

Article

Decomposition of Fertilizer Use Intensity and Its Environmental Risk in China's Grain Production Process

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Abstract: In order to fully explore the fertilizer use intensity and its potential threats to the ecological environment, this paper has studied the decomposition of fertilizer use intensity and its environmental risk in China's grain production. Based on the statistical data collected from 10 provinces during 2004–2015 in China's grain producing areas, this paper has analyzed the effect of fertilizer use intensity from a regional perspective. The environmental risk assessment model considers some factors such as the fertilizer application safety thresholds use efficiency, multiple cropping index, and environmental impact weight. The fertilizer application safety thresholds are calculated on the target output of local food crops. The results show that: (1) during 2004–2015, the fertilizer use intensity shows an increasing trend in China's grain producing areas, and the intensity is significantly higher than the upper limit of the international safety fertilization; (2) the cumulative contribution rate of the increase of fertilizer use intensity caused by regional fertilizer use efficiency and grain planting structure adjustment are 57.03% and 1.81% respectively; (3) in 2015, China's grain producing areas' environmental risk index of phosphorus and potash was low, with the values in these two provinces being quite different and indicating the characteristics of aggregation and distribution. Therefore, the Chinese government should unswervingly encourage the application of some technology that could save fertilizer and increase efficiency, establish environmental risk monitoring and control systems, and improve relevant policies and regulations.

Keywords: fertilizer use intensity; factor decomposition; efficiency; environmental risk; China's grain production

1. Introduction

Fertilizer use is one of the important land management practices that alleviated nitrogen limitation in grain production [1]. In the long run, it has been proven that fertilizer use can directly or indirectly affect the physical, chemical, and biological characteristics of the soil as well as the soil fertility and crop productivity [2–6]. In order to meet the food demand of an ever-increasing world population, most countries have shown an overload use of inorganic fertilizer in agricultural production [7,8]. As an important part of the “Green Revolution”, the production and application of fertilizer have dramatically increased, making considerable contribution to the improvement of crop production and hunger reduction worldwide [9,10]. However, a large number of empirical studies have shown that the excessive fertilizer use has been a source of agricultural non-point source pollution in addition to causing numerous environmental and ecological problems which include greenhouse gas emissions, water pollution, changes of soil properties, declining productivity, deterioration of agricultural production quality, as well as loss of biodiversity and ecosystem services [11–18]. Now,

research studies have paid more attention to the spatial and temporal variations of fertilizer use across the world. It is not difficult to find that China, India, and the United States have consumed more than 50% of the world's fertilizer in the past century. Even though the International Fertilizer Industry Association (IFA) and the Food and Agricultural Organization (FAO) have provided the annual fertilizer consumption data since 1961, most of these data were applied to the multiple bottom-up nutrient budget analyses [19–21], while the influencing factors of intensity and environmental risk in fertilizer use have been overlooked.

The production capacity of Chinese arable land is low. In order to promote agricultural production and ensure food security, a series of policies have been implemented to encourage the production and application of fertilizer in China during the past years [22]. The FAO found that over 30% of global fertilizer has been consumed by China, although (as of 2010) China's arable land only accounts for 7% of the global arable land [23]. Since the beginning of the 1980s, fertilizer consumption in China has grown intensively, with an average annual 3–5% growth, and the fertilizer use per unit area has been close to 4 times the global fertilizer use [24]. In China, the total consumption of nitrogen, phosphorus, and potash increased to 54.16 million tons from 0.73 million tons from 1961 to 2015, and this increasing trend is expected to continue in the following decades [25]. Data from the National Bureau of Statistics show that the fertilizer use associated with China's grain production accounted for more than 80% of China's fertilizer production in 2013. China's fertilizer use intensity shows a significant upward trend, with the consumption center shifting toward the central and western regions. Additionally, there are marked differences between different regions in the growth rates and the driving effects of fertilizer use intensity [24,26]. Actually, the efficient use rate of fertilizer in China is still no more than 50%. It is a common phenomenon that fertilizer is overused and misused in China's grain production [15,27]. This circumstance has caused many problems such as increasing agricultural production costs and environmental pollution. Due to the constraints of fertilizer use efficiency, farmers' incomes have been restricted and the risk of losing agricultural economic benefits has also increased, which has posed a serious threat and constraint for the healthy and sustainable development of China's agriculture [28,29]. Making matters worse, many areas which feature high degrees of agricultural intensification or large amounts of nitrogen fertilizer use are faced with serious groundwater nitrate pollution [30]. The environmental risks and potential pressure of excessive use of fertilizer in other countries are not so serious as China [31].

The government has paid considerable attention to the unsustainability of fertilizer use. To address such issues, the central government of China officially launched the 'Action Plan for the Zero Increase of Fertilizer Use' (APZIFU) in 2015 [15]. This plan intends to establish a scientific fertilization management system preliminary, with the aim to stop the increase of fertilizer use intensity by 2020. Since fertilizer use has already caused many negative problems, determining how to realize the high production of sufficient grains with less fertilizer and less pollution will be very urgent and arduous for China in the next few years. The solution to these problems will be of great importance to the development of sustainable agriculture and the reduction of environmental pollution in the world. The high intensity of fertilizer use in China has aroused widespread concern in the academia. The existing research studies on fertilizer use are mainly focused on the following three aspects. Firstly, some studies have focused on the calculation of fertilizer use intensity. However, these studies have mainly calculated the intensity of fertilizer use based on field data or macro data, with few studies on the differences among different countries, different regions, and different crops [24,32]. Secondly, some studies have discussed the influencing factors of fertilizer use intensity. These studies have mainly analyzed the effects of endogenous factors and exogenous factors on fertilizer use behavior based on micro-survey data. All of the factors have consisted of individuals, families, policies, economy, technology, and systems [33–37]. Thirdly, some studies have researched the environmental pollution caused by fertilizer use intensity. These research studies have mainly analyzed the influence of fertilizer use on agricultural non-point source pollution, greenhouse gases, and so on [38,39]. The existing research studies have played a positive role for the study of the intensity of fertilizer use in China. However, so far, few studies have

been conducted to examine China's fertilizer use in terms of crops, and the existing research studies are often at the national level or limited to some small administrative units [24,40,41]. Many scholars have concentrated on the environmental risk assessment of agricultural nitrogen, phosphorus, and heavy metal non-point source pollution, while there are few reports on the risk assessment of environmental pollution for intensity of fertilizer use [42,43]. The objectives of this paper are (i) to analyze the characteristics of fertilizer use intensity in China's grain production process comprehensively; (ii) to explore the structure-driven effect and efficiency-driven effect of the regional grain planting structure and technological progress of fertilizer use intensity; and (iii) to analyze the temporal and spatial changes of the environmental risk posed by fertilizer use intensity.

The rest of this paper proceeds as follows. Section 2 shows the materials and methods. Section 3 provides the results, including the decomposition of fertilizer use intensity and the environmental risks. Subsequently, Section 4 presents the discussions, and finally, Section 5 concludes the paper.

2. Materials and Methods

2.1. Study Area

In China, the natural conditions vary considerably in different regions, and the distribution of crops in different provinces is also quite different. This paper selects the corresponding major provinces for each crop as the research object. The study area is divided into three regions which include the Northeast Region (Region 1), the Yellow Sea Plain and Huaihai Plain (Region 2), and the Middle and Lower Reaches of the Yangtze River (Region 3), in accordance with China Fertilizer Regionalization and China's Comprehensive Agricultural Zoning [44,45]. Both the production structure and layout in these three regions are based on the kinds of grains that have occupied very important positions in the agricultural production and socio-economic backgrounds of the study areas. In fact, rice varieties including early indica rice, middle indica rice, late indica rice, and japonica rice are diverse, however, in this paper we have only considered japonica rice. We have also analyzed wheat and maize.

Region 1 includes Heilongjiang province, Jilin province, and Liaoning province, as shown in Figure 1. This region is an important commodity grain base in China. In particular, the production of maize in this region occupies an absolutely dominant position. Region 2 includes Shandong province, Hebei province, and Henan province, as shown in Figure 1. This region is also an important commodity grain base. In this region, the maize production and wheat production occupy a very important position in China. Region 3 includes Anhui province, Jiangsu province, Hubei province, and Zhejiang province, as shown in Figure 1. In this region, the japonica rice production accounts for an absolute majority [46]. In 2015, the cultivated area and total population in these three regions accounted for 50.2% and 46.0% of the whole country respectively, and the sown area and total yield including wheat, maize, and rice accounted for about 50.1% and 61.4%, respectively (Table 1). All of the aforementioned statistics indicate that the grain production of these three regions has a position of importance in China. Since the fertilizer consumption in these three regions accounts for 53.7% of China's total fertilizer consumption, the analysis of fertilizer use intensity and its environmental risk in the grain production will play a pivotal role in the pollution control and agricultural development.

Table 1. The grain production and the fertilizer consumption in 2015.

Region	Cultivated Area (1000 ha)	Sown Area (1000 ha)	Total Yield Including Wheat, Maize, and Rice (10,000 t)	Fertilizer Consumption (10,000 t)	Population (10,000 Person)
China	134,998.7	16,6374	56,304.2	6022.6	137,462
Region1	27,830.7	22,193	11,075.4	638.6	10,947
Region 2	22,242.4	34,191.3	13,538.7	1515.1	26,752
Region 3	17,681.4	26,938.4	9954.1	1080.1	25,511

Data sources: China Rural Statistical Yearbook (2016) [47] and China Statistical Yearbook (2016) [48].

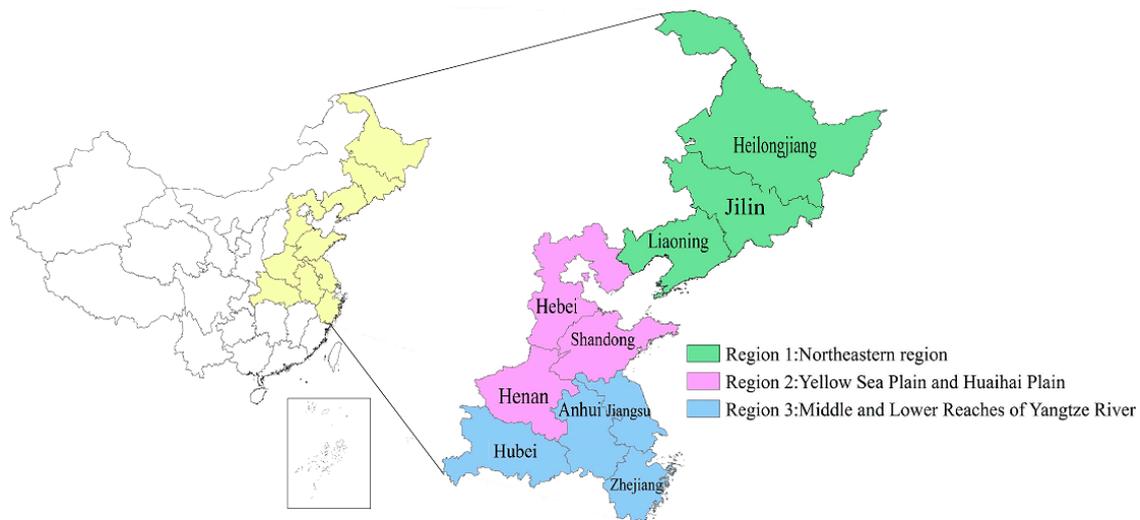


Figure 1. Geographic location of the study area and its administrative divisions.

2.2. Model Specifications

Usually we measure the intensity of fertilizer use as the use rate per unit area (kg/ha). The fertilizer use intensity is one of the important indicators with which to measure the efficiency of application in a country. This paper uses the Laspeyres model to analyze the structure-driven effect and the efficiency-driven effect, with the influencing factors of fertilizer use intensity analyzed at the regional level [49–51]. The model is shown as follows:

$$E = \frac{F}{S} = \frac{\sum_i f_i}{\sum_i s_i} = \sum_i e_i \cdot \omega_i \quad (1)$$

where f_i , s_i , e_i denote the amount of fertilizer use, crop acreage, and fertilizer use intensity respectively in region i ($i = 1, 2, 3$). F , S , E refer to the total fertilizer use, the total crop acreage, and the total fertilizer use intensity. ω_i stands for a proportion which is equal to the crop area in i region divided by the crop acreage of the whole study area. Therefore, the change in fertilizer use intensity for the interval $[t - 1, t]$ is expressed as follows:

$$\Delta E = E^t - E^{t-1} = \sum_i (e_i^t \omega_i^t - e_i^{t-1} \omega_i^{t-1}) \quad (2)$$

Using the Laspeyres index decomposition method indicates the influence of one explanatory variable as the change of explained variable caused by the explanatory variable when other explanatory variables remain constant. In essence, it is the differential expansion of each explanatory variable. Based on the Laspeyres index decomposition method, the change in fertilizer use intensity can be shown as:

$$\Delta E = \sum_i e_i^{t-1} (\omega_i^t - \omega_i^{t-1}) + \sum_i \omega_i^{t-1} (e_i^t - e_i^{t-1}) + \sum_i (\omega_i^t - \omega_i^{t-1}) (e_i^t - e_i^{t-1}) \quad (3)$$

According to the residual value of the joint production and equal contribution principle [52], the formula can be rewritten as follows:

$$\Delta E = \Delta ES + \Delta EE \quad (4)$$

$$\Delta ES = \sum_i \left[e_i^{t-1} (\omega_i^t - \omega_i^{t-1}) + \frac{1}{2} (\omega_i^t - \omega_i^{t-1}) (e_i^t - e_i^{t-1}) \right] \quad (5)$$

$$\Delta EE = \sum_i \left[\omega_i^{t-1} (e_i^t - e_i^{t-1}) + \frac{1}{2} (\omega_i^t - \omega_i^{t-1}) (e_i^t - e_i^{t-1}) \right] \quad (6)$$

where ΔES expresses the structure share, indicating changes of fertilizer use intensity caused by the regional structure adjustment when the fertilizer use efficiency remains unchanged. ΔEE means the effectiveness share, indicating changes caused by the fertilizer use efficiency when the regional structure remains unchanged.

Finally, we have calculated the structure-driven effect (C_{STR}) and the efficiency-driven effect (C_{EFF}). These indices are computed using Equations (7) and (8).

$$C_{STR} = \frac{\sum_i \left[e_i^{t-1} (\omega_i^t - \omega_i^{t-1}) + \frac{1}{2} (\omega_i^t - \omega_i^{t-1}) (e_i^t - e_i^{t-1}) \right]}{\sum_i e_i^t \omega_i^t - \sum_i e_i^{t-1} \omega_i^{t-1}} \quad (7)$$

$$C_{EFF} = \frac{\sum_i \left[\omega_i^{t-1} (e_i^t - e_i^{t-1}) + \frac{1}{2} (\omega_i^t - \omega_i^{t-1}) (e_i^t - e_i^{t-1}) \right]}{\sum_i e_i^t \omega_i^t - \sum_i e_i^{t-1} \omega_i^{t-1}} \quad (8)$$

If $C_{STR} > 0$ or $C_{EFF} > 0$, it indicates that the driving force and fertilizer use intensity change are in the same direction, otherwise it is the opposite.

2.3. Environmental Risk Index

The evaluation model of the fertilizer risk to environment is constructed with reference to Liu's methods [7,53], which is based on the Lars Hakanson [54] method. The risk index obtained by the Hakanson method is a positive number greater than 1, but the index has no upper and lower limits. It is difficult for the Hakanson method to compare the differences among different types of materials or different regions. In the new model, factors such as fertilizer application safety threshold, use efficiency, multiple cropping index, and environmental impact weight have been considered. Since the model in this paper uses a decimal number between 0 and 1, it is convenient to compare, sort, and manage the evaluation results. The fertilizer risk to environment indices will be obtained according to the following equations:

$$R_t = \sum_{j=1}^n q_j R_j \quad (9)$$

$$R_j = \left(\frac{F_j}{F_j + m T_j} \right)^{2u_i}$$

In Equation (9), R_t stands for the total index of the fertilizer pollution risk index; R_j represents the nitrogen, phosphorus, or potash risk index of environment; q_i refers to the weight coefficients of nitrogen, phosphorus, or potash environmental pollution. T_j is the fertilizer application safety threshold of nitrogen, phosphorus, or potash, which refers to the maximum application amount of a certain fertilizer that does not harm the environment in order to obtain the target output of a certain quarterly crop. F_j means the use intensities of nitrogen, phosphorus, potash, or total fertilizer in some year, and it refers to the fertilizer actually used for agricultural production during the year. From Equation (9) we can find that both R_t and R_j are between 0 and 1. When R_j (R_t) tends to 1, the fertilizer use intensity (F_j) is larger than the fertilization safety threshold (T_j). When R_j equals 1, the fertilizer use intensity leads to an extremely serious environmental risk. When R_j equals 0.5, the values of F_j and R_j are the same. Simultaneously, this is the critical point of fertilization safety threshold. When R_j (R_t) tends to 0, the fertilizer use intensity (F_j) is smaller than the fertilization safety threshold (T_j), which means that the use of fertilizer is 0, thus representing the state of organic farming. u_i stands for the fertilizer use efficiency, and m for the multiple cropping index. The main reason for the environmental risk is the lower fertilizer use efficiency, rather than the smaller multiple cropping index. We assume that the environmental risk index has a negative exponential correlation with the

fertilizer utilization rate. Due to the differences in crops and fertilizer varieties, it is difficult to consider the fertilizer use efficiency individually. As such, we set the fertilizer use efficiency to be 50%. We also assume that the environmental risk index has a negative linear correlation with the multiple cropping index in China's grain production process. In order to simplify the environmental risk assessment, we set the multiple cropping indexes in all provinces as to be 1.

The fertilizer application safety threshold is a key parameter in Equation (9). Internationally, in order to avoid the soil and ecological environmental disaster caused by excessive use of fertilizer, the warning line for fertilizer application safety threshold is set to be at 225 kg/ha [55,56]. In 2007, the ministry of environmental protection of China set the standard at 250 kg/ha [57]. Considering that food crops are the main crops in the study areas, the production can reflect the natural ecological conditions, socio-economic conditions, farm management level, and so on. In general, the fertilizer application safety threshold should be less than the maximum amount of fertilizer applied to the local food crop. The target yield of food crop was calculated according to the average production in a region for recent years. The appropriate fertilization rate determined on the target yield of food crops could neither waste fertilizer nor lose the proper output. In this paper, we determined the fertilizer application safety threshold based on the target yield of food crop. This means that different provinces have different thresholds in different years. As calculated, our fertilizer application safety thresholds vary from 170 to 320 kg/ha with the average value 267.10 ± 24.45 kg/ha during the last 12 years of China's grain production.

Due to the fact that different crops have different needs for nitrogen, phosphorus, and potash, the three chemical compounds' fertilizer application safety thresholds are also different. We have referred to the developed countries' practice of fertilization at the ratio of N, P, K, and taken into consideration the nutrient requirements for field crops production in China, with the ratio of nitrogen, phosphorus, or potash being 1:0.5:0.5 [53,58]. The fertilizer application safety thresholds of total fertilizer, nitrogen, phosphorus, and potash are calculated as follows:

$$\begin{aligned} T_t &= \frac{2\rho A}{n} \sum_{j=1}^n Y_j \\ T_N &= 0.5T_t \\ T_P &= T_K = 0.5T_N \end{aligned} \quad (10)$$

In Equation (10), T_t refers to the fertilizer application safety threshold; ρ represents the environmental protection threshold adjustment coefficient of fertilizer use intensity, with the threshold taken as 0.8; A is the amount of nitrogen required for the crop yield per unit; Y_j means the crop yield of the year j ; T_N , T_P , and T_K represent nitrogen, phosphorous, and potash thresholds of application safety, respectively.

Then we classified the environmental risk indexes. The degree of fertilizer environmental risk index has been divided into five different levels depending on the relationship between the fertilizer use intensity (F_j) and the fertilization safety threshold (T_t). The risk levels include safety, light risk, medium risk, serious risk, and extreme risk, which are shown in Table 2 [53]. Practically, the classification range of environmental risk indexes can be appropriately adjusted according to the needs and the current situation.

Table 2. Classification of environmental risk indexes.

Classes	Range of Environmental Risk Index	Type of Environmental Risk	Criteria: Amount of Fertilization \leq or $>$ Times of Threshold
4	(0.70,1.00]	Extreme risk	$F_j > 2.5T_j$
3	(0.66,0.70]	Serious risk	$2T_j < F_j \leq 2.5T_j$
2	(0.61,0.65]	Medium risk	$1.5T_j < F_j \leq 2T_j$
1	(0.51,0.60]	Light risk	$T_j < F_j \leq 1.5T_j$
0	[0.00,0.50]	Safety	$F_j \leq T_j$

2.4. Data Source

In this study, the data were collected from different sources, including the official statistical database, published papers, and government reports. Data about fertilizer, irrigation area, and total production were obtained from Compilation of National Cost of Agricultural Products [59] and China Rural Statistical Yearbook [47]. According to the data from the China Phosphate Fertilizer Industry Association, the 15-15-15 common type compound fertilizer (nitrogen, phosphorus, and potash in equal proportions) is the main variety and its market share is 54% [60,61]. Since the official statistical database did not cover the proportion of nitrogen, phosphorus, and potash in compound fertilizer, as such, in this paper we calculate the nitrogen, phosphorus, and potash in this way. The total production of crops mainly covered a bulk sum of grain (japonica rice, wheat, and maize). The data spanned from 2004 to 2015, according to the data availability.

3. Results

3.1. The Variation Characteristics of Fertilizer Use Intensity

The trend of fertilizer use intensity from 2004 to 2015, both overall and for each of the sub-regional study areas, is shown in Figure 2. According to the statistics from the FAO, the average fertilizer use intensity in the world is about 120 kg/ha [62]. From Figure 2, we can see that the average fertilizer use intensity is 341.45 ± 29.79 kg/ha across all of the study areas. The average fertilizer use intensity is 299.21 ± 36.60 kg/ha in Region 1, 358.80 ± 36.51 kg/ha in Region 2, and 354.59 ± 28.70 kg/ha in Region 3. Although the fertilizer use intensity of region 1 is the lowest in these three regions, it is still about 149.34% higher than the intensity of average fertilizer use in the world. We have analyzed the possible reasons from two aspects, one being the total amount and the other being the changing trend. It can be seen that reducing the fertilizer use intensity in China's grain production process is an important task that cannot be neglected in the future. Secondly, after analyzing the variation characteristics of fertilizer use intensity, we find that, although fertilizer use intensity has some fluctuations in the years from 2004 to 2015, it still shows an increasing trend in the grain production process. Compared with 2004, the fertilizer use intensity has increased significantly in 2015. The fertilizer use intensity grows with an average annual rate of 3.94% in Region 1, followed by 3.57% in Region 2 and 2.20% in Region 3. The above facts have shown that, in order to increase the grain production, farmers in the study area have to rely heavily on fertilizer. To a certain extent, this degree of dependence shows an increasing trend in recent years.

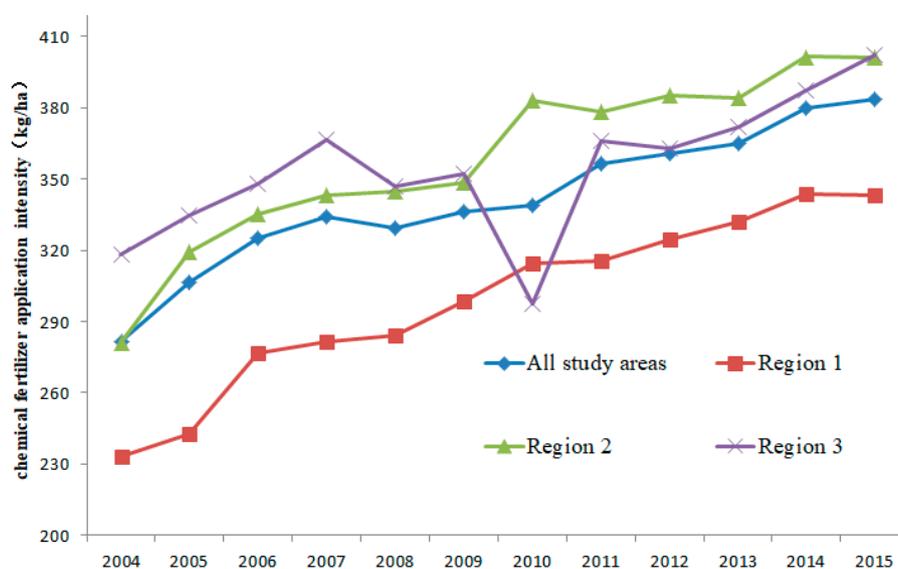


Figure 2. Trend of fertilizer use intensity from 2004 to 2015.

3.2. Driving Effect of Fertilizer Use Intensity

Based on the Laspeyres model, we decomposed the fertilizer use intensity of China's grain production at the regional level. The decomposition results from 2004 to 2015 are illustrated in Table 3. As the fertilizer use intensity shows a trend of growth, a positive value indicates that this factor has resulted in an increase for the fertilizer use intensity, while a negative value indicates that the factor has resulted in a decrease for the fertilizer use intensity. From Table 3, we can find that the cumulative contribution rate of the fertilizer use intensity caused by the regional grain planting structure adjustment and fertilizer use efficiency has increased positively from 2004 to 2015. The effect of regional fertilizer use efficiency whose cumulative contribution rate is 57.03% has more significant influence than that of the structure adjustment. The cumulative contribution rate of the regional grain planting structure adjustment is only 1.81%; as such, we can conclude that the agricultural production mode in China's grain production is still to a large degree based on fertilizer, and the new pattern of the fertilizer saving production mode has not yet been established.

- (1) Structural contribution rate. The contribution rate of the regional structure has experienced certain fluctuations from 2004 to 2015. The contribution rates of the regional structure have been negative except the years from 2004 to 2005 and from 2009 to 2010. The results above indicate that the grain planting structure adjustment in these years have effectively promoted the decline of fertilizer use intensity. This is mainly due to the negative contribution rate of the grain planting structure adjustment to fertilizer use intensity in Region 3 in these years. Furthermore, the negative contribution rate in Region 3 is bigger than the positive contribution rate in Region 1 and Region 2. Based on the regional characteristics, the regional structural adjustment of the cumulative contribution rate in Region 3 is -3.70% . This means that the "fertilizer-saving" agricultural mode in Region 3 is shifting more and more obviously. Simultaneously, the adjustment of the grain planting structure has also effectively alleviated the increase of fertilizer use intensity. However, the cumulative contribution rates in Region 1 and Region 2 are 2.26% and 3.26% , respectively, which means that the grain planting structure adjustment has significantly promoted the fertilizer use intensity increase in these two regions. Therefore, the crop planting structure based on "fertilizer consumption" in these two regions needs to be improved.
- (2) Efficiency contribution rate. The regional fertilizer use efficiency contribution has been positive from 2005 to 2015 and all of the annual driving efficiency values are more than 300% except years from 2009 to 2010. The results show that the change of fertilizer use efficiency is the key factor affecting the change of the intensity in the study area, and improving the fertilizer use efficiency is an important method to reduce the fertilizer use intensity and achieve the goal of reducing fertilizer use. We can see from the regional characteristics that the contribution rate of the fertilizer use efficiency differs greatly in different regions. The cumulative contribution rates are 24.93, 22.49, and 9.61% in these three regions, respectively. The possible reasons for the contribution of the fertilizer use efficiency in Region 1 and Region 2 being higher than that of Region 3 are shown below. Both the economic development level and the industrialization process in Region 1 and Region 2 are lagging behind Region 3. With the rapid development of industrialization, the rural laborers migrate from Region 1 and Region 2 to Region 3. Under the condition that the labor resources are constrained, most farmers have chosen the extensive land management model. In order to increase the agricultural output, most farmers usually input more fertilizer as well as other chemical compounds, which will inevitably lead to the decrease of fertilizer use efficiency. Therefore, it is necessary to take measures to increase the promotion of agricultural technology, strengthen farmers' training, and improve fertilizer use efficiency so as to control the growth of fertilizer use intensity.

Table 3. The driving effect of fertilizer use intensity change unit: %.

	Structure-Driven Effect	Effect of Regional Structural Adjustment			Efficiency-Driven Effect	Effect of Regional Efficiency Adjustment		
		Region 1	Region 2	Region 3		Region 1	Region 2	Region 3
2004–2005	305.45	68.07	20.54	216.84	−5.45	31.93	79.46	−116.84
2005–2006	−16.38	14.59	−3.89	−27.07	316.38	85.41	103.89	127.07
2006–2007	−8.52	0.59	8.83	−17.94	308.52	99.41	91.17	117.94
2007–2008	−61.06	8.68	2.13	−71.88	361.06	91.32	97.87	171.88
2008–2009	−2.25	−10.02	9.51	−1.74	302.25	110.02	90.49	101.74
2009–2010	0.02	−4.52	3.12	1.42	299.98	104.52	96.88	98.58
2010–2011	−25.04	9.65	2.51	−37.20	325.04	90.35	97.49	137.20
2011–2012	−13.44	3.91	3.46	−20.82	313.44	96.09	96.54	120.82
2012–2013	−11.40	6.04	3.67	−21.11	311.40	93.96	96.33	121.11
2013–2014	−10.11	2.05	8.56	−20.73	310.11	97.95	91.44	120.73
2014–2015	−15.66	−15.06	14.88	−15.48	315.66	115.06	85.12	115.48
Cumulative contribution rate	1.81	2.26	3.26	−3.70	57.03	24.93	22.49	9.61

3.3. Environmental Risk Assessment

Fertilizer application can increase food crop yield, and it also leads to potential risks to environmental pollution. Many studies have shown that the excessive use of fertilizer causes soil pollution, water pollution, air pollution, and biological contamination [63]. In fact, more than 50% of the nitrogen discharged into water comes from human's agricultural production. When ammonia nitrogen is applied into farmland, 13–15% of it is volatilized into the atmosphere. Nitrogen in soil releases large amounts of N_2O through nitrification and denitrification, and N_2O has a greater impact on the greenhouse effect than CO_2 . Due to the leaching of nitrate nitrogen, groundwater quality is declining, which is posing a great threat to human health. Many studies have shown that the nitrogen and phosphorus inputs from agriculture are the main reason for the eutrophication of water bodies. At the same time, excessive use of potash can impede the uptake of other ions by crops, reduce crop yields, and cause soil compaction [64]. Considering that the three chemical compounds execute different influences on the atmosphere, water, and soil environment, we determine the matrix according to the importance of 5, 3, and 1 in constructing the analytic hierarchy process, and the weight coefficients of nitrogen, phosphorus, and potash are 0.648, 0.230, and 0.122, respectively. Then we calculate the environmental risk indexes.

According to the environmental risk assessment model, we calculated the environmental risk indices including total risk index, nitrogen risk index, phosphorus risk index, and potash risk index in China's grain production, respectively. From Figure 3, we can find that the environmental risks among the ten provinces show a large difference and aggregation distribution. It can be seen from the spatial variation characteristics in Figure 3 that in 2015 (Figure 3a), the fertilizer use intensity shows a status of light risk in Heilongjiang province, Jilin province, Liaoning province, Shandong province, Hebei province, Anhui province, Hubei province, and Zhejiang province. The fertilizer use intensity displays the medium risk status in Henan province, which is the major province of labor export, and where most laborers transfer to the non-agricultural sectors. In order to make up for the lack of laborers, farmers increased the inputs of fertilizer and pesticide, resulting in the decrease of the fertilizer's marginal income and the increase of environmental risk. The fertilizer use intensity shows an extreme risk status in Jiangsu province.

The distribution of nitrogen environmental risk is consistent with the total environmental risk in all provinces except Heilongjiang province and Henan province. This indicates that the environmental risk of fertilizer use intensity comes mainly from the use of nitrogen in China's grain production (Figure 3b). Both phosphorus environmental risk and potash environmental risk are low. The differences in all these ten provinces are great, and environmental risk indices vary from safety to extreme risk. Jiangsu province is an extreme risk zone for phosphorus and potash, and Shandong province is a

medium risk zone for phosphorus and potash. Liaoning province is a safety zone for phosphorus while a light risk zone for potash, and Henan province is a light risk zone for phosphorus while a safety zone for potash. All of the remaining provinces are safety zones for phosphorus and potash (Figure 3c,d).

In other words, nitrogen presents a major risk of non-point source pollution in China's grain production. Although phosphorus environmental risk and potash environmental risk are not outstanding in China's grain production, these two chemical compounds still should be given considerable attention. At the same time, the inherent law about the aggregation distribution of the environmental risk still needs to be further explored.

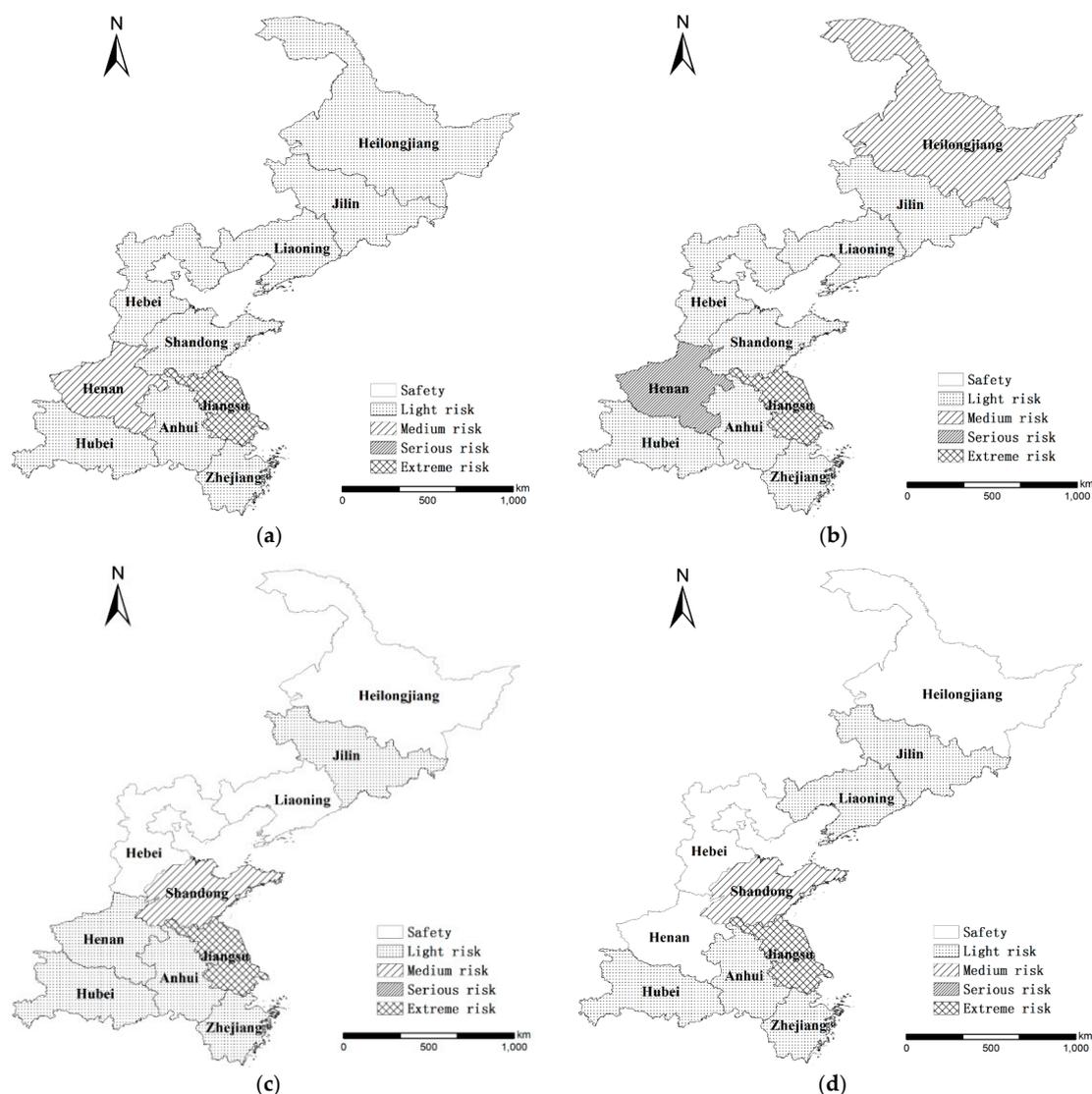


Figure 3. Distribution of total fertilizer and nitrogen, phosphorus, and potash environmental risks of China's grain production in 2015. (a) Total risk index; (b) Nitrogen risk index; (c) Phosphorus risk index; (d) Potash risk index.

4. Discussion

4.1. The Interpretation of Fertilizer Use Environmental Risk

In China's grain production process, the fertilizer use intensity is much higher than the average fertilizer use intensity in the world. Then we find that the cumulative contribution rate of regional fertilizer use efficiency is 55.22% which is higher than that of regional grain planting structure

adjustment. Improving the fertilizer use efficiency is an essential way to reduce the fertilizer use intensity. From the spatial variation characteristics of total risk index, we could find that 80% of these provinces show the status of light risk. To be more specific, nitrogen environmental risk is greater, while phosphorus environmental risk and potash environmental risk are smaller. It is easy to find that the fertilizer environmental security situation in Jiangsu province is the most severe. After further investigation, we find that the economy in Jiangsu province has been developing faster than that of the other provinces, and the farmer's agricultural marginal revenue is significantly lower than that of workers in non-agriculture sectors. With the decrease of the opportunity cost of non-agricultural employment, more and more farmers choose non-farm jobs. Under such circumstances, the fertilizer use efficiency reduces and the environmental risk index increases. At the same time, further studies of the environmental risks related to fertilizer use are needed.

4.2. Initiatives to Reduce the Fertilizer Use Intensity and Environmental Risk

In China's grain production process, the overuse of fertilizer is affected by policies, institutions, management, technology, traditional habits, and so on. The fertilizer use intensity still produces some environmental risk. We could find that fertilizer technology and improper management are the direct causes, while the agricultural policies and management systems are the root causes.

The Chinese government should promote and apply some forms of technology that could save fertilizer and increase efficiency, and meanwhile, improve the fertilizer use efficiency. The government should also study fertilization techniques in different tillage systems and under various soil conditions so as to promote scientific fertilization, soil testing, and other fertilization techniques based on the combination of regional resource endowments. It is equally important to optimize the grain planting structure and instruct the behavior of farmers to ensure that they behave rationally. These measures will improve the fertilizer use efficiency in China's grain production and at the same time reduce the environmental risks and environmental costs caused by excessive fertilization. Moreover, it is better for the government to construct the environmental risk monitoring system of fertilizers and establish an early warning mechanism for the agro-ecological environment. According to the environmental risk index of fertilization, the government has established the environmental pollution risk monitoring information network at provincial, city, and county levels. Then it will realize the rapid collection, audit, transmission, feedback, and forecast of pollution data. Grasping the current situation, source and development trends of fertilizer pollution risk are also of importance. Ultimately, some official departments have provided a scientific basis for the comprehensive prevention and control of fertilizer pollution.

Then, the government should formulate comprehensive management measures to reduce fertilizer use and environmental risks. For example, it is better for the environmental protection departments to pay more attention to cultivating farmers' awareness of environmental protection, as well as to improve relevant policies and regulations. Officers in these departments should educate and train farmers on agricultural production and environmental protection knowledge, enable farmers to understand the benefits of rational fertilization, and help them control fertilizer use. Simultaneously, these environmental protection departments must reduce the environmental risks of pesticides and fertilizer by establishing systems and regulations in order to achieve the sustainable development of agriculture.

5. Conclusions

Although the Chinese government has adopted a series of measures to regulate and reform the fertilizer market, farmers still have a strong dependence on fertilizers. The fertilizer use intensity in China's grain production is significantly higher than the international upper limit of safe fertilization (225 kg/ha). A rising trend of fertilizer use has been shown in the three regions. In Region 1, the fertilizer use intensity is the lowest, while the average annual rate is the highest; the cumulative contribution rate of the fertilizer use intensity caused by the regional fertilizer use efficiency is 57.03%;

the impacts are the most obvious in Region 1 and Region 2. While the cumulative contribution rate of the fertilizer use intensity caused by grain planting structure adjustment accounts for only 1.81%, the adjustment of grain planting structure in Region 3 has alleviated the increase of fertilizer use intensity in the whole study area effectively; the total fertilizer risk index and nitrogen risk index have shown declining trends in China's grain production. The risk of fertilizer use intensity is quite different, showing an aggregation distribution in different provinces. The environmental risk of the nitrogen was basically the same as that of the total fertilizer. The phosphorus risk index and potash risk index are low, with the differences notable among these provinces.

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