with more unsustainable risks and larger gaps to change. As mentioned previously, two scenarios were developed to explore improvement strategies for the sustainable N management of three cereal crops in China (Figure 5). S1 was established simply to eliminate the hotspot counties. S2, which built on S1, aimed to achieve fully sustainable N management of cereal crops in all regions of China. If S1 could be implemented, N removal would increase by 10%, whereas N surplus would decrease by 27% to 8.3 Mt. This would be accompanied by an average 13% reduction in N fertilizer inputs. Furthermore, if all of these counties could achieve the Win–Win goal of high N removal and low N surplus, crop yield and N removal would increase by 13–21% and N surplus would be reduced by 33–56%. The corresponding N fertilizer inputs would be reduced by 20–26%, and NUE would be increased to 0.55–0.70 (Table 5). In the end, the estimated N surplus for all counties and crops would decrease by 42% from the current 11.3 Mt to 6.0 Mt after optimization.



**Figure 5.** Scenarios for the sustainable N management of cereal crops in China. (a) concept graph of the two scenarios. Scenario 1 (S1) was set to eliminate the hotspot counties, to improve N removal and decrease N surplus to the Win–Win boundaries. Scenario 2 (S2) built on S1, aiming to fully achieve sustainable N management of cereal crops in all regions of China. N surplus of Win–Lose types reduced to and N removal of the Lose–Win types increase to the Win–Win boundaries, and the N removal and surplus of Win–Win types maintained unchanged. Current N surplus and removal status in county level for wheat ((b),  $n = 916$ ), maize ((c),  $n = 1324$ ), and rice ((d),  $n = 886$ ) in agricultural production in China. Each circle represents a county, and the size of the circle represents the relative planting area of each crop in its county, the red dots in the figure are the current average value. The blue and green line represent the N removal and surplus boundaries of the Win–Win types.

**Table 5.** Scenarios of N management for wheat, maize, and rice in agricultural production in China. The numbers in parentheses indicate the change for Scenario 1 (S1) and Scenario 2 (S2) compared to the Current.

| Crop  | Scenarios | Yield (t ha <sup>-1</sup> ) | $N_{fer}$ (Mt) | $N_{in}$ (Mt) | $N_{rem}$ (Mt) | $N_{sur}$ (Mt) | $N_{sur}/Yield$ (kg kg <sup>-1</sup> ) | NUE        |
|-------|-----------|-----------------------------|----------------|---------------|----------------|----------------|--|------------|
| Wheat | Current   | 5.8                         | 4.7            | 5.6           | 2.7            | 2.9            | 21.0                                   | 0.48       |
|       | S1        | 6.1 (4%)                    | 4.3 (−9%)      | 5.2 (−8%)     | 2.8 (4%)       | 2.4 (−19%)     | 16.4 (−22%)                            | 0.54 (13%) |
|       | S2        | 6.7 (15%)                   | 3.5 (−25%)     | 4.5 (−21%)    | 3.1 (15%)      | 1.4 (−53%)     | 8.5 (−59%)                             | 0.70 (44%) |
| Maize | Current   | 7.7                         | 6.4            | 7.9           | 3.6            | 4.3            | 17.4                                   | 0.45       |
|       | S1        | 8.9 (15%)                   | 5.2 (−19%)     | 6.7 (−15%)    | 4.1 (15%)      | 2.6 (−40%)     | 9.0 (−48%)                             | 0.62 (36%) |
|       | S2        | 9.4 (21%)                   | 4.8 (−26%)     | 6.2 (−21%)    | 4.3 (21%)      | 1.9 (−56%)     | 6.3 (−64%)                             | 0.70 (53%) |
| Rice  | Current   | 7.2                         | 5.2            | 7.0           | 2.9            | 4.1            | 19.4                                   | 0.41       |
|       | S1        | 7.8 (8%)                    | 4.7 (−11%)     | 6.5 (−8%)     | 3.1 (8%)       | 3.4 (−19%)     | 14.6 (−25%)                            | 0.48 (17%) |
|       | S2        | 8.1 (13%)                   | 4.2 (−20%)     | 6.0 (−15%)    | 3.2 (13%)      | 2.8 (−33%)     | 11.5 (−41%)                            | 0.54 (31%) |
| Total | Current   | 7.0                         | 16.4           | 20.5          | 9.2            | 11.3           | 57.8                                   | 0.45       |
|       | S1        | 7.7 (10%)                   | 14.2 (−13%)    | 18.3 (−11%)   | 10.0 (10%)     | 8.3 (−27%)     | 40.0 (−31%)                            | 0.55 (22%) |
|       | S2        | 8.2 (17%)                   | 12.5 (−24%)    | 16.6 (−19%)   | 10.6 (17%)     | 6.0 (−47%)     | 26.3 (−54%)                            | 0.64 (43%) |

Abbr.  $N_{fer}$ , Chemical N input;  $N_{in}$ , total N input;  $N_{rem}$ , N removal;  $N_{sur}$ , N surplus;  $N_{sur}/yield$ , N surplus per unit grain; NUE, N use efficiency.

## 4. Discussion

### 4.1. Driving Forces of High N Surplus and Spatial Variation in Cereal Crops

We obtained substantial data to investigate the universality and spatial variation of N surplus at the county level and also clarified the spatial distribution of hotspot areas across the whole of China. Several factors contributed to the high N surplus for the cereal crop systems in China. The relatively low price of N fertilizers [14], small farm sizes and high inter-farm variation [15,16], poorly educated of farmers [17], and the lack of agro-environmental policies [18] could contribute to the N surplus in China. The causes of the spatial variation in N surplus are complex and vary among different regions. Our research showed that  $N_{in}$ , especially  $N_{fer}$ , contributed to spatial variation in N surplus. High  $N_{fer}$  was observed in hotspots of  $N_{sur}$ , such as in southern China for maize. In northwest and southwest China, inputs of  $N_{man}$  aggravated the N surplus issue. Early reports have indicated that livestock is concentrated mainly in southwest China [19,37]. In southwest China, the ubiquity of small-scale animal farming is one reason for the higher rates of manure N application [38,39]. However, central China is also reported to be a major livestock and poultry breeding area. Although the amount of  $N_{fer}$  applied to wheat and maize in this region was very low, the large input of fertilizer, mechanization, and separation of planting and breeding could be important contributors to the N surplus issue [21].

### 4.2. Approaches for Improvement in N Management

For sustainable N management, we proposed the strategy of classified management for different counties, which requires different approaches to achieve the goal. We estimated that hotspots accounted for more than half of the total N surplus. Thus, targeting hotspots could reduce the N surplus and the environmental problems associated with intensive agriculture. Hotspot regions, especially counties classified as Lose–Lose, and farmers ranked in the top 10% in terms of N surplus in each county should be given special attention and management. These “counties” and “farmers”, showed lower yields and higher N inputs, according to the results, it also means that there is great potential to promote these counties and farmers. This requires timely changes in national, regional, and county-level policies and innovation in farmer practices.

To limit the N surplus and protect the environment in China, it is important to reduce fertilizer inputs. The Chinese government has signaled a change in direction for agricultural N use by setting policy goals, such as the “zero growth in chemical fertilizer use by 2020” initiative [40], which represents a first step toward reducing N use. Some progress has been made. For example, fertilizer use has achieved zero or even negative growth since 2015 [41]. However, this uniform and unfocused reduction in N fertilizer use throughout

China may be inefficient because of the large degree of spatial variation in N surplus. The Chinese government still requires more targeted policies to address the spatial variation (especially hotspots) in N surplus for cereal crops.

Regional N management approaches in China have been established across agroecological regions to ensure increasing yields while decreasing fertilizer inputs. It was found that the regionally optimal chemical N rate varies from 99 to 193 kg N ha<sup>-1</sup> for wheat, 150 to 219 kg N ha<sup>-1</sup> for maize, and 114 to 224 kg N ha<sup>-1</sup> for rice. This application rate could result in 17–21% less fertilizer and 11–31% lower greenhouse gas emissions than current farmer practices without incurring yield losses [42–44]. Recently, the Ecological Conservation Red Line initiative and planetary boundary concept [4,45], which focus more on human needs and environmental thresholds, promoted in-depth research into N management at regional and global scales. Notably, the planetary N boundary was used to evaluate county-scale N fertilizer limits for maize production in China, with consideration of ensuring groundwater safety [46]. Similar research on wheat and rice should be strengthened and accelerated to identify and evaluate hotspots in a more targeted manner.

The different characteristics of different regions in China also require a diversity of improvement strategies. For instance, wheat-growing areas in central China, a typical Win–Lose region, should reduce their chemical N inputs (Figure 4). In Lose–Lose regions, such as maize-growing areas in southern China, which are characterized by several adverse natural factors, including a mountainous landscape, sloping fields, low soil productivity, and inadequate sunlight [47–50], more integrated techniques for increasing yield and reducing N surplus and loss are required. In practice, some agroecological innovations in crop and soil management show great promise for reducing N surplus, thus achieving the yield benefits of intensive agriculture while greatly reducing harm to the environment. For example, integrated soil–crop system management controlled N surplus (chemical N fertilizer minus N uptake by crops) to within 2–16 kg N ha<sup>-1</sup> compared to 72–82 kg N ha<sup>-1</sup> for standard farming practices while also increasing yield by 10.8–11.5% and reducing N fertilizer application by 14.7–18.1% [27,51]. Due to the small farm sizes and numerous smallholders in China, although with difficulty, technology extension could be an important way of reducing hotspot abundance and assisting farmers with a high N surplus [17].

The substitution of manure N for chemical N is another approach for optimizing N management. In eastern Europe, Japan, and the United States, manure N accounts for more than 50% of the N input in crop production [52,53]. China is the largest livestock production region in the world; however, of the approximately 22.8 Mt of manure N produced annually, only about 33% of this N is used [20]. By contrast, 80% of the N input for cereal crops was derived from chemical N fertilizer, whereas only 6% was from manure (1.28 Mt) (Table 2). China has set the policy goal that the comprehensive use rate of livestock waste should surpass 90% by 2030. To achieve this goal, factors such as labor and transportation that restrict the efficiency of manure management should be considered carefully [20,52]. The return rate of crop straw also has potential for improvement in China [54]. Return of straw to the field contributes to reducing the N input and even decreases the total N removal. Furthermore, leaving more crop residues in cropland reduces N losses through leaching, volatilization, and soil erosion [55].

#### 4.3. Comparisons and Limitations

Our N surplus estimate for cereal crops across all of China was 11.3 Mt, which was consistent with that reported by Ma, et al. [24] (11.4 Mt). Our study estimated the N surplus for cereal crops to be 122–140 kg N ha<sup>-1</sup>, which was lower than the 189–231 kg N ha<sup>-1</sup> estimated by Zhang, et al. [4]. The latter study reported a higher total N input (272–336 kg N ha<sup>-1</sup>) and lower N removal (83–105 kg N ha<sup>-1</sup>) because straw was not included in the removal items. Conversely, our results showed much higher N surplus values than those of He, et al. [56] (76.9–83.2 kg N ha<sup>-1</sup>), Li, et al. [25] (60.6 kg N ha<sup>-1</sup>), and Wang, et al. [26] (59.6 kg N ha<sup>-1</sup>), because N losses were not included as an output item in this study.

The manure N input for cereal crops, accounting for 5–8% (11–20 kg N ha<sup>-1</sup>) of total N input, was relatively low in this study. Other regional farmer surveys also confirmed a low proportion of manure N input, such as 10% by Zhao, et al. [57] and 19.2% by Niu and Ju [58]. Most manure N input estimates for cereal crops in the early literature were derived from model calculations or conversion of data from the livestock and poultry industry [24,25]. In comparison with previous studies, our study quantified in more detail the proportion of organic N applied directly to farmland by smallholder farmers and revealed the associated spatial variability. However, due to limited reference materials, old N content values of manure varieties might have led to some errors in this study and some differences from other results.

Our reported chemical N input was lower than values from local reports in similar regions (Table S1). This difference could be due to survey sampling error, non-sampling error (e.g., measurements), or survey bias [59]. However, the results of previous local reports were often from a few villages, counties, or provincial regions, and at these sites, which often are hotspots, areas with low N fertilizer rates might have been neglected. For example, the chemical N input (235 kg N ha<sup>-1</sup>) for maize production in North China reported by Chen [60] was higher than that reported in our study (211 kg N ha<sup>-1</sup>). However, Chen [60] surveyed farmers from only three counties with relatively high chemical N use and grain yield. Similar to the above situation, it is easy to overestimate or underestimate the regional impact of N surplus, and assessment of the spatial variation and comparisons of different types of farmers could help to eliminate such biases.

We evaluated the N surplus of cereal crops at the county level in China using abundant farmer survey data at the national scale. However, the present study still had some limitations. First, we used regional parameters for N deposition, the straw return rate, and N fixation, which might have introduced regional bias into our results. However, the regional differences of these parameters are not sufficient to have influenced the conclusions. Second, manure N was recorded in the forms of pig slurry, cow slurry, farmyard manure, compost, etc., but the N content may vary even for the same type of manure due to differences in livestock feed, excreta treatment, and water content [61]. Third, the complex natural factors that can lead to changes in N surplus were not fully considered. For example, soil carbon, soil mineralization, and soil organic matter transformation can increase or decrease the N content in soil, thereby affecting N surplus [62–64]. Lastly, it is important for sustainable N management to explore further the amounts of surplus N that are leached, volatilized, or residual because the rates of N loss due to short-term precipitation, irrigation, soil type, and soil transformation of N differ among regions [65–68]. Additional regional data are needed for further research.

## 5. Conclusions

A nationwide survey of farmers revealed a widespread N surplus for the three main cereal crops in China, and the N surplus of the farmers in the top 10% in each county was more serious and conspicuous. N budgets exhibited tremendous spatial variation at the county level. Chemical N input was the most important contributor to N surplus, whereas manure N accounted for less than one-twentieth of the total N input. Higher inputs of manure N occurred only in the northwest and southwest regions. At the county level, hotspots, which contributed to more than half of the total N surplus in China, were identified based on boundaries for N surplus and N removal. Central China for wheat, central and southern China for maize, and southeast China and the Yangtze River Basin for rice were the major hotspot regions. Two scenarios were developed to explore improvement strategies for sustainable N management: Scenario 1 was established to eliminate hotspot counties by improving N removal and decreasing the N surplus; and Scenario 2, built on Scenario 1, aimed to achieve sustainable N management of cereal crops in all regions of China fully. These two scenarios for optimal N management that, if realized, would significantly reduce the N surplus. Our results provide updated estimates of N budgets and highlight hotspots of N surplus for cereal crop systems in China. Therefore, they

provide a benchmark for the development of new agricultural-N management policies and technologies in China.

**Supplementary Materials:** The following are available online at <https://www.mdpi.com/2073-4395/11/3/557/s1>, Detailed calculation parameters, tables, and figures of additional data (Table S1, Figures S1–S4, and references) is available in Supplementary materials.

**Author Contributions:** Q.Z., T.L., and Z.C. conceived the idea. Z.C. and F.Z. supervised the project. Q.Z., H.Y., and Y.Y. established the database and analyzed the data. Q.Z. wrote the manuscript. Z.C. polished the manuscript. All authors have read and agreed to the published version of the manuscript.

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