Abatement Costs of Emissions from Burning Maize Straw in Major Maize Regions of China: Balancing Food Security with the Environment

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Abstract

This paper estimates the shadow price of CO_2 from burning maize straw in the Chinese agricultural sector and explores the policy implications for decision makers. Using a parametric quadratic directional distance function, we evaluate the production inefficiency and shadow prices of CO_2 reduction for 7 major maize provinces in China from 1996-2014. The efficiency improves over time. In 2014, Shandong province ranks the top with full efficiency considering both economic and environmental impacts. The average efficiency will increase by 9% if conservation practices are adopted by assuming 10% decrease in yield and 50% decrease in burnt crop residue under conservation practices compared to conventional practices. The shadow price of CO_2 from burning crop residue is estimated to range from 0-0.913 yuan/ha (or US$152/t) with an average of 0.45yuan/kg (or US$75/t). The downward slope of marginal abatement cost implies a rational of abating CO_2 from the most polluted area. The abatement costs analysis imply that the whole society will benefit if the transaction cost of promoting adoption of conservation practices is less than 385 yuan/ha. This government offset would compensate farmers for yield reductions in favor of implementing conservation practices that would substantially reduce CO_2 emissions.

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Introduction

Agriculture is a major contributor to global emissions of the greenhouse gases (GHGs) that drive climate change. World agriculture accounted for an estimated direct emission of 5.1-6.1 Pg CO_2-equivalents per year, contributing 10-12% to the total global anthropogenic emissions of GHGs in 2005 (Smith et al., 2007). This number will increase to about 40% if indirect sources of emissions, such as producing fertilization, pesticides and machines, are considered. This makes the agricultural sector the world's second-largest emitter, after the energy sector (which includes emissions from power generation and transport). China, predominantly by rural and agriculture, is one of the largest producers of agricultural emissions in the world. GHGs from Chinese agriculture reached approximately 712 Tg CO_2e in 2014, accounting for 14% of the world (FAO, 2015).

Burning crop residues to clear the field for next season is a major source of CO_2 emissions in agricultural sector in China. Sun et al. (2016) estimates that in 2013 alone about 193 Tg of CO_2 was emitted by farmers' burning crop residues in farm fields in China, account for about 30% of the total CO_2 emissions from Chinese agriculture. About 2700 Tg of CO_2 have been emitted from burning agricultural residues in China from 1996-2013, which was about 45% of the total residential coal consumption over the same period. In Northeast China, more than 80% of crop residues are burned in field each year, of which over 2/3 is from maize straw. Burning crop residues not only harms human respiratory system, but also often results in low visibility that delays air flights and impedes ground transportation.

Conservation tillage offers a great opportunity for reducing burning crop residues. Conservation tillage is a range of cultivation techniques (including minimum till, strip till and no-till) designed to minimize soil disturbance for seed placement, by allowing crop residue to remain on soil after planting. Conservation tillage also has co-benefits, such as protecting soil from wind and water erosion. As indicated by the literature, there exists a risk for reduction of crop yield under conservation practices, especially in the short run (Zheng et al, 2014). Farmers lack of incentives to adopt conservation tillage due to the externality of GHGs emissions and possible crop yield reduction.

Several provinces in China, with the support from the Ministry of Finance (MOF) and the Ministry of Agriculture (MOA) recently piloted on Compensation for Soil Conservation Program (CSCP). The government wonders how much investment is appropriate to promote such programs. However, national and international markets do not exist for GHGs in most cases. Furthermore, measuring GHGs emissions from individual farms can be elusive, making cost-benefit analysis challenging. Crop production is an important component of food security, and simulation can be a useful tool for providing the government with information about potential impacts of management changes on crop yields. This paper provides the government with a reference to make an informed decision about CSCP.

It is promised that by 2030 China will reduce 60-65% of CO_2 intensity (tons per dollar of GDP) compared to 2005. Although scholars predict that China's agricultural sector has the potential to reduce GHGs by 20%, how to allocate abatement missions among sectors are still a critical question to policy makers. Theoretically, the optimal abatement scheme is to maximize the total GDP given the constraint of abatement mission. This will result to an abatement level where marginal cost of each sector is equal. Therefore, it is important to estimate the abatement cost for each sector from this perspective.

In the literature, many studies exist on estimating abatement cost of undesirable outputs, such as CO_2, with the concept of shadow prices. However, there is little literature to estimate the shadow prices of agricultural emissions in China. Zhou et al. (2014) conducted a systematic review of the studies on estimating shadow prices of undesirable outputs with efficiency models. These studies were primarily focused on energy generation. The shadow price of undesirable output can be interpreted as the opportunity cost of abating one additional unit of undesirable output in terms of the loss of one unit of desirable output. A prevalent practice is to use the Shephard or directional distance function to derive the shadow price, which can be further calculated by parametric or nonparametric efficiency models. In application, the earlier studies have estimated shadow prices of GHGs at the plant, sector and even regional economic levels. Wei et al. (2013) estimates the shadow price of CO_2 and explores its determinants for thermal power enterprises in China. The mean value of the CO_2 shadow price is $249 in 2004 using linear programming approach. They also found that the shadow price is a negative function of firm size, age, and coal share, and is positively correlated with the technology level. Du et al. (2015) investigated the technical inefficiency, shadow price and substitution elasticity of CO_2 emissions of China based on a provincial panel data from 2001-2010. They show that China's technical inefficiency increases over the period implying further scope for CO_2 emissions reduction in the medium and longer term at best by 4.5% and 4.9% respectively. The shadow price of CO_2 abatement increases from 1000 yuan/t in 2001 to 2100 yuan/t in 2010.

The paper is the first to estimate the CO_2 shadow price associated with the practice of burning crop residue in China. The directional distance function in quadratic form is used to quantify the efficiency and CO_2 shadow price for 7 major maize production provinces from 1996-2014. Furthermore, the paper simulates the efficiency and abatement cost of CO_2 under a scenario of adopting soil conservation practices. By comparing the two cases, i.e. baseline technology and conservation technology, we provide how much the government should invest to promote soil conservation practices.

From a policy perspective, the results of our research are expected to be of great interest and use to decision makers as a decision support tool, since they provide the first CO2 shadow price estimates in the framework of burning crop residues. This paper also contributes to the literature about abatement costs of agricultural emissions. Being able to assess the marginal abatement costs is an important first step in environmental policy issues, since these costs can be used when fixing carbon tax rates and ascertaining an initial market price for a trading system(Fare et al, 1993; Wei et al., 2013).

Estimating abatement costs with a distance function model

Directional distance function is another way of depicting production process in addition to production function. The advantage of directional distance function over traditional production function is that it can deal with multiple outputs properly, including undesirable outputs. Following Hou et al. (2015), four steps are presented to estimate the shadow prices. First, a production possibility set is defined. The technologies that produce desirable and undesirable outputs jointly are presented by a production possibility set as follows:

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

where $\mathrm{x} = (\mathrm{x}_1, \dots, \mathrm{x}_\mathrm{N}) \in \Re_+^\mathrm{N}$ is a vector of N inputs, $\mathrm{y} = (\mathrm{y}_1, \dots, \mathrm{y}_\mathrm{M}) \in \Re_+^\mathrm{M}$ is a vector of M desirable outputs and $\mathrm{b} = \left(\mathrm{b}_1, \dots, \mathrm{b}_\mathrm{J}\right) \in \Re_+^\mathrm{J}$ is a vector of J undesirable outputs. The PPS satisfies several assumptions, including standard convex and compaction, free disposability of good outputs, weak disposability of desirable and undesirable outputs, and null-jointness (Färe et al., 2005). The second step is to define a directional distance function linking to the PPS. Given the production possibility set $\mathrm{P(x)}$, a directional output distance function for the *i*th observation $(\mathrm{x}_i, \mathrm{y}_i, \mathrm{b}_i)$ is defined as the simultaneous maximum reduction in undesirable outputs and expansion in desirable outputs along a direction $\mathrm{g} = (\mathrm{g_y}, \mathrm{g_b})$. Its mathematical form is:

$$\mathrm{D_i}\left(\mathrm{x_i}, \mathrm{y_i}, \mathrm{b_i}; \mathrm{g_y}, \mathrm{g_b}\right) = \max\left\{\varphi_\mathrm{i} > 0: \left(\mathrm{y_i} + \varphi_\mathrm{i}\mathrm{g_y}, \mathrm{b_i} + \varphi_\mathrm{i}\mathrm{g_b}\right) \in \mathrm{P(x_i)}\right\}, \qquad (2)$$

where $\mathrm{D_i}$ is the distance function value for the *i^th^* observation $(\mathrm{x_i}, \mathrm{y_i}, \mathrm{b_i})$ given the directional vector $(\mathrm{g_y}, \mathrm{g_b})$, and φ_i is the simultaneous change of desirable and undesirable outputs satisfying $\left(\mathrm{y_i} + \varphi_\mathrm{i}\mathrm{g_y}, \mathrm{b_i} + \varphi_\mathrm{i}\mathrm{g_b}\right) \in \mathrm{P(x_i)}$. Corresponding to the assumptions of the production possibility set, the distance function satisfies some properties (Färe et al., 2005).

The third step is to define shadow price. The shadow prices of undesirable outputs are derived from the first order condition for maximizing net revenue subject to a production technology; maximizing revenue is equivalent to maximizing profit when subject to a fixed and shared input level. The revenue function, which considers the negative effect generated by the undesirable outputs is defined as:

$$\mathrm{R_i}\left(\mathbf{x_i}, \mathbf{p_y}, \mathbf{p_b}\right) = \max_{\mathbf{y,b}}\{\mathbf{p_y}\mathbf{y_i} + \mathbf{p_b}\mathbf{b_i}: (\mathbf{y}, \mathbf{b}) \in \mathrm{P}(\mathbf{x})\}. \qquad (3)$$

or

$$\mathrm{R_i}\left(\mathbf{x_i}, \mathbf{p_y}, \mathbf{p_b}\right) = \max_{\mathbf{y,b}}\{\mathbf{p_y}\mathbf{y_i} + \mathbf{p_b}\mathbf{b_i}: \mathbf{D_i}\left(\mathbf{x_i}, \mathbf{y_i}, \mathbf{b_i}; \mathbf{g_y}, \mathbf{g_b}\right) \geq 0\}. \qquad (4)$$

Where $\mathrm{R_i}\left(\mathbf{x_i}, \mathbf{p_y}, \mathbf{p_b}\right)$ represents the revenue for the *i*th observation, $\mathbf{p_y} = (\mathrm{p_{y1}}, \dots \mathrm{p_{yM}}) \in \Re_+^\mathrm{M}$ represents desirable output prices $\mathbf{p_b} = (\mathrm{p_{b1}}, \dots, \mathrm{p_{bJ}}) \in \Re_-^\mathrm{J}$ for undesirable output prices. Applying the envelope theorem to the maximization problem in Eq.(4) yields:

$$\nabla_b D_i(\mathbf{x_i}, \mathbf{y_i}, \mathbf{b_i}; \mathbf{g}) = \frac{-p_b}{p_y g_y + p_b g_b} \geq 0 \quad (5)$$

and

$$\nabla_y D_i(\mathbf{x_i}, \mathbf{y_i}, \mathbf{b_i}; \mathbf{g}) = \frac{-p_y}{p_b g_y + p_b g_b} \leq 0. \quad (6)$$

Thus, given the *m*th desirable output price, say p_{ym}, the shadow price of the *j*th undesirable output can be recovered by taking the ratio of Eq.(5) and Eq. (6):

$$\frac{p_{bj}}{p_{ym}} = \frac{\partial D_i(\mathbf{x_i}, \mathbf{y_i}, \mathbf{b_i}; \mathbf{g})/\partial b_j}{\partial D_i(\mathbf{x_i}, \mathbf{y_i}, \mathbf{b_i}; \mathbf{g})/\partial y_m} \quad (7)$$

or

$$p_{bj} = p_{ym}\left(\frac{\partial D_i(\mathbf{x_i}, \mathbf{y_i}, \mathbf{b_i}; \mathbf{g})/\partial b_j}{\partial D_i(\mathbf{x_i}, \mathbf{y_i}, \mathbf{b_i}; \mathbf{g})/\partial y_m}\right). \quad (8)$$

Eq. (8) implies that revenue is maximized where marginal rate of transformation between an undesirable output and a desirable output equals the price ratio of the two. Shadow price cannot be observed directly, but can be derived as shown in Eq. (8) by multiplying Eq.(7) by p_{ym}. The negative shadow prices of undesirable outputs are interpreted as marginal opportunity costs in terms of foregone desirable outputs (Färe et al., 2005).

The last step is parameterizing the distance function, since the derivatives of the distance function are utilized in Eq.(8). A quadratic function is used to represent the distance function, since Färe et al. (2010) suggest that quadratic models outperform translog parameterizations when modelling the production technology. A linear programming technique is employed to calibrate the unknown parameters in the distance function. Many literatures set the directional vector g = (1,-1) (Färe et al., 2006; Wei et al., 2013), which implies simultaneous expansion in desirable outputs and undesirable outputs. We propose to set the directional vector based on empirical data. We use the ratio of the means of the desirable output and undesirable input to set the directional vector (1,-1.06). A detailed description of estimation technique is shown in Appendix A.

Data

We consider the case of one desirable output, maize yield, one undesirable output, CO_2 emissions from burning maize straw, and a single input, total cost, including both labor and materials costs. Materials costs includes costs for machinery depreciation or rental, fuels, seeds, fertilization and organic manure, irrigation, pesticides, etc. Our data is provincial level yearly panel data that covers seven major maize provinces in China, including Anhui, Hebei, Henan and Shandong in North China Plain and Heilongjiang, Jilin and Liaoning in Northeast China from 1996 to 2014. The seven provinces produce over 60% of maize in China in 2014.

Maize yield in measured in kg/ha. Total cost is measured in yuan/ha. Maize yield and total cost are from the Compiled Materials of Costs and Profits of Agricultural Products of China (1996-2014), published by the State Development and Planning Commission. To eliminate the influence of inflation, we deflate grain price and total costs to the 2010 price. Consumer price index of rural residents from China Statistical Yearbook is used. CO_2 emission is measured in kg/ha and estimated using the following formula:

$$CO_2=Y*R*B*CF*EF,$$

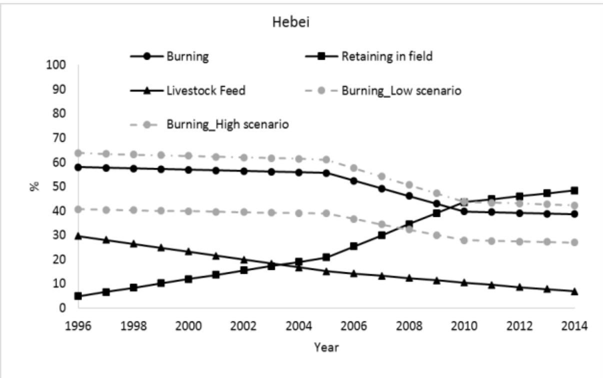
where Y for maize yield in kg/ha, R for residue to crop ratio, B for percentage of burnt crop residue, CF for combustion factor, and EF for emission factor in kg/kg, as described in Table 1.

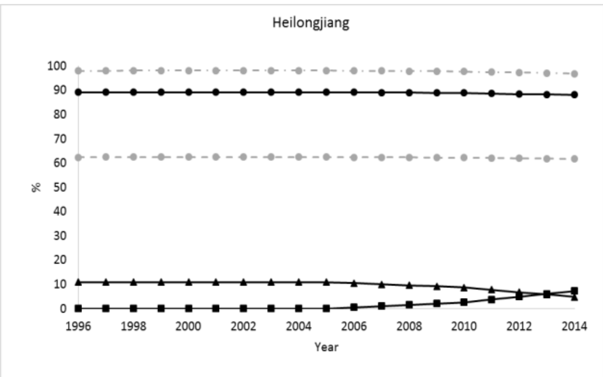
Table 1 Description of key variables in the estimation of CO_2 emission

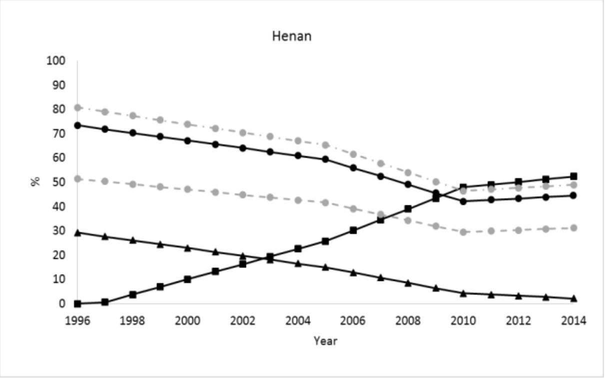
Variable	Description	Data range	Source
Y	Maize yield (kg/ha)	3982-8211	The Compiled Materials of Costs and Profits of Agricultural Products of China, 1996-2014, published by the State Development and Planning Commission
R	Residue to crop ratio	1.25	Median from the following literature: Yukihiko et al. (2005); Liu et al. (2008); Kim and Dale (2004); Zeng et al. (2007); Lal (2005); Shen et al. (2010); Cui et al. (2008); Song (2010); Jia (2006); Bi (2010); Ministry of Science and Technology (1999); Renewable Energy Project (2008)
B	Percentage of burnt crop residue (%)	38-89	Surveys on village leaders by the authors
CF	Combustion factor, which is the fraction of the mass combusted during the course of a fire	0.92	Streets et al. (2003); Turn (2007)
EF	Emission factor (kg/kg), which is the amount of CO2 in g emitted by burning 1 kg maize straw	1.35	Streets et al. (2003); Turn (2007)

The percentage of burnt maize straw is key to estimating the CO_2 emissions. We surveyed 10 village leaders randomly in each province to estimate the utilization of maize straw in percentage in their villages in 2015, 5 years ago (2010), 10 years ago (2005) and 15 years ago (2000). Then we expand the survey data to other years from 1996 to 2014 by assuming a constant change rate between every 5 years. To do a sensitivity analysis, we also consider two other scenarios as plotted in Figure 2 in gray: low scenario, which is 70% of the surveyed burnt percentage, and high scenario, which is 110% of the surveyed burnt percentage.

The utilization of maize straw differs largely across provinces (Figure 2). Three major utilization types include burning, livestock feed and biomass residue kept in field. Livestock production has been specialized and separated from grain production over the past decades. Therefore, it is not surprising to see that a decreasing percentage of maize straw used as livestock feed in all provinces. Nearly 1/3 of maize straw were used to feed animals in the seven provinces in 1996, while it decreased to only 5% in 2014. As soil conservation technology, including retaining crop residue in field, has been promoted by the government, more and more crop residue has been retained in field to keep nutrients in the soil. Moreover, the practice of returning crop residue to the field is less common in Northeast China than North China Plain. One possible reason is that crop residue is difficult to decay due to the cold weather in Northeast China. In North China Plain, the percentage of retaining maize straw in field increased from less than 1% in 1996 to around 37 % in 2014. Northeast China started to adopt conservation practices only from 2006. The growth rate is also very low. Only less than 5% of maize straw is retained to field in Northeast China in 2014. The percentages of burnt maize straw differ across provinces. It shows a significant decrease in Hebei and Henan provinces, especially after 2005. It increased in Anhui before 2005 but decrease slightly after 2005. In Shandong, it increases by about 5% over 1996-2014. In Heilongjiang and Jilin, it shows a very slight decrease while Liaoning increases a lot.



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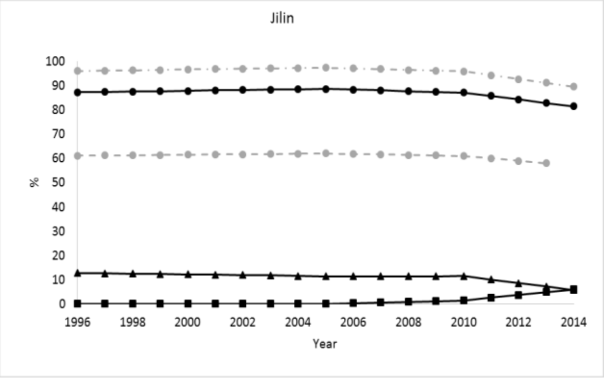
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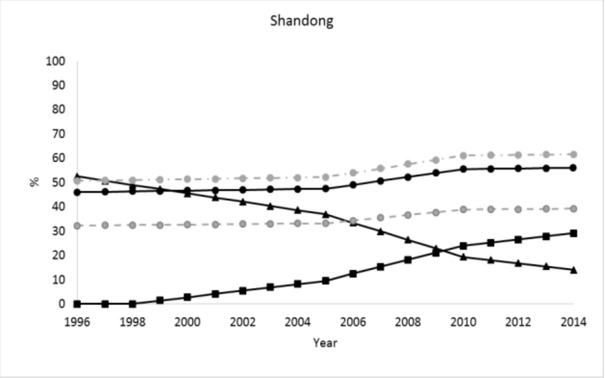
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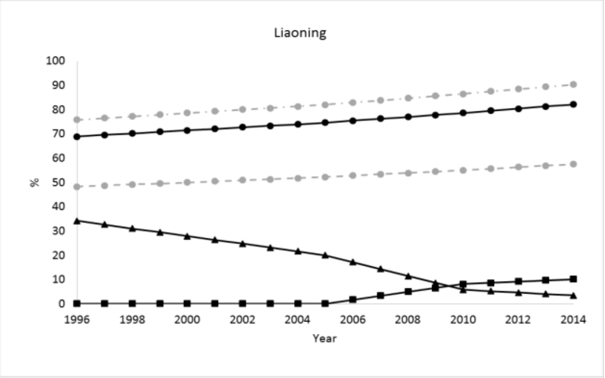
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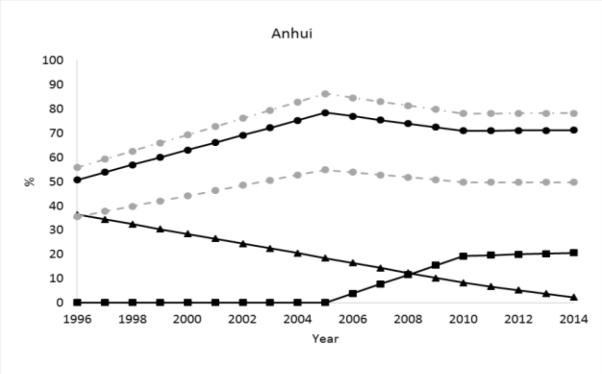


Figure 2 Utilization of maize straw by province, 1996-2014 (%)

The descriptive statistics of the key variables are presented in Table2.

Table 2 Descriptive statistics of the variables used in the distance function

Variable	Mean	Std. Dev.	Minimum	Maximum
Total cost (yuan/ha)	5,757	1,940	3,249	11,045
Maize yield (kg/ha)	6,232	995	3,982	8,211
CO_2 from burning maize straw (kg/ha)	6,605	2,035	3,241	11,128

Results

The parameter estimates for the quadratic form of the distance functions are provided in Appendix Table 1. As stated in Section 3, to do the sensitivity analysis for the percentage of burning maize straw, we assumed two other scenarios, i.e. low scenario and high scenario. Under each scenario, we run two models, i.e. baseline technology and conservation technology models. According to the literature, in the conservation technology model, we assume that farmers adopt conservation practices (i.e. no tillage and retaining maize straw in field), which lead to a decrease of 10% in maize yield and a decrease of 50% in the percentage of burning maize straw, compared to the baseline technology model.

Inefficiency is measured by $D(\boldsymbol{x}, \mathbf{y}, \mathbf{b}; \mathrm{g}_y, \mathrm{g}_b)$, which means a producer will reach the full efficiency if the desirable output can be increased by $\mathrm{D} \cdot \mathrm{g}_y$ and the undeniable output can be decreased by $\mathrm{D} \cdot \mathrm{g}_b$, given the amount of inputs. For the sample under the survey data scenario, the directional distance function has a mean of 0.12 and ranges from a low of 0 to a high of 0.35 for Jilin in 1997. The maximum of the distance function implies that Jilin in 1997 has the least efficiency among the whole sample, and will be on the efficiency frontier if its desirable output increases by 2181kg/ha (0.35*6232), and its undesirable output decreases by 2450kg/ha (0.35*1.106*6605). Not surprisingly, there is a downward trend in inefficiency from 1996 to 2014 under all three scenarios (Figure 3). This implies that the economic efficiency and/or the environmental efficiency improves over time. In 2014, Shandong province ranks the top with full efficiency considering both economic and environmental efficiency, followed by Jilin and Hebei (Table 3).

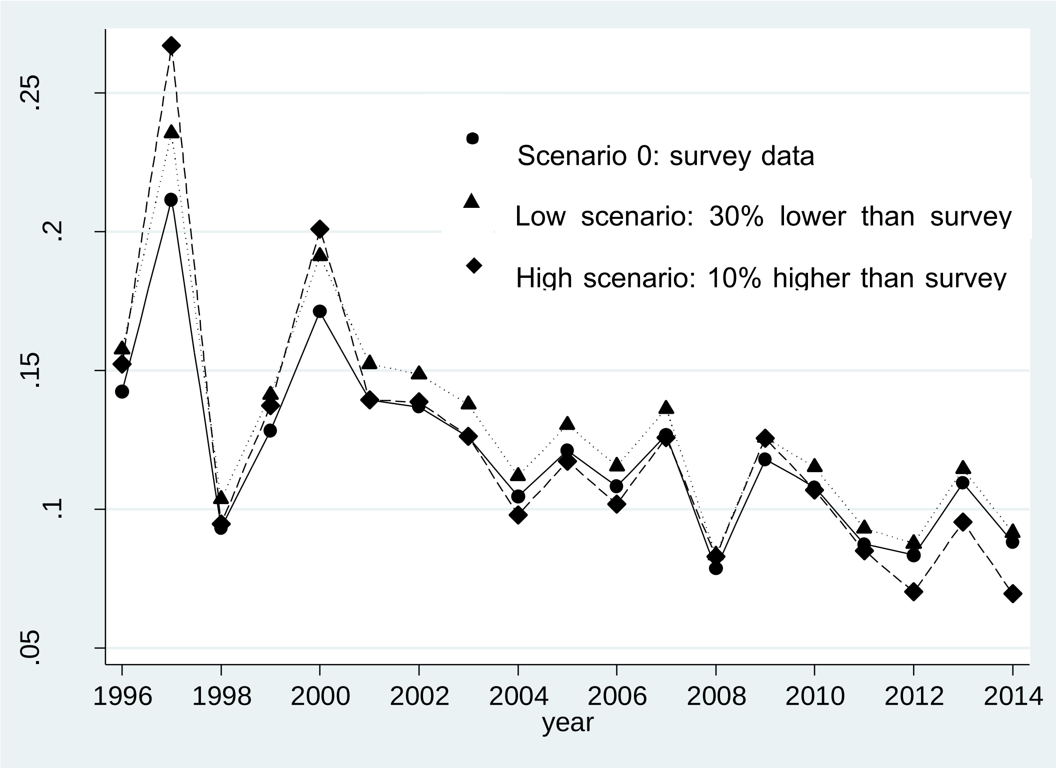


Figure 3 Average of directional distance function in all seven provinces from 1996 to 2014

Table 3 Inefficiency scores by province under different scenarios in 2014

Province	Survey data scenario	30% Lower than survey data	10% Higher than survey data
North China Plain			
Hebei	0.072	0.073	0.057
Henan	0.101	0.104	0.096
Shandong	0.000	0.000	0.000
Anhui	0.118	0.124	0.058
Northeast China			
Heilongjiang	0.085	0.091	0.072
Jilin	0.070	0.072	0.053
Liaoning	0.170	0.176	0.151

The shadow prices of CO_2 in Northeast China is lower than that in North China Plain (Table 4). The shadow price of CO_2 in Northeast China is 0.328 yuan/kg, while it is 0.541 yuan/kg in North China Plain. It implies that policy makers had better to start the abatement of CO_2 emissions from Northeast China until the shadow prices of CO_2 is equal or larger than that in North China Plain.

Table 4 Summary of descriptive statistics of shadow price for CO_2 by province under the survey data scenario, 1996-2014 (yuan/kg)

	Mean	Std. Dev.	Min	Max
All seven provinces	0.450	0.174	0.000	0.913
Northeast China	0.328	0.134	0.000	0.598
Heilongjiang	0.383	0.090	0.214	0.542
Jilin	0.229	0.123	0.000	0.467
Liaoning	0.371	0.131	0.104	0.598
North China Plain	0.541	0.141	0.128	0.913
Anhui	0.562	0.181	0.221	0.913
Hebei	0.553	0.097	0.357	0.689
Henan	0.567	0.117	0.324	0.790
Shandong	0.485	0.152	0.128	0.733

Low scenario: 30% lower than survey cost has a downward sloping (Figure 4). It implies that as the emissions of CO_2 increases, the marginal abatement cost is less expensive. It shows the rational that abatement activities should start from the most polluted areas.

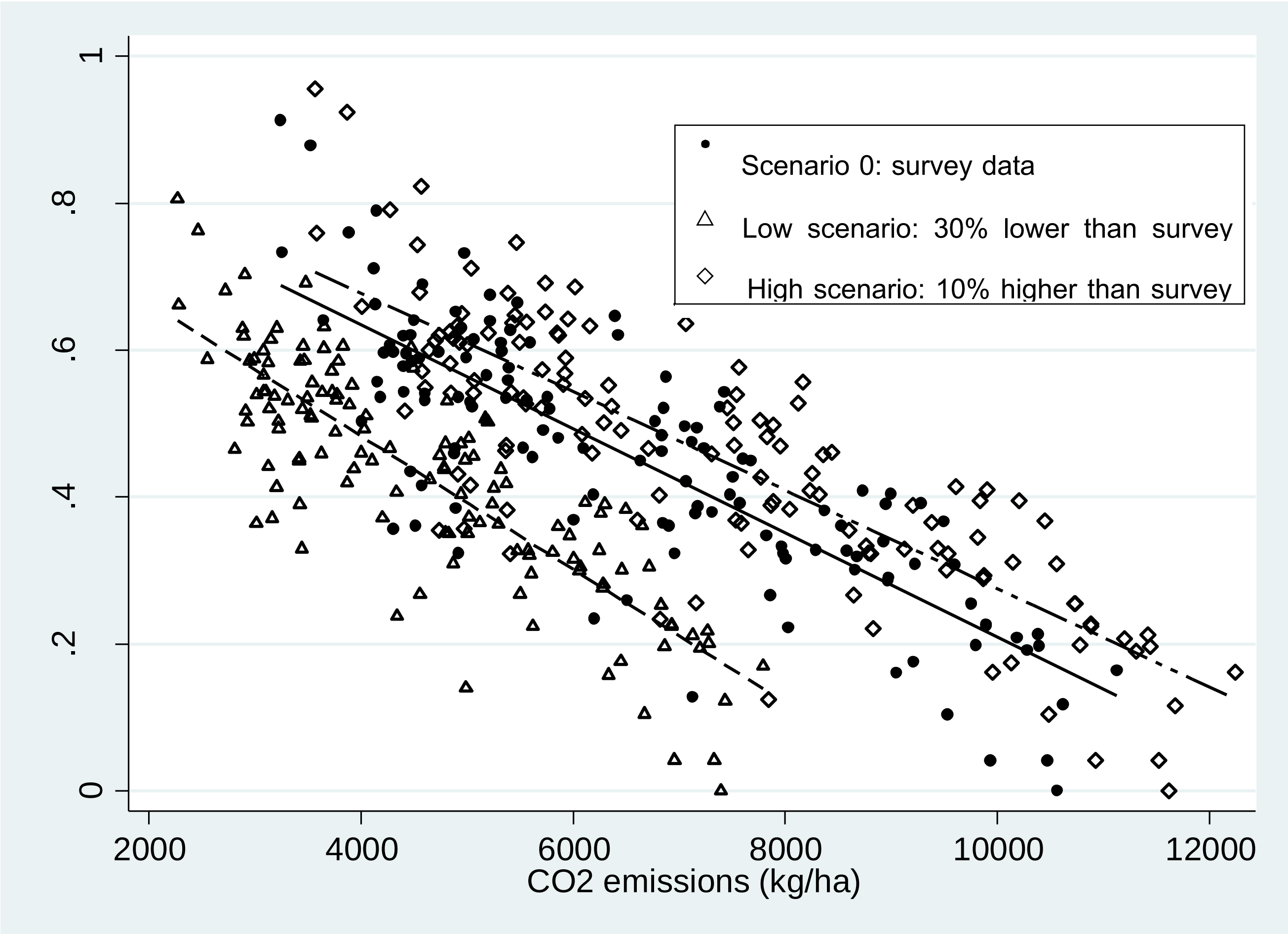
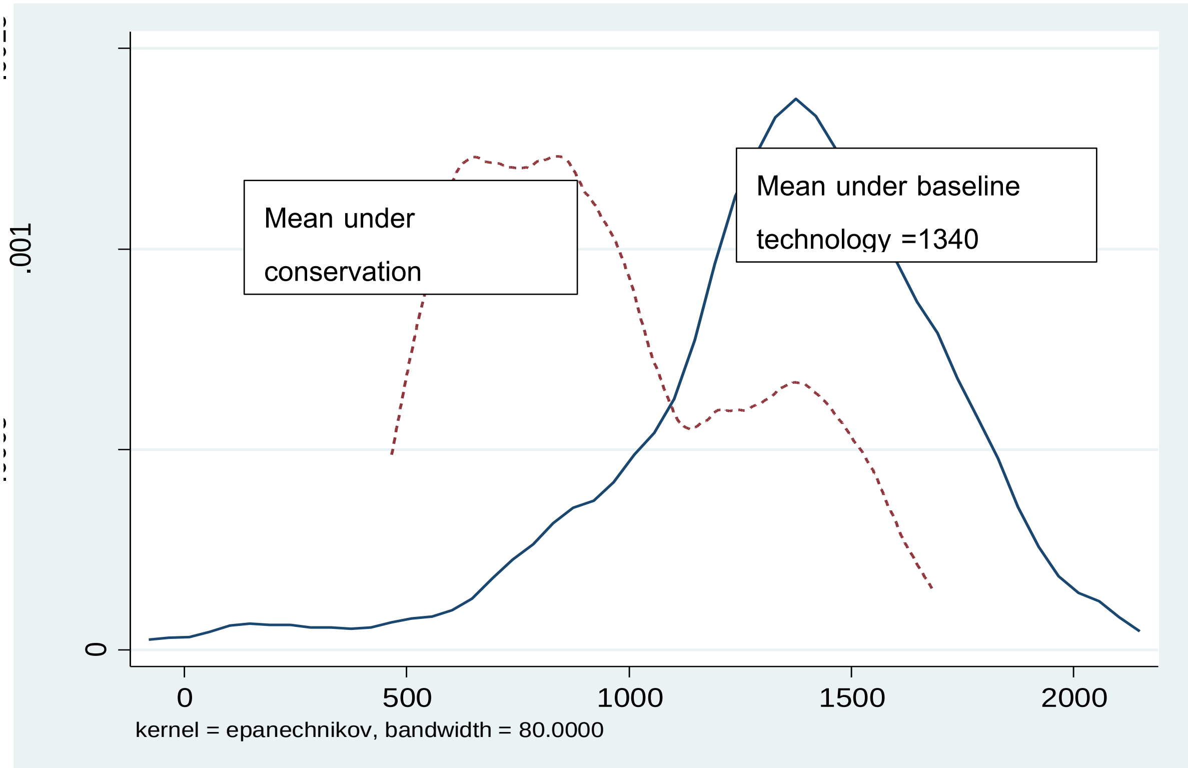


Figure 4 Marginal abatement cost under different scenarios

More importantly, comparing the total abatements costs between baseline scenarios and conservation scenarios can provide a guideline for policy makers to decide on whether to promote conservation practices and how much to invest. Under baseline technology, the total abatement cost of reducing 50% of CO_2 emissions is equal to the shadow price multiplied by the abatement amount. Using conservation technology, the abatement cost is equal to the loss of crop yield due to adoption of conservation technology. If the abatement cost under baseline scenario is lower than that under conservation scenario given a level of abatement, then reducing desirable output as abatement tool is favorable than promoting conservation technology, and vise verse. As stated in Section 3, we assume that conservation technology can lead to 50% abatement of CO_2 and 10% reduction in crop yield. It implies that the abatement cost of 50% of CO_2 is equal to the value of 10% of crop yield. In our case, the mean of the abatement cost is 1340 yuan/ha under baseline technology, while it is 955yuan/ha under conservation technology. The difference (385 yuan/ha) provides a reference as maximum transaction cost for policy makers to promote adoption of conservation practices. The whole society will benefit if the transaction cost is less than 385 yuan/ha.

Figure 5 Kernel density estimate of abatement cost under baseline technology vs. conservation technology



In addition, the efficiency for all provinces from 1996-2014 can increase by 39.5% if conservation practices are adopted (Figure 6). The mean of the inefficiency scores for all provinces from 1996-2014 decreases from 0.190 under baseline technology to 0.115 under conservation technology.

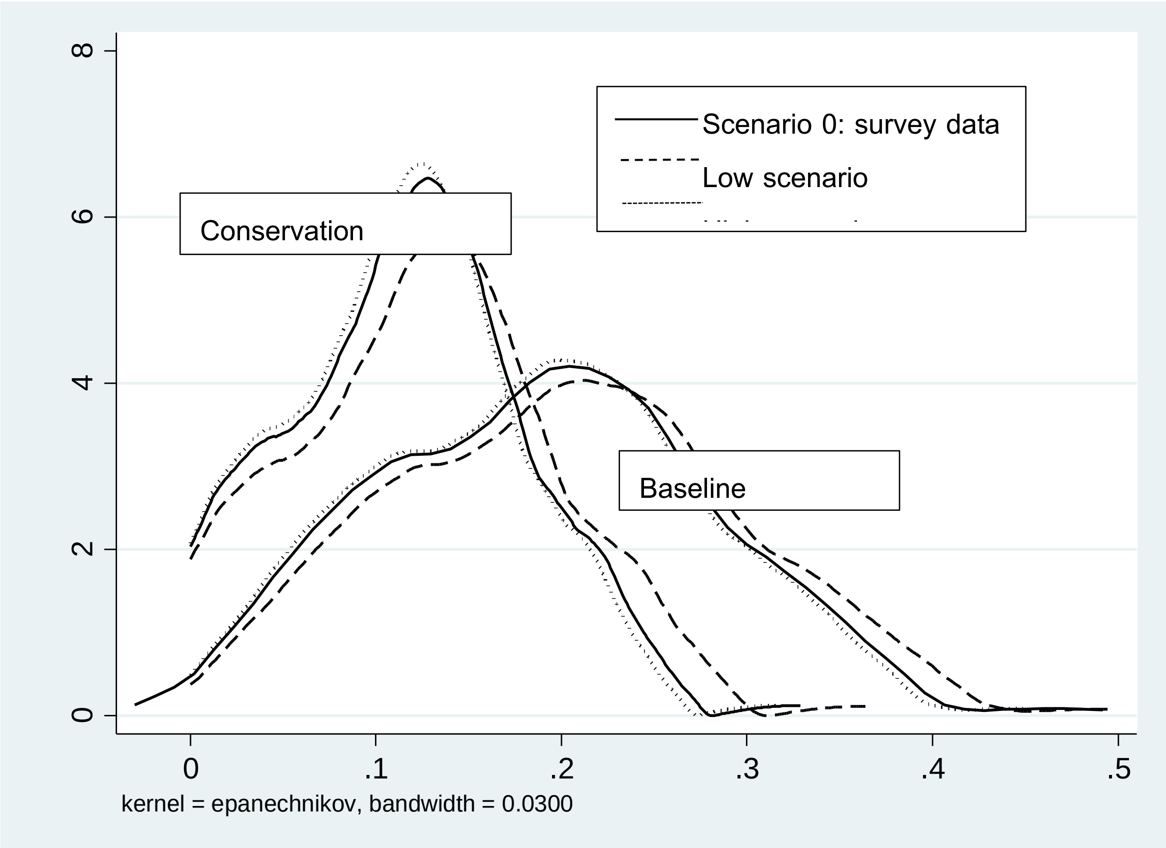


Figure 6 Kernel density estimate of inefficiency scores under baseline technology vs. conservation technology

Discussion and conclusions

In this paper, we estimated the shadow prices and abatement costs of CO_2 emissions from burning maize straw, using the data from 7 major maize provinces in China from 1996-2014. The estimated shadow price of CO_2 from burning maize straw ranges from 0-0.913 yuan/ha (or US$152/t) with an average of 0.450yuan/kg (or US$75/t). There is a wide range of shadow prices of CO_2 depending on the study period, sector, sample and model (Table 5). Our estimation results fall in the range in the literature.

Table 5. Comparison with previous studies[1]

Study	Period	Sector	Sample	Model[2]	Mean value ($/t)[3]
Wang et al. (2011)	2007	Economy	30 Provinces in China	DEA	62.5
Wei et al. (2012)	1995-2007	Economy	30 Provinces in China	DEA	13.9
Du et al. (2015)	2001-2010	Economy	30 Provinces in China	DDF+LP	120-310
Wei et al. (2013)	2004	Energy	124 Power plants in China	DDF+LP, DDF+ML	248.2, 73.8
Tang et al. (2016)	1998-2005	Agriculture	29 farms in Australia	DF+LP	29.3
Thamo et al. (2013)	Simulation data	Agriculture	Farms in Western Australia	MIDAS[4]	50
Flugge and Abadi (2006)	Simulation data	Agriculture	Two regions in Western Australia	MIDAS	55
This study	1996-2013	Agriculture	7 provinces in China	DDF+LP	75[5]

[1]Adapted from Du et al.(2005)

[2]SDF, DDF, LP, ML, DEA denote Shephard Distance Function, Directional Distance Function, Linear Pro-ta Envelopment Analysis, respectively

[3]All the shadow prices are transformed into US dollars according to the corresponding exchange rate for the convenience of comparison

[4] A steady-state optimization farm model

[5] US$ 1 = 6 yuan

More importantly, our results provide a reference value for policy makers to decide the spending on conservation practices program. Given the policy goal of 50% reduction of CO_2 from burning maize straw, the abatement cost will be 1340 yuan/ha by reducing maize production, while it will be 955 yuan/ha by adopting conservation practices. If the transaction cost of promoting conservation practices is less than 385yuan/ha, the welfare of the whole society will be improved. Furthermore, the efficiency will be increased by almost 40% if conservation practices are adopted.

There are several practical policy implications arising from this study. One area that merits additional exploration is the trade-off between reduced yields and practices that substantially decrease CO2 emissions. Decreasing CO2 emissions provides marginal social benefits that may conflict with societal food security goals and individual farmer production. Clearly, the results from this model show that there are not incentives for farmers to implement production practices that decrease yield and presumably, profits. Thus, it would be paramount for the government's willingness to compensate farmers to implement conservation practices that will reduce CO2 emissions. However, the implications of reduced agricultural yields may be juxtaposed with other dietary and nutritional goals that otherwise enhance food security. Furthermore, there may be differences between the regions that warrant additional consideration, and as a result, the regions might not be managed uniformly. In summary, this preliminary analysis provides guidance about environmental and agricultural targets that require more extensive research, and that may have implications at many tiers, extending from the level of the farm to the international scale.

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Appendix

Appendix Table 1. Estimated Coefficients in the Quadratic Distance Function

Coefficient	Variable	True Scenario		Low Scenario		High Scenario	
		Baseline	Simulation	Baseline	Simulation	Baseline	Simulation
α_0	Intercept	-0.021	0.158	0.086	0.232	-0.056	0.134
α_1	x	0.468	0.359	0.490	0.398	0.461	0.349
β_1	y	-0.373	-0.518	-0.555	-0.659	-0.315	-0.473
γ_1	z	0.592	0.576	0.601	0.582	0.588	0.573
α_{11}	$\frac{1}{2}x^2$	-0.019	-0.135	-0.052	-0.169	-0.009	-0.124
β_{11}	$\frac{1}{2}y^2$	-0.123	-0.110	-0.067	-0.062	-0.144	-0.127
γ_{11}	$\frac{1}{2}z^2$	-0.110	-0.157	-0.122	-0.181	-0.106	-0.150
δ	xy	-0.145	-0.026	-0.110	-0.015	-0.156	-0.030
η	xz	-0.137	-0.031	-0.149	-0.025	-0.134	-0.032
μ	yz	-0.116	-0.131	-0.091	-0.106	-0.123	-0.138