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Payment for Rice Growers to Reduce Using N Fertilizer in the GHG Mitigation Program Driven by the Government: Evidence from Shanghai

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Abstract: The overuse of N fertilizer by rice growers triggers excessive greenhouse gas (GHG) emission, leading to the environmental and climatic problem. However, growers will probably suffer loss in profits if they reduce the use of N fertilizer under the existing technology condition. The payment in market-based or government-driven way may overcome the potential barrier. For the appropriate carbon trading market is absent, the government-driven program will play a role in the payment. Three key issues in the designed program are the price of the payment, the participation rate of rice growers, and the variation of items associated with the social welfare. Due to the difficulty in estimating the economic value, prices of the payment can be set according to shadow prices. This paper applies the parametric directional output distance function to derive shadow prices of CO₂ for 308 rice growers in Shanghai from 2008–2015. Average shadow prices range from RMB 1130 to 3769 yuan/ton (or US 163 to 618 \$/ton). Taking the year of 2015 as sample, this paper predicts the participation rate (97.08%) of rice growers with the aim of 10% N fertilizer reduction and the specific price of the payment (7.47 yuan/kg). Moreover, this paper discusses on the variation of factors linked with the social welfare, and derive two important relationships from it. In detail, the relationship between the yield of the rice and the reduction of the N fertilizer should be balanced; the relationship between the improvement on the profit of rice growers (or the participation rate) in the program and the payment by the government should also be balanced.

Keywords: N fertilizer; GHG mitigation program; prices of the payment; participation rate; social welfare

1. Introduction

China is one of the main countries emitting the greenhouse gas (GHG) in the world. As one of the major sources, agriculture contributes for 15–19% of the total emission of China, which is above the global average level of 13.5% [1]. Especially, overusing N fertilizer leads to the excessive GHG emission from Chinese agriculture and rural environmental deterioration [1–3]. To relieve climatic and environmental problems, the Chinese government drew up a plan on reducing the use of N fertilizer, and declares to pursue the “green, low-carbon, sustainable” agricultural development.

In Shanghai, the yield of the rice account for over 80% of the total crop yield. Meanwhile, rice growers overuse N fertilizer in the process of planting. How to guide rice growers to reduce using N fertilizer has aroused high attention by the local government and the public. Moreover, as the pilot city of the agricultural development and reform, Shanghai will provide references on reducing the use of N fertilizer to other regions in China.

Some experiments focus on the relationship between the reduction of the N fertilizer and the rice yield [4–6]. Results show that if growers apply specific ‘low-carbon’ technologies to the process of

planting, the rice yield will remain unchanged with 10–30% reduction of the N fertilizer. However, whether reducing using N fertilizer or not depends on growers. In practice, rice growers tend to use more N fertilizer than the suggestion provided by experiments. They apply ‘excessive’ N fertilizer to guarantee the yield and the profit, for the actual production condition is more complex than the standardized experiment.

In essence, the ‘excessive’ N fertilizer reflects the gap between the social optimum and the individual choice. Approaches such as taxation or administrative restriction on the use of N fertilizer are unreasonable, for the mitigation can not be realized at sacrifice of growers’ interests. To bridge the gap, this paper learns lesson from the Payment for the Environment or Ecosystem Services (PES) program, and pay growers for the ‘additional’ GHG mitigation due to their reduction of N fertilizer. Judging from the PES program, this paper divides the existing payment into two major forms: market-based and government-driven [7–13]. The former mainly includes the ‘cap and trade’ market and some local markets. On the one hand, the ‘cap and trade’ market is built to control the total GHG emission by industrial and energy enterprises. If enterprises emit more GHG than their initial permits, they can buy permits from other enterprises or specific carbon sink programs in the ‘cap and trade’ market. On the other hand, local markets are suitable for tradable carbon-sink programs that are not allowed to enter the ‘cap and trade’ market, but meet the needs of the Kyoto Protocol [14–16]. The latter is government-driven. It is mainly composed of environmental or ecological protection programs advocated and sponsored by the government [10,13,17–19].

Compared with the market-based one, the government-driven program is preferable. First, the carbon-sink collected from Chinese agriculture is not allowed to enter either the ‘cap and trade’ market or the local one [1,14–16]. Obviously, the GHG mitigation caused by the reduction of N fertilizer can’t get payment from the market in the short term. Second, the GHG mitigation from agriculture not only has characteristics of public goods, but also needs giant financial support due to its high transaction costs [19–21]. Thus, the government-driven program should pay growers for the ‘additional’ GHG mitigation caused by their reduction of N fertilizer.

After choosing the payment in the form of the government-driven program, this paper wants to learn how much money should be paid for one unit of the GHG mitigation. In other words, what are prices of the payment for the GHG mitigation due to the reduction of N fertilizer? Unfortunately, few studies focused on them. Thus, this paper decides to take reference from some suggestions and practices in PES programs again.

First, the payment reflects the opportunity cost of environmental and ecological services [22–26]. However, objects of the payment are the additional GHG mitigation caused by the reduction of N fertilizer rather than the action or service itself. In other words, the payment for the reduction of N fertilizer should be formulated based on the additional amount of GHG caused by the action.

Second, the payment reflects the economic value that the reduction of ‘additional’ negative externalities creates for the whole society. On the one hand, some experts suggest prices of the carbon trade market should be used to reflect prices of the carbon sink in specific forest programs [16,27,28]. However, the GHG mitigation from Chinese agriculture is not allowed to enter market. Thus, prices of the carbon market can’t be used to represent prices of the payment. On the other hand, based on specific models and the calibration of parameters, some experts apply the (dynamic) computable general equilibrium method to calculate the economic value of negative externalities [29–31]. However, results of the economic value are not only close linked with specific models, but also decided by the calibration of parameters from mature cases. Obviously, this method is also unsuitable. Finally, some studies show that it will be difficult to obtain the real economic value of negative externalities if the market is missing [10,11,20]. In detail, scholars tend to overestimate the economic value, for associated services bring the whole society complicated and diverse environmental or ecological improvement.

Although the economic value of the reduction of ‘additional’ negative externalities is not easy to get, the marginal abatement cost can be calculated in relative methods. The marginal abatement cost implies how much money will be spent to reduce one unit of undesirable output such as the pollution

or the GHG emission. It means the economic value is the upper bound of the price of the payment for the GHG mitigation, while the marginal abatement cost is the floor limit. If the price of the payment is set below the marginal cost of the GHG mitigation, the grower will suffer loss in reality.

As the base of permits price for the cap and trade market or the reference for the environmental taxation, the shadow price is often used to measure the marginal abatement cost of undesirable outputs [32–41]. Shadow prices of desirable and undesirable outputs are originally gained from the duality theory [32]. The advantage of this approach is that it doesn't need any prior information on regulatory constraint. Then, shadow prices are estimated by the parametric output distance function in translog style or the parametric directional output distance function in quadratic way. Compared with the former, the latter witnesses expansion of desirable outputs and contraction of undesirable ones simultaneously. This property fits policy makers' preference in gaining more desirable outputs with the reduction of undesirable ones [35,36]. Notably, few studies focused on the marginal abatement cost of CO₂ for rice growers in China due to the lack of microdata. A similar study is about shadow prices of carbon emissions for China's planting industry [34]. The directional output distance function is applied to estimate shadow prices of carbon emissions caused by the planting industry in 30 Chinese provinces from 1997–2014. Average shadow prices ranges from 5.06–664.35 yuan/ton.

From the aspect of the payer, this paper wants to design the mitigation program, and solve three key issues in it. They are made up of how much prices of the payment will be, the participation rate of rice growers and the variation of items associated with the social welfare. The latter two issues are closely linked with the first one, which influences the implementation of the program. Four steps are adopt to solve key issues. First, this paper depicts the design of the program. Second, the parametric directional output distance function (DDF) is used to calculate shadow prices of CO₂ from 2008–2015 based on the sample of rice growers in Shanghai. Meanwhile, this paper derive individual prices of the payment from shadow prices. Third, given prices of the payment and the aim of reduction on the N fertilizer, this paper predicts the participation rate and the variation of items associated with the social welfare. Forth, two important relationships are emphasized, for their balance decides whether the mitigation program will be sustainable or not.

The remaining paper is composed as follows. Section 2 depicts the design of the program. Section 3 introduces the empirical model and the estimated method of the parametric directional output distance function. Section 4 describes the data of inputs and outputs. Section 5 gets the directional output distance function and shadow prices of CO₂. Section 6 derives individual prices of the payment from shadow prices of CO₂, explores the participation rate of rice growers, discusses on the variation of items associated with the social welfare, and mentions two important relationships. Section 7 makes conclusion of the paper, and analyses the limitation of the study.

2. The Design of the Program

2.1. The Element of the Program

Like other PES programs, the program of reducing using the N fertilizer is fundamentally made up of the payer, the supplier of the service, the object, and prices of the payment.

- The payer: the government. The program is driven and sponsored by the government.
- The supplier of the service: rice growers. Rice growers decide reducing using the N fertilizer or not
- The object of the program: additional GHG mitigation caused by the reduction of the N fertilizer. The essence of the object is the reduction of negative externalities due to the services rather than the service itself.
- Prices of the payment: combining the marginal abatement cost of the GHG and the amount of the GHG mitigation caused by the reduction of the N fertilizer. On the one hand, the marginal abatement cost of the GHG is gained from the shadow prices. On the other hand, the amount of the GHG mitigation can be calculated according to the formula.

2.2. The Shadow Price

The shadow price is applied to gain prices of the payment, which is the first key issue in the program. Also, it is the base of the solution to the second and third key issue.

In practice, growers not only produce the desirable output, such as the rice, but also trigger the undesirable one, including the GHG emission. Obviously, the classical technology focusing only on desirable outputs cannot fully reflect the agriculture production in reality. Under this circumstance, this paper defines the technology as the compact output sets [35]:

$$P(x) = \{(y, b) : x \text{ produce } (y, b)\} \quad (1)$$

where inputs $x = (x_1 \dots x_N) \in R_+^N$, desirable outputs $y = (y_1 \dots y_M) \in R_+^M$ and undesirable outputs $b = (b_1 \dots b_J) \in R_+^J$.

Four properties associated with the output sets $P(x)$ are mentioned below:

1. The free disposability of inputs: when $x' \leq x$, $P(x') \subseteq P(x)$.
2. The free disposability of desirable outputs: if $(y, b) \in P(x)$ and $y' \leq y$, then $(y', b) \in P(x)$. It is possible to gain less desirable output without any cost in the comparable situation.
3. The weak disposability of the desirable and undesirable output: if $(y, b) \in P(x)$ and $0 \leq \theta \leq 1$, then $(\theta y, \theta b) \in P(x)$. It is feasible that desirable and undesirable outputs meet the same proportional change. In other words, the reduction of undesirable outputs is realized at the cost of the decrease in desirable ones.
4. The null-jointness: if $(y, b) \in P(x)$ and $b = 0$, then $y = 0$. Undesirable outputs will be the byproduct of desirable ones unless the latter are not produced.

Based on assumptions of the technology, this paper adopts the directional output distance function defined as:

$$\bar{D}_0(x, y, b; g) = \max \left\{ \beta : (y + \beta g_y, b - \beta g_b) \in P(x) \right\} \quad (2)$$

where the directional vector $g = (g_y, -g_b)$, with $g \in R_+^M \times R_+^J$.

Obviously, the function aims to realize the maximum of the desirable outputs and the minimum of the undesirable ones. In detail, given a specific directional set $g = (g_y, -g_b)$, we can expand desirable outputs and contract undesirable ones until the group of outputs reaches the boundary of the output sets $P(x)$ at the point of $(y + \beta^* g_y, b - \beta^* g_b)$, where $\beta^* = \bar{D}_0(x, y, b; g)$.

Just like the technology $P(x)$, there also exist six properties associated with the directional output distance function as followed:

First, $\bar{D}_0(x, y, b; g)$ is concave. If $(y, b) \in P(x)$, then $\bar{D}_0(x, y, b; g) \geq 0$. In detail, when the directional output distance function equals zero, the group of desirable and undesirable outputs will be on the boundary of the output sets $P(x)$, meaning the production achieves the efficiency. Meanwhile, the production will be more inefficient with the increasing value of the directional output distance function.

Second, if $x' \leq x$, then $\bar{D}_0(x', y, b; g) \leq \bar{D}_0(x, y, b; g)$. Given constant desirable and undesirable outputs, the production will be more efficient with fewer inputs.

Third, if $y' \leq y$, then $\bar{D}_0(x, y', b; g) \geq \bar{D}_0(x, y, b; g)$. Given constant inputs and undesirable outputs, the production will be more efficient with more desirable outputs.

Fourth, if $b' \leq b$, then $\bar{D}_0(x, y, b'; g) \leq \bar{D}_0(x, y, b; g)$. Given constant inputs and desirable outputs, the production will be more efficient with fewer undesirable outputs.

Judging from the second to fourth property, we can learn that more desirable outputs, less input and undesirable outputs contribute to the more efficient production.

Fifth, if $\bar{D}_0(x, y, b; g) \geq 0$ and $0 \leq \theta \leq 1$, then $\bar{D}_0(x, \theta y, \theta b; g) \geq 0$. It means that the weak disposability of desirable and undesirable outputs exists in the directional output distance function.

Sixth, the translation property is that $\vec{D}_0(x, y + \alpha g_y, b + \alpha g_b; g) = \vec{D}_0(x, y, b; g) - \alpha, \alpha \in \mathbb{R}$. The property highlights that if desirable outputs expand by αg_y and undesirable ones narrow by αg_b , then the directional output distance function will become more efficient by the amount of α .

In order to gain the shadow price of the undesirable output, this paper uses the method suggested by [36]. Let $p = (p_1, \dots, p_M) \in \mathbb{R}_+^M$ denote desirable output prices, and let $q = (q_1, \dots, q_M) \in \mathbb{R}_+^M$ denote undesirable output prices. Based on the directional output distance function, the revenue function involving the negative revenue caused by undesirable outputs is defined as:

$$R(x, p, q) = \max_{y, b} \{py - qb : (y, b) \in P(x)\} \quad (3)$$

The revenue function aims at maximizing the total revenue, which are made up of the positive revenue from desirable outputs and the negative one from undesirable outputs. Combining with the first property of the directional output distance function, this paper rewrites the maximum revenue function that:

$$R(x, p, q) = \max_{y, b} \{py - qb : \vec{D}_0(x, y, b; g) > 0\} \quad (4)$$

Given a directional vector $g = (g_y, -g_b)$, the revenue equation can be rewrite again as:

$$R(x, p, q) \geq (py - qb) + p\vec{D}_0(x, y, b; g)g_y + q\vec{D}_0(x, y, b; g) \quad (5)$$

The left side of the equation is the maximum revenue, while the right side equals the actual revenue plus the extra revenue brought by the improvement of the technical efficiency. In detail, the extra revenue is divided into two parts including the increase in desirable outputs and the decrease in undesirable puts. Rearranging Equation (5), this paper obtains the relationship between the directional output distance and the maximum revenue function as follows:

$$\vec{D}_0(x, y, b; g) \leq \frac{R(x, p, q) - (py - qb)}{pg_y + qg_b}, \text{ which means } \vec{D}_0(x, y, b; g) = \min_{p, q} \left\{ \frac{R(x, p, q) - (py - qb)}{pg_y + qg_b} \right\} \quad (6)$$

Then, this paper applies the Envelop Theorem to the equation and get the first-order condition with regard to the desirable output and the undesirable one, respectively:

$$\nabla_y \vec{D}_0(x, y, b; g) = \frac{-p}{pg_y + qg_b} \leq 0 \text{ and } \nabla_b \vec{D}_0(x, y, b; g) = \frac{q}{pg_y + qg_b} \geq 0 \quad (7)$$

Provided that the price of m -th desirable output is known, the shadow price of the j -th undesirable output can be expressed as:

$$q_j = -p_m \left(\frac{\partial \vec{D}_0(x, y, b; g) / \partial b_j}{\partial \vec{D}_0(x, y, b; g) / \partial y_m} \right) \quad (8)$$

2.2.1. Predicting the Rice Growers' Participation

The participation of rice growers is important to the implementation of the program. Thus, predicting the rice growers' participation is the second key issue in the program.

For the rice grower, the production function is $Y = f(X_1, \dots, X_k, \dots, X_n)$, where Y is the yield of the rice, X_i is the input ($i = 1 \dots k \dots n$), and X_k is the N fertilizer. Meanwhile, the price of the rice is P , and prices of the inputs are $W_1 \dots W_k \dots W_n$.

Without the payment, the rice grower's profit $\pi_0 = P \times f(X_1, \dots, X_k, \dots, X_n) - W_1 \times X_1 - \dots - W_k \times X_k - \dots - W_n \times X_n$, where $X_1, \dots, X_k, \dots, X_n$ are initial inputs the rice grower apply to the production.

Then, the government pursues C% reduction of the initial N fertilizer, and pays rice growers for their realizing the reduction. In detail, the government sets the price of the payment S according to Individual prices of the payment. The latter can be gained from the Equation (9).

Individual prices of the payment for reducing the use of N fertilizer = the amount of CO₂ mitigation caused by reducing 1 kg N fertilizer × marginal abatement costs of CO₂ (or shadow prices) of each rice grower (Equation (9)).

Provided that prices of the yield and inputs keep constant in short term, and rice growers can or will only change the use of N fertilizer, the rice grower's profit will be:

$$\pi_1 = P \times f(X_1, \dots, (1 - C\%) \times X_k, \dots, X_n) - W_1 \times X_1 - \dots - W_k \times (1 - C\%) \times X_k - \dots - W_n \times X_n + S \times C\% \times X_k \quad (9)$$

If $\pi_1 \geq \pi_0$, the rice grower will take part in the program; If $\pi_1 < \pi_0$, otherwise.

2.3. The Variation of Items Associated with the Social Welfare

In addition to the participation of rice growers, the government focuses on factors linked with the social welfare, which is the third key issue in the program. In detail, (1) the amount of the N fertilizer not only decides the aim of the mitigation, but also decides the yield of the rice. (2) The yield of the rice is close related to the food security, which draws high attention from the government. (3) The profit not only decides whether the rice grower takes part in the mitigation program, but also implies the living standard of the grower. (4) The payment is one kind of the financial expenditure, needing consideration by the government. Table 1 shows the variation of the yield, the amount of the N fertilizer, the profit of the rice grower, and the payment from the government. It is supposed that the yield of the rice declines with the reduction of the N fertilizer. Although the rice grower gains more from the payment, the government will hold an extra financial burden.

Table 1. The variation of factors linked with the social welfare after the payment.

Factors Linked with the Social Welfare		Variation	Sign
(1)	The yield of the rice	$f(X_1, \dots, X_k, \dots, X_n) - f(X_1, \dots, (1 - C\%) \times X_k, \dots, X_n)$	−
(2)	The amount of the N fertilizer	$C\% \times X_k$	−
(3)	The profit of the rice grower	$\pi_1 - \pi_0$	+
(4)	The payment by the government	$S \times C\% \times X_k$	+

3. Empirical Model

The directional output distance function can be estimated either in the parametric or non-parametric way. Although the non-parametric way enables us not to consider the specific form of the function, this paper still decides to adopt the parametric way due to our aim at gaining shadow prices of undesirable outputs from the differentiable function just like [35–37]. Meanwhile, the directional output distance function can be expressed as the translog or quadratic form. Compared with the translog one, the quadratic form satisfies the translation property restrictively mentioned below [35–37]. So, the quadratic form is preferable. Moreover, this paper sets the directional vector $g = (1, -1)$, which meets the need of the mitigation regulation that achieve the increase in desirable outputs and the reduction in undesirable ones.

The GHG emission associated with rice growers are made up of two parts: (a) the CH₄ emission from rice fields, and (b) the direct and indirect emission of N₂O from the soil [42]. Thus, this paper calculates the amount of CH₄ and N₂O correspondingly, and then convert them to CO₂ according to their thermodynamic value. In detail, the desirable output y is the rice yield, while the undesirable one b is the amount of CO₂ emission. Additionally, inputs are composed of X_1 —farmland devoted to

the rice, X_2 —agricultural labor, and X_3 —other intermediate inputs made up of the fertilizer, pesticides, and seeds. The year of the data ranges from 2008 to 2015, and 308 rice growers in Shanghai are taken into consideration.

Consequently, the parametric directional output distance function in the form of quadratic is defined as followed:

$$\begin{aligned} \vec{D}_0(X_{nkt}, y_{kt}, b_{kt}; 1, -1) = & \alpha_0 + \sum_{n=1}^3 \alpha_n X_{nkt} + \beta_1 y_{kt} + \gamma_1 b_{kt} + \\ & \frac{1}{2} \sum_{n=1}^3 \sum_{n'=1}^3 \alpha_{nn'} X_{nkt} X_{n'kt} \\ & + \frac{1}{2} \beta_2 y_{kt}^2 + \frac{1}{2} \gamma_2 b_{kt}^2 + \sum_{n=1}^3 \delta_n X_{nkt} y_{kt} + \sum_{n=1}^3 \eta_n X_{nkt} b_{kt} + u_1 b_{kt} y_{kt} \end{aligned} \quad (10)$$

where n denotes the n -th input, $n = 1 \dots 3$; k denotes the k -th rice grower, $k = 1 \dots 308$; t denotes year t , $t = 2008 \dots 2015$.

Based on the translation property and the direction vector, we set the restriction of parameters that:

$$\beta_1 - \gamma_2 = -1; \beta_2 = \gamma_2 = u_1; \eta_n - \delta_n = 0; \alpha_{nn'} = \alpha_{n'n}, n \neq n' (n = 1 \dots 3)$$

To estimate unknown parameters of the directional output distance function, this paper uses the deterministic approach [43]. In detail, the linear programming (LP) method is applied to estimate parameters by minimizing the sum of the differences between observable distance values and zero:

$$\min \sum_{k=1}^{308} \sum_{t=2008}^{2015} \left[\vec{D}_0(X_{nkt}, y_{kt}, b_{kt}; 1, -1) - 0 \right] \quad (11)$$

s.t

1. $\vec{D}_0(X_{nkt}, y_{kt}, b_{kt}; 1, -1) \geq 0$;
2. $\frac{\partial \vec{D}_0(X_{nkt}, y_{kt}, b_{kt}; 1, -1)}{\partial X_{nkt}} \geq 0$;
3. $\frac{\partial \vec{D}_0(X_{nkt}, y_{kt}, b_{kt}; 1, -1)}{\partial y_{kt}} \leq 0$;
4. $\frac{\partial \vec{D}_0(X_{nkt}, y_{kt}, b_{kt}; 1, -1)}{\partial b_{kt}} \geq 0$;
5. $\beta_1 - \gamma_1 = -1, \beta_2 = \gamma_2 = u_1, \eta_n - \delta_n = 0, n \neq n' (n = 1 \dots 3)$;
6. $\alpha_{nn'} = \alpha_{n'n}, n \neq n' (n = 1 \dots 3)$.

The constraint 1 implies that groups of desirable and undesirable outputs are located at or close to the technology frontier. Constraints 2–4 imply the monotonicity of inputs or outputs. Constraints 5 and 6 satisfy the translation property and the symmetry condition accordingly.

4. Data

The data comes from the information management and performance evaluation system of the agricultural operation in Shanghai. The research object of the system covers 800 farmers from nine districts of Shanghai. Meanwhile, agriculture products include grain, oil, vegetables, fruits, flowers, and so on. Moreover, the information of the system includes farmland, labor, and other input factors such as fertilizers and pesticide, crop yield and prices, etc. Though others changed the type of crop from 2008–2015, 308 farmers kept growing rice during the same time. Their information is important for the government to set up and implement the mitigation program. Given the payment, 308 rice growers decide to reduce the N fertilizer or not, and are closely linked with the yield of the rice.

Thus, this paper applies the information of 308 rice growers from 2008–2015 to the analysis. In detail, the information consists of inputs and desirable outputs, such as X_1 —the farmland devoted to the rice, X_2 —the agricultural labor, X_3 —other intermediate inputs, and y —the rice yield. However, the data of undesirable outputs, such as CH_4 and N_2O are not available from the system. Thus, this paper calculates the amount of GHG emission according to the formulas [42,44–46]. Formulas are revealed

in the Appendix A. Then, this paper converts them to CO₂ according to their thermodynamic value. Finally, the statistical analysis of inputs, and desirable and undesirable outputs for 308 rice growers from 2008–2015 are shown in Table 2.

Table 2. The statistical analysis of inputs, and desirable and undesirable outputs for 308 rice growers from 2008–2015.

Variable		Mean	Std. Dev.	Min	Max	Observations
y	Overall	24,406.07	44,112.47	200.00	448,750.00	N = 2464
	Between		36,890.36	353.75	257,631.10	n = 308
	Within		24,266.83	−231,005.10	274,209.10	T = 8
x ₁	Overall	67.95	139.62	0.50	1250.00	N = 2464
	Between		130.24	1.73	950.00	n = 308
	Within		50.81	−334.96	712.10	T = 8
x ₂	Overall	135.61	427.40	2.00	14,129.00	N = 2464
	Between		304.65	4.69	2772.13	n = 308
	Within		300.20	−2476.51	11,492.49	T = 8
x ₃	Overall	4533.13	20,288.27	0.00	700,960.00	N = 2464
	Between		13,241.32	103.87	178,150.30	n = 308
	Within		15,387.64	−162,697.10	527,342.90	T = 8
x ₃₁	Overall	1784.36	4286.24	0.00	65,000.00	N = 2464
	Between		3164.14	0.00	28,751.25	n = 308
	Within		2896.28	−26,401.26	38,448.74	T = 8
b ₁	Overall	815.40	1675.49	6.00	15,000.00	N = 2464
	Between		1562.84	20.76	11,400.00	n = 308
	Within		609.72	−4019.49	8545.15	T = 8
b ₂	Overall	9.11	21.89	0.00	331.96	N = 2464
	Between		16.16	0.00	146.84	n = 308
	Within		14.79	−134.84	196.36	T = 8
b	Overall	23,209.94	45,060.32	319.79	375,000.00	N = 2464
	Between		41,749.69	636.34	289,155.90	n = 308
	Within		17,098.23	−102,681.80	233,794.00	T = 8

Note: Inputs include X₁—the farmland devoted to the rice (Mu = 0.0667 hectares), X₂—the agricultural labor and X₃—other intermediate inputs including fertilizers, pesticides and seeds (Kg). The desirable output is represented by Y—the rice yield (Kg). Undesirable outputs are consisted of b₁—the amount of CH₄ emission (kg), b₂—the amount of N₂O emission (kg) and b—the amount of CO₂ emission converted by b₁ and b₂. Furthermore, we are interested in X₃₁—the N fertilizer (Kg), despite its absent in the directional output distance function.

First, this paper explores the relationship among the inputs, rice yield, and the GHG emission. The average amount of inputs, desirable and undesirable outputs for 308 rice growers from 2008–2015 are shown in Table 3. The average rice yield increased from 14,695.35 kg in 2008 to 31,155.68 kg in 2015, which means the productivity of rice growers improved a great deal. Meanwhile, the amount of the farmland and labor devoted to the rice witnessed irregular changes from 2008–2015. Moreover, the average amount of other intermediate inputs increased from 2367.72 kg in 2008 to 4343.15 kg in 2015. The similar trend was due to the N fertilizer, whose average amount increased from 1394.34 kg to 2339.06 kg during eight years. Obviously, the more application of other intermediate inputs including the N fertilizer contributed for the growth of the rice yield.

Second, the efficiency of inputs to the rice yield through ratios is showed in Table 4. In theory, the efficiency of inputs to the rice yield improves with smaller ratios. Obviously, the efficiency of the farmland improved from 2008–2013, but fell and kept constant since 2014. Although the efficiency of the labor experienced irregular change from 2008–2015, it improved a great deal during the decade. Compared with the trend of the farmland or the labor, the efficiency of other immediate inputs, including the N fertilizer, deteriorated since 2011. This implies that growers applied more and more N fertilizer to rice in recent years, or the marginal effect on the yield of the rice exerted by N fertilizer declined since 2011.

Table 3. The average value of inputs, desirable and undesirable outputs of about 308 rice growers from 2008–2015.

Year	2008	2009	2010	2011	2012	2013	2014	2015
y	14,695.35	18,042.85	20,926.47	23,822.4	27,039.67	30,801.09	28,765.06	31,155.68
X ₁	69.63	68.69	64.05	68.57	64.72	59.8	70.63	77.52
X ₂	117.45	110.52	129.37	139.28	130.95	149.71	174.02	133.62
X ₃	2367.72	2666.55	2970.14	2856.32	3398.02	4011.18	3845.91	4343.15
X ₃₁	1394.34	1425.41	1545.85	1509.73	1772.82	2263.93	2023.78	2339.06
b ₁	835.59	524.31	768.58	822.8	776.58	717.59	847.52	930.2
b ₂	7.12	7.28	7.90	7.71	9.05	11.56	10.34	11.95
b	23,097.15	22,864.36	21,661.95	22,960.22	22,221.25	21,524.11	24,392.15	26,958.34

Note: Inputs include X₁—the farmland devoted to the rice (Mu = 0.0667 hectares), X₂—the agricultural labor, X₃—other intermediate inputs including fertilizers, pesticides and seeds (Kg), and x₃₁—the N fertilizer (Kg), The desirable output is represented by Y—the rice yield (Kg). Undesirable outputs are consisted of b₁—the amount of CH₄ emission (kg), b₂—the amount of N₂O emission (kg) and b—the amount of CO₂ emission converted by b₁ and b₂.

Table 4. The ratio of farmland, labor, other immediate inputs, and N fertilizer to rice yield.

Year	2008	2009	2010	2011	2012	2013	2014	2015
X ₁ /y	0.0047	0.0038	0.0031	0.0029	0.0024	0.0019	0.0025	0.0025
X ₂ /y	0.0080	0.0061	0.0062	0.0058	0.0048	0.0049	0.0060	0.0043
X ₃ /y	0.1611	0.1478	0.1419	0.1199	0.1257	0.1302	0.1337	0.1394
X ₃₁ /y	0.0949	0.0790	0.0739	0.0634	0.0656	0.0735	0.0704	0.0751

Note: Inputs include X₁—the farmland devoted to the rice (Mu = 0.0667 hectares), X₂—the agricultural labor, X₃—other intermediate inputs including fertilizers, pesticides and seeds (Kg), and x₃₁—the N fertilizer (Kg), The desirable output is represented by Y—the rice yield (Kg).

Third, attention should be paid to the higher and higher level of the N fertilizer. On the one hand, N₂O emission is close linked with the N fertilizer. The average amount of N₂O emission increased from 7.12 kg in 2008 to 11.95 kg in 2015, and that of CO₂ emission also increased from 23,097.15 kg to 26,958.34 kg during eight years showed in Table 3. The excessive GHG emission causes the environmental and climatic problem. On the other hand, reducing the use of N fertilize will probably not only improve the productivity efficiency, but also leads to the reduction of the yield. Under this circumstance, measures such as reducing the use of N fertilizer should be considered in the GHG mitigation program. Meanwhile, the relationship between reducing the use of N fertilizer and the fall of the yield may also be thought about in the program.

5. Results

This paper applies the deterministic method (LP) to estimate coefficients of the parameters of the directional output distance function. In order to solve potential convergence problems in the model, this paper normalizes input and output variables by their mean values [35,39]. The estimation is displayed in Table 5. For this paper imposes constraints on the minimization of the total value of observed directional distance functions in advanced, observations of the directional output distance function comply with the monotonicity of inputs and outputs, the translation property and the symmetry condition except the null-jointness. Thus, this paper checks whether the directional output distance functions satisfy the null-jointness. It is found that observations of the deterministic method model comply with the null-jointness at the level of 96.59% (2380/2464), which means the quadratic function is suitable to represent the true directional distance function.

Table 5. Estimated results of the deterministic method (LP).

Coefficient	Value	Coefficient	Value
α_0	−0.0111	$\alpha_{13} = \alpha_{31}$	0
α_1	0	α_{22}	−0.0027
α_2	0.0534	$\alpha_{23} = \alpha_{32}$	−0.00001
α_3	0.0021	α_{33}	−0.00002
β_1	−0.0912	$\beta_2 = \gamma_2 = u_1$	−0.0080
$\gamma_1 = \beta_1 + 1$	0.9088	$\eta_1 = \delta_1$	0
α_{11}	0	$\eta_2 = \delta_2$	0.0030
$\alpha_{12} = \alpha_{21}$	0	$\eta_3 = \delta_3$	−0.0001

This paper calculates the average shadow prices of CO₂ for rice growers from 2008–2015. According to Figure 1, average shadow prices of CO₂ experienced an upward trend at first. It increased from RMB 1.13 yuan/kg in 2008 to RMB 3.67 yuan/kg in 2015. Furthermore, shadow prices fell and reached 3.14 yuan/kg in 2015. In theory, the financial burden held by rice growers to reduce CO₂ emission became heavier and heavier from 2008–2013, but has obtained relief since 2014. So, price of the payment set by the government should decline following the trend of shadow prices.

Figure 1. Average shadow prices of CO₂ for rice growers from 2008–2015 (RMB: yuan/kg).

Based on the trend of average shadow prices of CO₂, this paper further gets the distribution of shadow prices for each growers in 2008, 2013, and 2015. Results in Figure 2 show that the shape of the distribution for 2015 is similar to that for 2013, but different from that for 2008. It implies that shadow prices for rice growers in the sample are widely distributed in 2013 or 2015, while concentrated relatively in 2008. In other words, the degree of deviation on financial burden of the GHG mitigation held by rice growers was much higher in 2015 than that in 2008. As the payer of the program, the government should take that fact into consideration when setting prices of the payment.

As there are few studies focusing on shadow prices of the GHG emission from Chinese agriculture, this paper cannot gain enough findings to make comparison with our results. Thus, this paper mainly list studies on Chinese issues showed in Table 6. Average shadow prices in this paper are RMB 1130–3769 yuan/ton (or US 163–618 \$/ton) from 2008 to 2015. They are similar to results of some studies, but different from others. The GHG emission from the agricultural has the property of non-point source, and the scale of growers' production is comparatively small. Under this circumstance, it is possible for rice growers to have higher shadow prices or marginal abatement costs than other industrial or energy enterprises do.

Figure 2. The distribution of shadow prices for rice growers (year: a = 2008, b = 2013, c = 2015).

Table 6. Shadow prices of CO₂ in comparable studies.

Study	Period	Sample	Model	Shadow Price
[34]	1997–2014	carbon emissions from China's planting industry	DDF (paramatic)	5.06–664.35 yuan/ton
[39]	2004	124 power enterprises in China	DDF (paramatic)	\$249 per ton (stochastic); \$74 per ton (deterministic)
[47]	2009	30 Chinese manufacturing industries	IDF (paramatic)	3.13 \$/ton (deterministic)
[48]	2006–2015	CO ₂ shadow price in 29 provinces of China from 2006 to 2015	DEPFF (paramatic)	184.16 \$/ton (average)
[49]	2001–2010	CO ₂ emission in China based on a provincial panel	DDF (nonparamatic)	500–5800 yuan/ton

Notes: DDF represents the directional output distance function, IDF represents the input distance function, and DEPFF represents Directional Environmental Production Frontier Function. The deterministic method is mainly the linear program method, while the stochastic method consists of COLS regression and the ML estimation.

6. Discussion

6.1. Individual Prices of the Payment for Reducing the Use of N Fertilizer

Individual prices of payment means how much money rice growers should get due to their effort in reducing 1 kg N fertilizer. It can be predicted by the Equation (9). Reducing 1 kg N fertilizer will cause about 6.89 kg CO₂ mitigation according to the formula in the Appendix A. Meanwhile, this paper derives marginal abatement costs of rice growers from shadow prices of CO₂. The statistical analysis on individual prices of the payment are showed in Table 7. Judging from individual ones, the government could set the actual price of the payment in the mitigation program.

Table 7. Individual prices of the payment for rice growers from 2008 to 2015 (RMB: yuan/kg).

Year	Mean	Std. Dev.	Min	Max
2008	7.79	1.16	3.13	9.12
2009	9.87	1.93	4.23	27.71
2010	15.82	3.85	6.58	65.47
2011	18.65	3.09	7.57	38.46
2012	21.72	3.63	9.93	43.30
2013	25.97	6.14	7.75	72.76
2014	22.12	4.62	7.30	64.20
2015	21.63	5.93	7.47	74.59

6.2. The Production Function of Rice Growers

Given the price of the payment, predicting the participation of rice growers is essential to the mitigation program. As is mentioned in the Section 2, the production function of rice growers is indispensable. The Cobb–Douglas Model is widely used in predicting the production function associated with the agriculture [50]. So, this paper chooses the Cobb–Douglas Model as the production function:

$$Y_{it} = A \times X_{1it}^{\alpha_1} \times X_{2it}^{\alpha_2} \times X_{3it}^{\alpha_3} \times X_{4it}^{\alpha_4} \times X_{5it}^{\alpha_5} \quad (12)$$

where Y is the yield of rice (Kg), X_1 is the N fertilizer (Kg), X_2 is the farmland devoted to the rice ($\text{Mu} = 0.0667$ hectares), X_3 is the amount of labor used, X_4 is the seed (kg), X_5 is the pesticide (Kg), $i: 1 \dots 308$, $t: 2008\text{--}2015$.

Then, the regression model can be written as:

$$\ln(Y_{it}) = \ln(A) + \alpha_1 \ln(X_{1it}) + \alpha_2 \ln(X_{2it}) + \alpha_3 \ln(X_{3it}) + \alpha_4 \ln(X_{4it}) + \alpha_5 \ln(X_{5it}) + \lambda_t + \mu_i + \varepsilon_{it} \quad (13)$$

where λ_t is the time fixed effect; μ_i is the rice grower's fixed effect; ε_{it} is the error term of the equation. Results of the regression are showed in Table 8.

Table 8. Results of the regression on the production function.

Coefficient	(1)	(2)	(3)	(4)	(5)
α_1	0.6085 *** (0.0553)	0.6085 *** (0.0559)	0.2635 *** (0.0447)	0.2631 *** (0.0447)	0.1244 *** (0.0280)
α_2		0.0027 (0.0253)			
α_3			0.6919 *** (0.0412)	0.6867 *** (0.0404)	0.3568 *** (0.0455)
α_4				0.0062 (0.0087)	
α_5					0.4755 *** (0.0497)
constant	4.5989 *** (0.3310)	4.5928 *** (0.3229)	4.2534 *** (0.1599)	4.2551 *** (0.1606)	4.9823 *** (0.1225)
sigma u	0.7855	0.7822	0.4928	0.4895	0.3089
sigma e	0.5008	0.5009	0.3506	0.3506	0.2773
rho	0.7110	0.7091	0.6639	0.6609	0.5537
AIC	3051.20	3053.15	1409.30	1410.24	329.69
BIC	3097.14	3104.83	1460.98	1467.66	387.12

Notes: standard errors in parentheses; *** $p < 0.01$.

Among five estimated equations, the 5th regression equation is preferable for its smallest value of AIC and BIC. It is found that the N fertilizer, the amount of labor used and the pesticide contributed to the yield of the rice, while the farmland and the seed did not have significant influence on it. Meanwhile, inputs, such as the N fertilizer, the pesticide, and the amount of labor used led to the growth of the rice. Moreover, this paper obtains two other findings. First, the production of the rice growers has the property of decreasing returns to scale, for the sum of estimated coefficients in the 5th regression equation is about 0.96 (<1). Second, the influence of the N fertilizer exerted on the yield is smaller than those of the amount of labor used and the pesticide. To some extent, two findings explains why the efficiency of the N fertilizer deteriorated since 2011.

6.3. Participation Rate of the Rice Grower and the Variation of Factors Linked with the Social Welfare

After getting the production function of rice growers, this paper further predicts the participation of the rice grower. As is mentioned in Section 2, the government is supposed to pursue 10% reduction of the initial N fertilizer, and sets a unified price of the payment at 7.47 yuan/kg (the minimum individual price of the payment). Taking the year of 2015 as the sample, this paper calculates the variation of each rice grower's profit with the payment at first. If the variation is positive, the rice grower is supposed to participate the program. Then, this paper calculates average variation of profits for rice growers participating the program. Results are shown in Table 9.

Table 9. Average variation of the profit for rice growers participating the program (RMB: yuan).

Average Loss on the reduction of the rice yield	Average Cost saved from the reduction of the N fertilizer	Average net Loss without the payment	Average gain from the payment by the government	Average variation of the rice grower's profit with the payment
538.48	485.57	77.91	1774.80	1697.09

Given the price of the payment (7.47 yuan/kg) and the estimated rate of participation (97.08%), this paper further discusses about factors linked with the social welfare. Results are showed in Table 10. It is found that the amount of the N fertilizer drops 9.99%, while the yield of the rice will witnesses a reduction of 1.32%. Meanwhile, the profit of the rice grower improves by 3%, and the payment reaches 4.62% of the total existing subsidy to rice growers in the sample. If the government wants to gain 100% participation and realize 10% reduction of the N fertilizer, the price of the payment should be set higher to cover the net loss of rice growers.

Table 10. The ratio of the variation to the initial total value in the sample (%).

No	Factors Linked with the Social Welfare	The Ratio of the Variation to the Initial Total Value
1	the amount of the N fertilizer	−9.99
2	the yield of the rice	−1.32
3	the profit of the rice grower	3.00
4	the payment by the government	4.62

Furthermore, this paper derives two relationships from the variation of factors linked with the social welfare.

First, the relationship between the yield of the rice and the reduction of the N fertilizer should be balanced. Although the reduction of the N fertilizer does good to alleviate the climatic and environmental problem caused by agriculture, the issue of the food security cannot be ignored by the government. For the rice is one of the main food for people, the government should set the aim of the N fertilizer within the security scope of the rice yield.

Second, the relationship between the improvement on the profit of rice growers (or the participation rate) in the program and the payment by the government should be balanced. The improvement on the profit brought by the payment decides the participation rate of growers. Obviously, the more the payment is, the higher the participation rate will be. However, the payment is one kind of the financial expenditure. The government should carefully think of the financial burden due to the payment.

Notably, prices of the payment has a wide range of choices. Taking the year of 2015 as the sample, individual prices of the payment range from 7.47 yuan/kg to 74.59 yuan/kg. When the actual price of the payment is set 7.47 yuan/kg, the participation rate is about 97%. Meanwhile, the payment by the government reaches no more than 5% of the total existing subsidy. So, there exists a great potential for the government to adjust prices of the payment according to the aim of participation rate.

7. Conclusions

Though the N fertilizer contributes a lot for the rice yield in Shanghai, it is closely associated with environmental and climatic problems. Reducing the use of the N fertilizer should be considered in the GHG mitigation. As there does not exist any kind of trading market for the GHG mitigation from Chinese agriculture in the short-term, the government-driven program will play a great role in realizing the goal of the mitigation. To reduce the excessive GHG emission, the government could pay rice growers for the additional GHG mitigation caused by their effort in reducing the N fertilizer.

From the perspective of the payer, this paper designs the program, discusses on three key issues in it, and gains three notable findings. First, if shadow prices follows the downward trend since 2011, the financial burden held by rice growers will relieve. Under this circumstance, prices of the payment should decline correspondingly, which favors the implementation of the designed program. Second, the production of the rice growers has the property of decreasing returns to scale, and the influence of the N fertilizer exerted on the yield is significant. It explains why the efficiency of the N fertilizer deteriorated since 2011, and implies the reduction of N fertilizer will lead to the fall of the yield. Third, two relationships means the government should set the feasible aim of reducing N fertilizer basing on the food security and the fiscal transfer from the government to rice growers. Moreover, this paper puts forward the four suggestion below.

First, the payment alleviating the climatic and environmental problem should become one part of the existing subsidy to the agriculture. Obviously, the agricultural development relying on the high input of chemicals dooms unsustainable. Also, the climatic and environmental problem brought by the excessive use of N fertilizer will worsen the habitat for humanity. Under this circumstance, the payment alleviating the climatic and environmental problem will not only change growers' behavior, but also favor achieving the goal of the "green, low-carbon, sustainable" agricultural development pursued by the government.

Second, technologies guaranteeing the yield of rice should be recommended to growers. The reduction of the N fertilizer probably sacrifices the yield of the rice, and the food security is always related to the social stability. Thus, the government should recommend suitable technologies to make up the loss of the rice yield caused by the reduction of the N. Correspondingly, the payment should cover the additional cost caused by technologies.

Third, the government should monitor rice growers' behavior in reducing the N fertilizer. To avoid the moral risk in the mitigation program, the government could apply technologies, such as the soil testing to the monitor. Moreover, rice growers violating the responsibility required by the program must be punished.

Fourth, the market power should also play a role in realizing the goal of the mitigation from agriculture in the future. The government undertakes the main responsibility of the payment at the first stage of the mitigation program. Meanwhile, it is essential to speed up building the local market for the mitigation from agriculture. In the long run, the government should establish and maintain the market order, while the market reallocates resources and promotes the GHG mitigation from agriculture. Shanghai may be a suitable pilot area for the program of the agricultural mitigation.

Finally, the analysis of this paper has some limitation. First, when predicting the participation rate, rice growers is supposed to change the use of N fertilizer only. However, rice growers will probably change other inputs even in the short term. Second, the payment is limited to the 10% reduction of the initial amount. It means the part exceeding the 10% reduction will not obtain the corresponding payment. Third, to predict the participation rate of the sample, the aim of a 10% reduction in the N fertilizer is planned to achieve in an 'egalitarian' way. In reality, some rice growers are willing to reduce more than 10% of their initial amount at lower prices of the payment. In other words, 10% reduction of the N fertilizer will probably achieved with less payment. Fourth, this paper discusses on the participation rate of the rice growers and the variation of factors linked with the social welfare from the aspect of the government. Will rice growers' willingness be consistent with the prediction?

Will rice growers need other technologies to make up the loss of yield caused by the reduction of N fertilizer? Answers to these questions will be explored in further studies.

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Appendix A

Judging from [42,44–46], we list the calculation formulas of CH₄ and N₂O emission below.

1. The CH₄ emission from the rice land

The CH₄ emission = $\sum (EF \times t \times A / 10^6)$, where EF are emission factors of the CH₄ emission from the farmland devoted to the rice per day, t is the growing period of the rice, and A is the farmland devoted to rice.

In detail, EF = 1.8 kg/(hectareday); growing periods of early season rices, middle season and late rices, double cropping late rice are about 115, 122, and 110 days accordingly.

2. The direct N₂O emission from the soil

The direct N₂O emission from the soil = the amount of nitrogen in chemical fertilizer × the emission factor of the direct N₂O emission from the soil × $\frac{44}{28}$

(1) The amount of nitrogen in chemical fertilizer is mainly gained from the N fertilizer;

(2) The Emission factors of the direct N₂O emission (kg N₂O-N/kg N) from the soil is 0.0109.

3. The indirect N₂O emission from the soil

(1) The indirect N₂O emission from the soil through the atmospheric deposition of volatile nitrogen = the amount of nitrogen in chemical fertilizer × Frac_{GASF} × EF × $\frac{44}{28}$

where:
Frac_{GASF} is the volatilization ratio of the nitrogen in chemical fertilizer in the form of NH₃ and NO_x, which is set 0.1;

EF is the emission factor for the edaphic and atmospheric deposition of N₂O, which is set 0.01 kg N₂O-N/kg N.

(2) The indirect N₂O emission from the soil through the leaching and runoff = the amount of nitrogen in chemical fertilizer × Frac_{lr} × EF × $\frac{44}{28}$

where:

Frac_{lr} is the loss rate of leaching and runoff, which is set 0.3; and

EF is the emission factor for the N₂O emission through the leaching and runoff, which is set 0.0075 kg N₂O-N/kg N.

References

1. Foucherot, C.; Bellassen, V. Carbon Offset Projects in the Agricultural Sector. Ph.D. Thesis, CDC Climate Research, Strasbourg, France, 2011.
2. González-Ramírez, J.; Kling, C.L.; Valcu, A. An overview of carbon offsets from agriculture. *Annu. Rev. Resour. Econ.* **2012**, *4*, 145–160. [[CrossRef](#)]
3. Norse, D. Low carbon agriculture: Objectives and policy pathways. *Environ. Dev.* **2012**, *1*, 25–39. [[CrossRef](#)]
4. Zheng, S.X.; Nie, J.; Dai, P.A.; Zheng, Y.J. Nitrogen recovery and nitrate leaching of controlled release nitrogen fertilizer in irrigated paddy soil. *Agric. Sci. Technol.* **2004**, *5*, 2–10.

5. Zhuang, G.Q.; Guo, H.Y.; Yang, L.; Yuan, Y.C.; Zhao, Y.; Tong, J. Impact of silicon, zinc, boron combined with reduced nitrogen fertilization on rice growth. *Agric. Sci. Technol.* **2016**, *17*, 1618–1620.
6. Xiong, H.; Zhang, L.; Zhu, Y.C.; Guo, X.Y.; Jiang, P.; Liu, M.; Zhou, X.B.; Xu, F.X. Yields and nitrogen use efficiencies of rice (*Oryza sativa*) at different sites using different nitrogen fertilizer application rates and controlled-release urea to conventional urea ratios. *Agric. Biotechnol.* **2018**, *7*, 149–157.
7. Flethcer, R.; Büscher, B. The PES Conceit: Revisiting the Relationship between Payments for Environmental Services and Neoliberal Conservation. *Ecol. Econ.* **2017**, *132*, 224–231.
8. Kuhfuss, L.; Preget, R.; Thoyer, S.; Hanley, N. Nudging farmers to enrol land into agri-environmental schemes: The role of a collective bonus. *Eur. Rev. Agric. Econ.* **2016**, *43*, 609–636. [[CrossRef](#)]
9. Wunder, S. The efficiency of payments for environmental services in tropical conservation. *Conserv. Biol.* **2007**, *21*, 48–58. [[CrossRef](#)]
10. Engel, S.; Pagiola, S.; Wunder, S. Designing payments for environmental services in theory and practice: An overview of the issues. *Ecol. Econ.* **2008**, *65*, 663–674. [[CrossRef](#)]
11. Gómez-Baggethun, E.; De Groot, R.; Lomas, P.L.; Montes, C. The history of ecosystem services in economic theory and practice: From early notions to markets and payment schemes. *Ecol. Econ.* **2010**, *69*, 1209–1218. [[CrossRef](#)]
12. Muradian, R.; Corbera, E.; Pascual, U.; Kosoy, N.; May, P.H. Reconciling theory and practice: An alternative conceptual framework for understanding payments for environmental services. *Ecol. Econ.* **2010**, *69*, 1202–1208. [[CrossRef](#)]
13. Schomers, S.; Matzdorf, B. Payments for ecosystem services: A review and comparison of developing and industrialized countries. *Ecosyst. Serv.* **2013**, *6*, 16–30. [[CrossRef](#)]
14. Gerowitt, B.; Isselstein, J.; Marggraf, R. Rewards for ecological goods—Requirements and perspectives for agricultural land use. *Agric. Ecosyst. Environ.* **2003**, *98*, 541–547. [[CrossRef](#)]
15. Pagiola, S. Payments for environmental services in Costa Rica. *Ecol. Econ.* **2008**, *65*, 712–724. [[CrossRef](#)]
16. Alexander, P.; Paustian, K.; Smith, P.; Moran, D. The economics of soil C sequestration and agricultural emissions abatement. *Soil* **2015**, *1*, 331. [[CrossRef](#)]
17. Milder, J.; Scherr, S.; Bracer, C. Trends and future potential of payment for ecosystem services to alleviate rural poverty in developing countries. *Ecol. Soc.* **2010**, *15*, 4. [[CrossRef](#)]
18. Vatn, A. An institutional analysis of payments for environmental services. *Ecol. Econ.* **2010**, *69*, 1245–1252. [[CrossRef](#)]
19. Van Hecken, G.; Bastiaensen, J. Payments for ecosystem services: Justified or not? A political view. *Environ. Sci. Policy* **2010**, *13*, 785–792. [[CrossRef](#)]
20. Wunder, S.; Engel, S.; Pagiola, S. Taking stock: A comparative analysis of payments for environmental services programs in developed and developing countries. *Ecol. Econ.* **2008**, *65*, 834–852. [[CrossRef](#)]
21. Farley, J.; Costanza, R. Payments for ecosystem services: From local to global. *Ecol. Econ.* **2010**, *69*, 2060–2068. [[CrossRef](#)]
22. Hecken, G.V.; Merlet, P.; Lindtner, M.; Bastiaensen, J. Can Financial Incentives Change Farmers' Motivations? An Agrarian System Approach to Development Pathways at the Nicaraguan Agricultural Frontier. *Ecol. Econ.* **2019**, *156*, 519–529. [[CrossRef](#)]
23. Ding, X.; Zhou, C.; Mauerhofer, V.; Zhong, W.; Li, G. From Environmental Soundness to Sustainable Development: Improving Applicability of Payment for Ecosystem Services Scheme for Diverting Regional Sustainability Transition in Developing Countries. *Sustainability* **2019**, *11*, 361. [[CrossRef](#)]
24. Krishna, V.V.; Drucker, A.G.; Pascual, U.; Raghu, P.T.; King, E.I.O. Estimating compensation payments for on-farm conservation of agricultural biodiversity in developing countries. *Ecol. Econ.* **2013**, *87*, 110–123. [[CrossRef](#)]
25. Corbera, E. Valuing nature, paying for ecosystem services and realizing social justice: A response to Matulis 2014. *Ecol. Econ.* **2014**, *1*, 154–157. [[CrossRef](#)]
26. Duke, J.M.; Dundas, S.J.; Johnston, R.J.; Messer, K.D. Prioritizing payment for environmental services: Using nonmarket benefits and costs for optimal selection. *Ecol. Econ.* **2014**, *105*, 319–329. [[CrossRef](#)]
27. Crossman, N.D.; Bryan, B.A.; Summers, D.M. Carbon Payments and Low-Cost Conservation. *Conserv. Biol.* **2011**, *25*, 835–845. [[CrossRef](#)] [[PubMed](#)]
28. Corbera, E. Problematising REDD+ as an experiment in payments for ecosystem services. *Curr. Opin. Environ. Sustain.* **2012**, *4*, 612–619. [[CrossRef](#)]

29. Antle, J.; Capalbo, S.; Mooney, S.; Elliott, E.; Paustian, K. Spatial heterogeneity, contract design, and the efficiency of carbon sequestration policies for agriculture. *J. Environ. Econ. Manag.* **2003**, *46*, 231–250. [\[CrossRef\]](#)
30. Bell, A.; Parkhurst, G.; Droppelmann, K.; Benton, T.G. Scaling up pro-environmental agricultural practice using agglomeration payments: Proof of concept from an agent-based model. *Ecol. Econ.* **2016**, *126*, 32–41. [\[CrossRef\]](#)
31. Bryan, B.A.; Nolan, M.; Harwood, T.D.; Connor, J.D.; Navarro-Garcia, J.; King, D.; Harman, I. Supply of carbon sequestration and biodiversity services from Australia's agricultural land under global change. *Environ. Chang.* **2014**, *28*, 166–181. [\[CrossRef\]](#)
32. Pittman, R.W. Multilateral productivity comparisons with undesirable outputs. *Econ. J.* **1983**, *93*, 883–891. [\[CrossRef\]](#)
33. Färe, R.; Grosskopf, S.; Lovell, C.K.; Yaisawarng, S. Derivation of shadow prices for undesirable outputs: A distance function approach. *Rev. Econ. Stat.* **1993**, *75*, 374–380. [\[CrossRef\]](#)
34. Guan, X.; Zhang, J.; Wu, X.; Cheng, L. The Shadow Prices of Carbon Emissions in China's Planting Industry. *Sustainability* **2018**, *10*, 753. [\[CrossRef\]](#)
35. Färe, R.; Grosskopf, S.; Noh, D.W.; Weber, W. Characteristics of a polluting technology: Theory and practice. *J. Econ.* **2005**, *126*, 469–492. [\[CrossRef\]](#)
36. Färe, R.; Grosskopf, S.; Weber, W.L. Shadow prices and pollution costs in US agriculture. *Ecol. Econ.* **2006**, *56*, 89–103. [\[CrossRef\]](#)
37. Murty, M.N.; Kumar, S.; Dhavala, K.K. Measuring environmental efficiency of industry: A case study of thermal power generation in India. *Environ. Resour. Econ.* **2007**, *38*, 31–50. [\[CrossRef\]](#)
38. Boussemart, J.; Leleu, H.; Shen, Z. Worldwide carbon shadow prices during 1990–2011. *Energy Policy* **2017**, *109*, 288–296. [\[CrossRef\]](#)
39. Wei, C.; Löschel, A.; Liu, B. An empirical analysis of the CO₂ shadow price in Chinese thermal power enterprises. *Energy Econ.* **2013**, *40*, 22–31. [\[CrossRef\]](#)
40. Lee, S.C.; Oh, D.H.; Lee, J.D. A new approach to measuring shadow price: Reconciling engineering and economic perspectives. *Energy Econ.* **2014**, *46*, 66–77. [\[CrossRef\]](#)
41. Zhou, P.; Zhou, X.; Fan, L.W. On estimating shadow prices of undesirable outputs with efficiency models: A literature review. *Appl. Energy* **2014**, *130*, 799–806. [\[CrossRef\]](#)
42. IPCC. 2006 IPCC Guidance for National Greenhouse Gas Inventories; IEA/OECD: Paris CEDEX, France, 2006.
43. Aigner, D.J.; Chu, S.F. On estimating the industry production function. *Am. Econ. Rev.* **1968**, *58*, 826–839.
44. National Development and Reform Commission. *The People's Republic of China National Greenhouse Gas Inventory*, 1st ed.; China Environmental Press: Beijing, China, 2014; pp. 177–275.
45. Mi, S.H. *Study on China's Low-Carbon Modern Agriculture Development-From Views of Carbon Footprint Calculation and Applicable Mitigation Technology Application*, 1st ed.; China Agriculture Press: Beijing, China, 2013; pp. 200–204.
46. Qi, Y.B.; Wang, G. *Low-Carbon Agriculture Development: Mechanism, Dilemma, Pattern and System Design*, 1st ed.; China Agriculture Press: Beijing, China, 2013; pp. 40–42.
47. Lee, M.; Zhang, N. Technical efficiency, shadow price of carbon dioxide emissions, and substitutability for energy in the Chinese manufacturing industries. *Energy Econ.* **2012**, *34*, 1492–1497. [\[CrossRef\]](#)
48. Wu, Q.; Li, H. Estimating Regional Shadow Prices of CO₂ in China: A Directional Environmental Production Frontier Approach. *Sustainability* **2019**, *11*, 429. [\[CrossRef\]](#)
49. Du, L.; Hanley, A.; Wei, C. Estimating the marginal abatement cost curve of CO₂ emissions in China: Provincial Panel Data Analysis. *Energy Econ.* **2015**, *48*, 217–229. [\[CrossRef\]](#)
50. Takeshima, H. Custom-hired tractor services and returns to scale in smallholder agriculture: A production function approach. *Agric. Econ.* **2017**, *48*, 363–372. [\[CrossRef\]](#)