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Decoupling Agricultural Nonpoint Source Pollution from Crop Production: A Case Study of Heilongjiang Land Reclamation Area, China

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Abstract: Modern agriculture often leads to nonpoint source pollution. From the perspective of a decoupling analysis, this research evaluates the relationship between crop production and agricultural nonpoint source pollution (via fertilizer application), using the Heilongjiang land reclamation area as a case study. As it is the largest commodity grain base and green food base in China, more than 80% of water pollution in this area comes from fertilizer application. This study adopts an export coefficient model to hindcast nitrogen loss delivered to surface water via fertilizer application and conduct a further analysis of decoupling agricultural nonpoint source pollution from crop production. The results indicated that weak decoupling frequently occurred. However, this tendency was not steady in the period 2001–2012, and weak decoupling was typical in each branch based on the average value. Regarding the example of decoupling agricultural nonpoint source pollution from rice production, weak decoupling occurred more often, but this tendency was not steady over time. In addition, expansive coupling occurred in 2006, 2010 and 2012, and there were no definite signs of it improving. All branches, except for the Suihua branch, reached the degree of weak decoupling. A basic fact is that a decoupling tendency and environmental deterioration coexist in both the past and present. The decoupling analysis will contribute to localized strategies for sustainable agricultural development.

Keywords: decoupling analysis; agricultural nonpoint source pollution; crop production; export coefficient model

1. Introduction

Whether environmental pressure can be reduced during periods of economic growth has been intensively discussed [1,2]. From the perspective of methods to evaluate the relationship between economic growth and environmental pressure, following the Environmental Kuznets Curve (EKC) [3], "decoupling", originating from physics, was extended to break the link between "environmental bads" and "economic goods" [4]. When used in this extended sense, decoupling implies that the growth rate of environmental pressure is less than that of its economic development over a given period (Figure 1) [5]. Now, decoupling environmental pressure from human well-being has become the policy goal of the Green Economy Initiative of the United Nations Environment Programme (UNEP) and the European Union (EU).

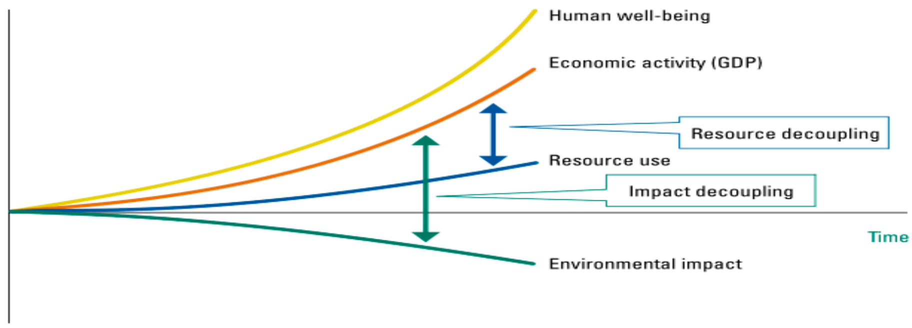

Figure 1. Stylized expression of decoupling [5].

Literature on decoupling/coupling degrees generally considers strong decoupling, weak decoupling, recessive decoupling, strong coupling, weak coupling and expansive coupling [6–10], and both indicators and methods of decoupling analysis are in continuous development [11–14]. However, literature on decoupling analysis of crop production is rare, such as decoupling crop production from soil erosion, irrigation water consumption and fertilizer application [15–17] and decoupling agricultural water consumption and environmental impact from crop production based on the water footprint method [18].

Fertilizer application is a leading cause of agriculture nonpoint source (AGNPS) pollution in China, the United States and worldwide [19–22]. China is the biggest fertilizer user in the world, its ratio of fertilizer utilization is low (30–35%), but studies on AGNPS pollution are still in an early stage of development [23]. The lack of reliable data further limits accurate evaluation of AGNPS pollution, which hampers local decision making and regional sustainable development. The Heilongjiang land reclamation area (HLRA) is located in Northeast China, its arable land area per capita is 15 times greater than that of the national average, and its crop yield per unit area exceeds that of the United States. With the crop yield continuously increasing for 12 years, AGNPS pollution via fertilizer application constitutes 80% of the water pollution in the HLRA [24], which further threatens regional food security and ecological security.

The purpose of this study is to examine the decoupling/coupling degrees between high crop yield and agricultural water pollution during 2001–2012 in the HLRA. The remainder of this paper has four parts: Section 2 introduces methods and materials, including the decoupling index, export coefficient model, study area and data source; Section 3 provides results; Section 4 is the discussion; and Section 5 states the final conclusions.

2. Methods and Materials

2.1. Decoupling Index (DI)

In this article, the decoupling index (DI) aims to indicate the relationship between the change in the rate of AGNPS pollutant emission and change in the rate of crop yield within a certain time period (typically 1 year). The DI is expressed as

$$DI = \Delta E_{AGNPS}/\Delta Y = (E_{AGNPSi}/E_{AGNPSi-1} - 1)/(Y_i/Y_{i-1} - 1) \quad (1)$$

where E_{AGNPS} represents the load of nutrient loss (via fertilizer application) exported into surface water; E_{AGNPSi} and $E_{AGNPSi-1}$ represent AGNPS pollutant emission at the last phase and the base period, respectively; Y represents crop yield; and Y_i and Y_{i-1} represent the crop yield at the last phase and the base period, respectively. Using the difference (Δ) between AGNPS pollutant emission (E_{AGNPS}) and crop yield (Y) at two points in time (1 year in this study), ΔE_{AGNPS} represents the change rate of AGNPS pollutant emission from the last phase to the base period. ΔY is the growth rate of crop yield from the last phase to the base period. Six possible combinations of change in E_{AGNPS}, Y and E_{AGNPS}/Y can be interpreted as different degrees of the decoupling/coupling process (Table 1).

Table 1. Criteria for degrees of decoupling/coupling AGNPS pollution from crop production.

Decoupling/Coupling Degrees	Relationship between Crop Production and AGNPS Pollution
Strong decoupling	$\Delta E_{AGNPS} \leq 0$, $\Delta Y > 0$, $DI \leq 0$
Strong coupling	$\Delta E_{AGNPS} \geq 0$, $\Delta Y < 0$, $DI \leq 0$
Weak decoupling	$\Delta E_{AGNPS} > 0$, $\Delta Y > 0$, $0 < DI < 1$
Expansive coupling	$\Delta E_{AGNPS} > 0$, $\Delta Y > 0$, $DI \geq 1$
Weak coupling	$\Delta E_{AGNPS} < 0$, $\Delta Y < 0$, $0 < DI < 1$
Recessive decoupling	$\Delta E_{AGNPS} <0$, $\Delta Y < 0$, $DI \geq 1$

2.2. Export Coefficient Model

Based on the limited available data and the scattered farmland, AGNPS pollution from fertilizer application in the HLRA was estimated and hindcast using the export coefficient model [19], where fertilizer inputs and export coefficients are divided by each agricultural crop. The AGNPS pollutant emission was computed using the following equation:

$$L = \sum_{i=1}^{n} E_i[A_i(I_i)] + P \quad (2)$$

where L is loss of nutrients. In this study, we take the nitrogen loss leached into surface water as the indicator for AGNPS pollution in the HLRA. E is the export coefficient for nutrient source i; A is the area of catchment occupied by crop i, where the main crops in the HLRA include rice, corn, soybean and wheat; I is the input of nutrients to source i; and P is the input of nutrients out of rainfall (omitted here) [19].

Nitrogen (the most substantial component of the fertilizers) is used as the case pollutant to account for AGNPS pollution [25–27]. In this study, a chemical fertilizer application was deployed as the main pollutant; nitrogen loss was adopted as the main pollutant indicator; and, however, pesticide application was not considered due to its complexity [28,29]. In the HLRA, chemical pesticide is normally applied by aero spraying, and the application dosage of chemical pesticides is only 3.69 kg/ha, which is far below the national standard of 15.23 kg/ha [18,30]. Therefore, the AGNPS pollutant emission in this study is relatively conservative.

The overall scheme for the decoupling analysis is shown in Figure 2.

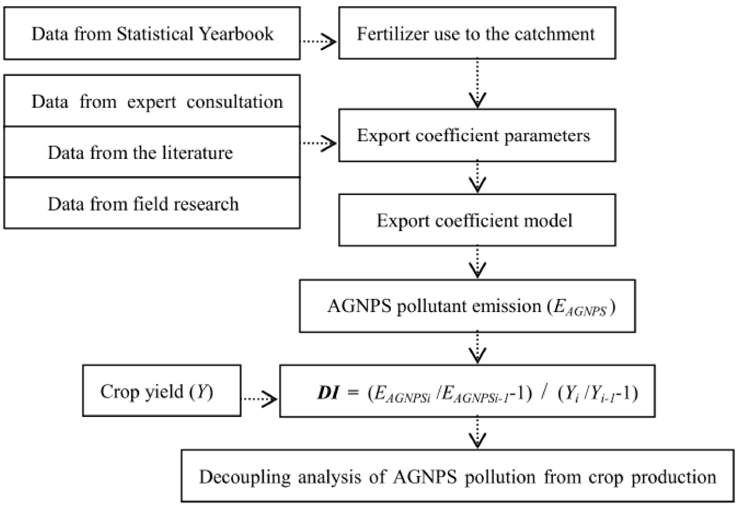

Figure 2. Steps in the decoupling analysis.

2.3. Study Area and Data Source

The HLRA is located at 123°32′–134°33′ E, 43°56′–50°21′ N, covering an area of 57,600 km^2 and including 113 state farms attached to nine branches. It is characteristic of the mid-temperate and cold temperate continental monsoon climate. The annual rainfall is approximately 540 mm/year, with 80–90% of precipitation occurring from May to September. The study area belongs to three fluvial systems, including the Heilong River, the Wusuli River and the Songhua River (Figure 3), and the total amount of water resources in the HLRA is 9.76 billion m^3, including 5.6 billion m^3 of surface water and 4.09 billion m^3 of groundwater [31].

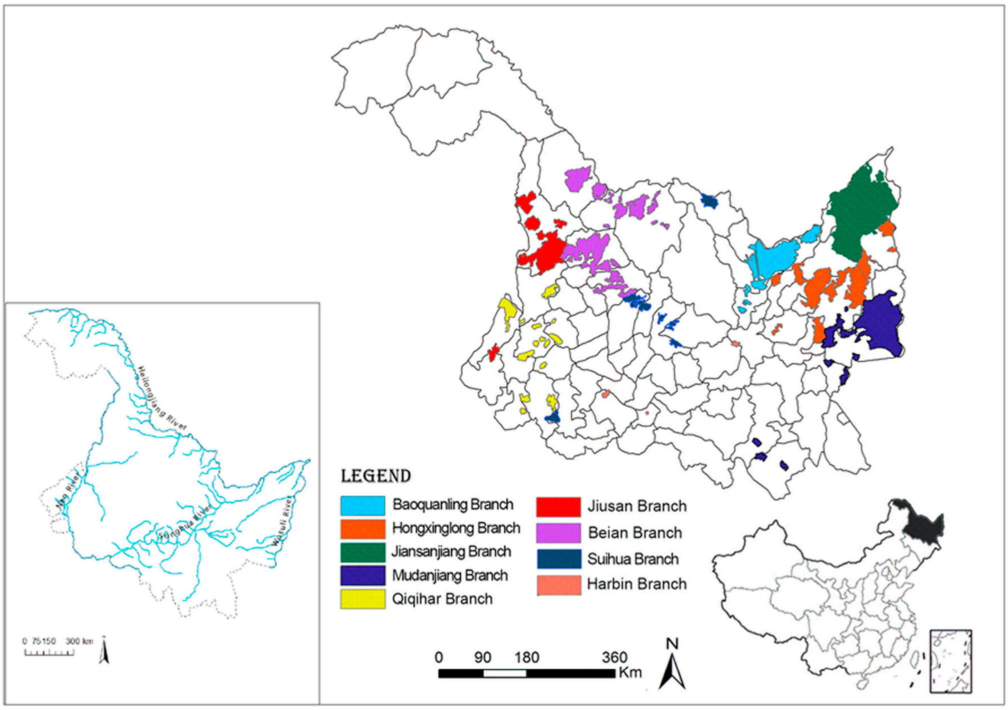

Figure 3. Location and catchment of the study area.

The main crops in the HLRA include rice, corn, soybean and wheat, which accounted for approximately 95% of the total crop yield in the most recent decade [32]. The data used for the export coefficient model included data on crop yield, fertilizer usage and annual loads of nitrogen loss delivered into surface water. Historical data on crop yield and fertilizer usage came from the Statistical Yearbook of Heilongjiang Land Reclamation Area (2002–2013). The fertilizers applied in crop growth included urea, diammonium phosphate, potassium chloride and potassium sulfate. Export coefficients for the four main crops in the HLRA were calculated based on data from field research, literature [18,24,33–35] and expert consultation, as shown on Table 2.

Table 2. Fertilizer usage and export coefficients parameters in the HLRA.

Crops	Fertilizer Inputs (Pure Quantity)	Eastern Humid Region	Western Arid Region
	Total Amount of Nitrogen (kg/ha)	**Nitrogen Leaching Rate (%)**	**Nitrogen Leaching Rate (%)**
Rice	110.4	14	12
Corn	110.4	12	10
Soybean	18.4	5	4
Wheat	76	13	11

3. Results

3.1. Relationship between Crop Yield and AGNPS Pollution

The changes in crop yield and AGNPS pollution via fertilizer application during 2001–2012 in the HLRA are shown in Figure 4.

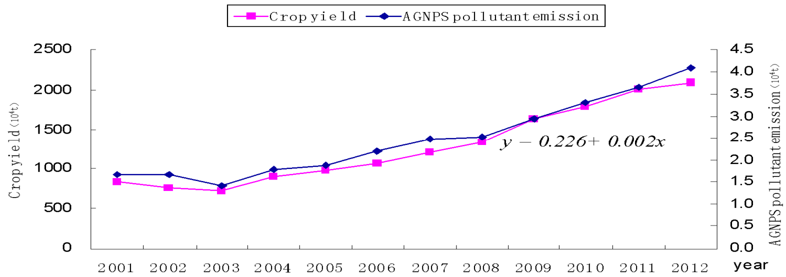

Figure 4. Relationship between crop yield and AGNPS pollution in the HLRA (2001–2012).

Both crop yield and AGNPS pollutant emission via fertilizer application generally increased during these years. The correlation coefficient *r* between crop yield and the AGNPS pollutant emission was 0.993 at the 0.01 significance level. Using crop yield as the independent variable *x* and the AGNPS pollutant emission as the dependent variable *y*, the equation used to relate these two factors is $y = 0.226 + 0.002x$. The r^2 value was 0.985, and the adjusted r^2 value was 0.984. The goodness-of-fit of the equation was higher, and the high r^2 value indicated a close relationship between the AGNPS pollutant emission and crop yield, especially in 2009–2011.

3.2. Decoupling AGNPS Pollution from Crop Production

Based on the criteria for the decoupling/coupling degrees (Table 2), the results of decoupling AGNPS pollution from crop production during 2001–2012 in the HLRA are shown in Table 3, and the results based on the average value between 2001 and 2012 are shown in Table 4.

Table 3. Results of decoupling AGNPS pollution from crop production in the HLRA (2001–2012).

Year	Crop Yield (10^4 t)	Growth Rate of Crop Yield (%)	AGNPS Pollutant Emission (10^4 t)	Growth Rate of AGNPS Pollutant Emission (%)	DI	Degrees of Decoupling/Coupling
2001	832.17	-	1.67	-	-	-
2002	761.31	−8.52	1.66	−1.03	0.12	Weak coupling
2003	717.41	−5.77	1.42	−14.17	2.46	Recessive decoupling
2004	901.22	25.62	1.78	25.44	0.99	Weak decoupling
2005	973.10	7.98	1.87	4.78	0.60	Weak decoupling
2006	1065.11	9.46	2.20	17.45	1.84	Expansive coupling
2007	1210.07	13.61	2.49	13.50	0.99	Weak decoupling
2008	1337.51	10.53	2.53	1.48	0.14	Weak decoupling
2009	1631.90	22.01	2.95	16.76	0.76	Weak decoupling
2010	1794.78	9.98	3.32	12.36	1.24	Expansive coupling
2011	2014.16	12.22	3.67	10.64	0.87	Weak decoupling
2012	2085.14	3.52	4.09	11.50	3.27	Expansive coupling

During 2001–2012, weak decoupling occurred for 6 years, recessive decoupling occurred for 1 year, weak coupling occurred for 1 year, and expansive coupling occurred for 3 years. In the years of decoupling tendency, AGNPS pollution via fertilizer application rapidly increased, and the increase in crop yield was greater than the increase of AGNPS pollutant emission via fertilizer application. Weak decoupling frequently occurred but was accompanied by fluctuation, and no strong decoupling occurred during those years. During the years of coupling tendency, the increase in crop yield was less than the increase in AGNPS pollutant emission via fertilizer application. The fact that expansive coupling occurred for 3 years indicated that the HLRA had a long way to go for constructing an ecological agricultural production system, despite its high crop yield and high potential productivity in China.

Table 4. Results of decoupling AGNPS pollution from crop production in the HLRA (based on the average value in the period 2001–2012).

Branch	Crop Yield (10^4 t)	Growth Rate of Crop Yield (%)	AGNPS Pollutant Emission (10^4 t)	Growth Rate of AGNPS Pollutant Emission (%)	DI	Degrees of Decoupling/Coupling
BQL	211.35	9.09	0.41	7.53	0.83	Weak decoupling
HXL	259.74	9.26	0.47	7.57	0.82	Weak decoupling
JSJ	405.10	13.64	0.76	11.49	0.84	Weak decoupling
MDJ	262.57	7.65	0.52	7.57	0.99	Weak decoupling
BA	102.83	17.71	0.12	14.96	0.84	Weak decoupling
JS	78.85	15.23	0.08	10.44	0.69	Weak decoupling
QQH	60.53	12.78	0.10	11.05	0.86	Weak decoupling
SH	38.05	8.71	0.06	7.60	0.87	Weak decoupling
HB	11.27	13.20	0.02	9.66	0.73	Weak decoupling

Due to the close relationship between crop production and AGNPS pollution, crop yield largely depended on increased fertilizer application. According to Table 4, which was based on the mean values in 2001–2012, each branch in the HLRA had a weak decoupling relationship between crop production and AGNPS pollution from fertilizer use. The growth rate of crop yield for each branch was greater than that of the increasing rate of AGNPS pollutant emission from fertilizer application, which showed the potential to reach a strong decoupling across the whole HLRA.

3.3. Example: Decoupling AGNPS Pollution from Rice Production

Rice is a primary food source and an important cereal plant. Rice yield in Northeast China accounted for 40% of the Country's production [36]. Due to rice's comparative advantage and famous quality, the cultivated area of rice in the HLRA increased rapidly, except in 2003 and 2008, and the rice yield in the four eastern branches constituted 92.76% of the total rice yield in the HLRA. In addition, water consumption for rice production constituted half of the total during crop growth [18,24], and rice production became the largest source of AGNPS pollution in the HLRA (Figure 5).

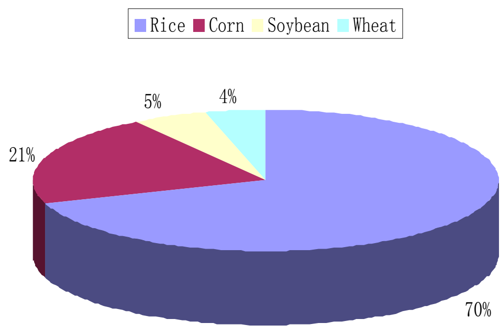

Figure 5. AGNPS pollution from fertilizer usage in the HLRA (2001–2012).

The results of decoupling AGNPS pollution from rice production during 2001–2012, which are based on the average value of each branch in the HLRA (2001–2012), are shown in Tables 5 and 6.

Table 5. Results of decoupling AGNPS pollution from rice production in the HLRA (2001–2012).

Year	Rice Yield (10^4 t)	Growth Rate of Rice Yield (%)	AGNPS Pollutant Emission (10^4 t)	Growth Rate of AGNPS Pollutant Emission (%)	DI	Degrees of Decoupling/Coupling
2001	527.42	-	1.21	-	-	-
2002	452.77	−14.15	1.24	2.46	−0.17	Strong coupling
2003	424.16	−6.32	0.99	−20.11	3.18	Recessive decoupling
2004	528.62	24.63	1.23	24.23	0.98	Weak decoupling
2005	573.43	8.48	1.31	6.08	0.72	Weak decoupling
2006	682.50	19.02	1.57	19.70	1.04	Expansive coupling
2007	798.07	16.93	1.76	12.19	0.72	Weak decoupling
2008	842.18	5.53	1.79	1.91	0.35	Weak decoupling
2009	927.32	10.11	1.91	6.51	0.64	Weak decoupling
2010	1094.39	18.02	2.26	18.49	1.03	Expansive coupling
2011	1278.91	16.86	2.58	14.13	0.84	Weak decoupling
2012	1370.42	7.16	2.82	9.39	1.31	Expansive coupling

Table 6. Results of decoupling AGNPS pollution from rice production for each branch in the HLRA (based on the average value in the period 2001–2012).

Branch	Rice Yield (10^4 t)	Growth Rate of Rice Yield (%)	AGNPS Pollutant Emission (10^4 t)	Growth Rate of AGNPSPollutant Emission (%)	DI	Degrees of Decoupling/Coupling
BQL	114.87	12.43	0.25	9.48	0.76	Weak decoupling
HXL	140.84	6.20	0.30	4.99	0.80	Weak decoupling
JSJ	352.76	15.77	0.69	12.77	0.81	Weak decoupling
MDJ	195.72	6.53	0.42	6.30	0.96	Weak decoupling
BA	2.82	86.55	0.01	57.42	0.66	Weak decoupling
JS	2.74	59.56	0.01	48.18	0.81	Weak decoupling
QQH	35.77	13.74	0.06	10.65	0.78	Weak decoupling
SH	16.08	4.90	0.03	5.27	1.08	Expansion coupling
HB	5.67	8.95	0.01	6.87	0.77	Weak decoupling

According to Table 5, during 2001–2012 in the HLRA, weak decoupling occurred for 6 years, expansive coupling occurred for 3 years, and recessive decoupling and strong coupling occurred for 1 year. Compared with the base year of 2002, although the HLRA achieved the largest reduction in AGNPS pollutant emission (−20.11%) in 2003, the growth rate of rice yield also decreased (−6.32%), which was not ideal for coordinating the relationship between crop growth and environmental protection. The worst degree of strong coupling occurred in 2002, when the growth rate of rice yield decreased 14.15% and the growth rate of AGNPS pollutant emission increased 2.46%. Expansive coupling occurred in 2006, 2010 and 2012, which indicated that there were no definite signs of improvement to the water environment in rice production.

In Table 6, based on the average value of each branch during 2001–2012, all branches in the HLRA, except for the Suihua branch, reached weak decoupling. The Suihua branch achieved a lower growth rate of AGNPS pollutant emission (5.27%); however, it achieved the lowest growth rate of rice yield (4.90%). Thus, it was the backward branch, and its degree of expansion coupling urgently needs improvement.

According to Figure 5, Tables 5 and 6, it was found that the key problem resulted from rice production and that it is necessary to pay more attention to optimizing fertilizer application and field management during the process of rice growth, both for the whole HLRA and for the Suihua branch in particular.

4. Discussion

Based on the results of this study, some related findings and discussions are proposed to promote sustainability studies.

(1) Ensuring food safety is the first priority for China, which is both the most populous country and a vast agricultural country. However, increasingly serious environmental problems and the

need for sustainable agricultural development both force us to pay close attention to environmental protection. Great efforts have been made to coordinate crop production and the agricultural ecological environment in China, including the "Water Pollution Control Action Plan", issued in 2015. However, progress in AGNPS control is still slow.

The HLRA is the representative of advanced crop production and the largest green-food production base in China; the rate of its agricultural mechanization has reached 94%, the mode of testing soil for formulated fertilization occupies 90% of field planting, and fertilizer application by aerial spraying is widespread (generally an airplane can apply fertilizer to a 40 thousand ha paddy field) [24]. However, it is uncertain whether this study area has done its best to coordinate crop growth with environmental pressure or how great the gap is between what has been accomplished here and what has been accomplished in developed countries and regions.

As seen from the indicators of fertilizer application in different countries/regions (Table 7), it is not possible to draw a conclusion based on only fertilizer application amount, fertilizer input per unit area or fertilizer input per unit crop yield. Even with similar values of fertilizer application, AGNPS pollution during the process of crop production may vary widely, due to differences in annual rainfall, efficiency of agricultural water use, fertilizer use efficiency, fertilizer leaching rate, crop structure, cropping system and technology innovation. In light of these considerations, it is tenable to use the decoupling analysis as a practical method for regional comparative study based on a spatiotemporal angle.

Table 7. Comparison of fertilizer use based on the average value during the years 2005–2010. Data in the table are from the Statistical Yearbook of Heilongjiang State Farms (2006–2011), China Statistical Yearbook (2006–2011) and International Statistical Yearbook (2006–2011).

Country (Region)	Fertilizer Application Amount (10^8 kg)	Fertilizer Input per unit Area (kg/ha)	Fertilizer Input per Unit Crop Yield (kg/10^3 kg)
Heilongjiang Land Reclamation Area	3.91	157	28.6
China	516.83	331	100.3
The United States	214.59	219.5	45.37
England	14.82	370.75	69.73
Germany	22.88	248.88	50.15
France	32.08	263.88	49.57
Italy	8.18	213.25	53.03
Canada	26.63	113.63	50.13
Japan	12.93	489.5	106.98
Korea	6.51	489.88	94.53

(2) Scholars prefer to adopt sustainability assessment methods with more indicators that are used more prevalently in the literature; adopting these methods facilitates comparison and mutual authentication [37]. On the topic of examining the relationship between economic growth and environmental pressure, a decoupling analysis can be integrated with other traditional methods. For example, it is possible to compare the decoupling/coupling degrees with the corresponding stages of the EKC, according to different DI and the corresponding area A, B and C shown in Figure 6 [5]. When integrated in this way, these two methods can corroborate, complement and reinforce each other.

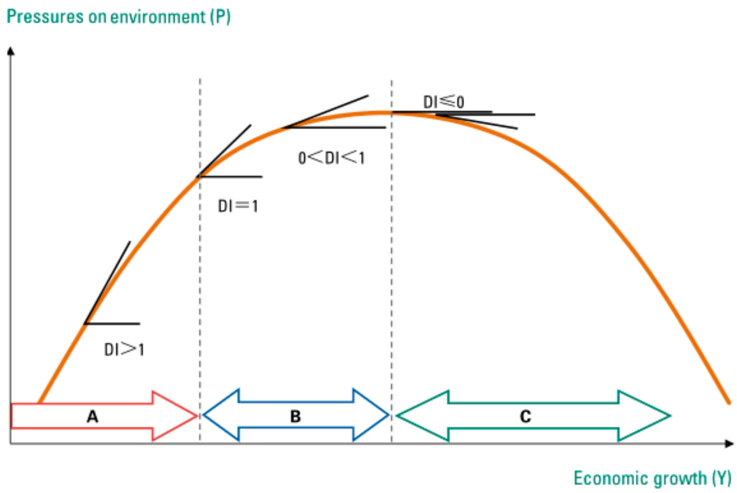

Figure 6. Integrating decoupling analysis with the EKC [5].

(3) Decoupling indicators shed light on particular aspects of a complex reality but leave out other aspects, and the decoupling concept lacks an automatic link to the environment's process [5,11]. As a result, a policy based on decoupling analysis is not enough to coordinate the relationship between crop production and environmental degradation. It is, however, known that over-use of fertilizer and low fertilizer-use efficiency are contributors to AGNPS pollution. The next step is to put forward pertinent suggestions for local policy making, especially for factors playing a role in reducing AGNPS pollution, such as the efficiency of agricultural water use, fertilizer variety, fertilizer use efficiency, crop structural adjustment, cropping system and technology innovation.

5. Conclusions

Using decoupling analysis to evaluate the relationship between regional economic growth and environmental impact has received increasing attention in sustainability studies. From the perspective of AGNPS pollution, fertilizer application has been a major source of water pollution in recent decades accompanied by an increasing crop yield, and this trend will likely continue in many countries.

The results of decoupling AGNPS pollution from crop production in the HLRA indicated that the trend of weak decoupling occurred for 6 years, and that recessive decoupling occurred for 1 year in 2001–2012. In addition, weak decoupling occurred more in each branch, as is evident from the average value (2001–2012). For the example of decoupling AGNPS pollution from rice production, weak decoupling occurred half of the time during 2001–2012, and all branches, except for the Suihua branch, in the HLRA reached weak decoupling from the standpoint of the average value (2001–2012).

According to the results of the decoupling analysis, the authors found a high appearance frequency of weak decoupling during 2001–2012 in the HLRA, but the status of weak decoupling was not steady over time. A decoupling tendency and environmental deterioration coexist in the past and present, and the high appearance frequency of weak decoupling does not mean that a strong decoupling will be realized over the next decade or at some later time. It was also revealed that rice production is the leading source of AGNPS pollution in the HLRA, and that optimizing the fertilizer application and field management of rice growth will become a very important task in the future.

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Author Contributions: Q.Y. conceptualized the study design. J.L. collected and analyzed the data. Y.Z. conducted the data analysis and wrote the manuscript. All authors read, revised and approved the final manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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