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Ji-Qin Ni

Weiqing Bao

Lei Zhao

Guang Hui Xie

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Yang Yang [1,2], Ji-Qin Ni [2], Weiqing Bao [1], Lei Zhao [3] and Guang Hui Xie [1,*]

[1] College of Agronomy and Biotechnology, China Agricultural University, Beijing 100193, China; yangyangjunior2012@163.com (Y.Y.); baowq@cau.edu.cn (W.B.)
[2] Department of Agricultural and Biological Engineering, Purdue University, West Lafayette, IN 47907, USA; jiqin@purdue.edu
[3] Symbior Biocrude Limited, Hong Kong 999077, China; yangsj@cau.edu.cn
* Correspondence: xiegh@cau.edu.cn; Tel.: +86-10-62734888; Fax: +86-10-62734850

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Abstract: Corn stover is an abundant raw material that can be used to produce ethanol and reduce air pollution. This paper studied the potential reductions in greenhouse gas (GHG) and fine particulate matter ($PM_{2.5}$) emissions across China if corn stover was used for ethanol production. Field surveys in nine provincial regions were conducted. Life-cycle assessment (LCA) was used to assess the GHG and $PM_{2.5}$ emissions from a corn stover based ethanol system. The LCA system boundaries included several process stages from corn planting to ethanol fuel used in vehicles. Corn stover geographical distributions and emission reduction factors were combined. Results showed that the total surplus quantity of corn stover in China was 86.2 million metric tons (Mt) in 2015. It was sufficient to reach the ethanol production target set by the Chinese government. In the scenario that 38.5 Mt or 44.6% of corn stover surplus were used for ethanol production, the total potential emission reductions were 36.5 Mt CO_2-eq GHG and 450.9 kt $PM_{2.5}$. Among the 31 provincial regions in China, the reduction potentials varied from 0.001 to 8.9 Mt CO_2-eq for GHG and from 0.013 to 109.7 kt for $PM_{2.5}$. This study provided useful information to policy makers, researchers and industry managers who work on environmental control and corn stover management.

Keywords: environmental pollutant; crop residues; life-cycle assessment; emission reductions

1. Introduction

Emissions of greenhouse gas (GHG) are believed to link to climate change and emissions of fine particulate matter ($PM_{2.5}$, particulate matter ≤ 2.5 μm in diameter) are confirmed to relate to smog. Climate change has drawn great concerns around the world [1], including China [2]. The notorious haze issue caused by air pollution also gained much attention in recent years. Pursuing co-benefits in bioenergy production is an effective approach to simultaneously respond to air pollution problems, including GHG emissions [3].

Corn is a staple food in many parts of the world. Its production increased from 8.5 Mt (million metric tons) in 2010/2011 to 11.3 Mt in 2018/2019. The United States, China, and Brazil are the three major corn producing countries in 2018/2019 [4]. Corn stover is a desirable raw material for producing cellulosic ethanol [5–7]. Corn stover for ethanol production can provide co-benefits because it can improve energy security and reduce air pollution [8–13]. Corn stover for fuel production has a great potential in China because corn made up 39.2% of all cereals in 2017 [14]. The amount of corn stover accounted for 28.0% in 2010 [15] and 24.2% in 2013 of all crop residues in China [16]. A previous study reported that the available agricultural residue as feedstock for bioenergy production could amount to 55.2 Mt, among which 41.1% could be utilized for bioethanol production by 2025 in China [17].

China has been the largest GHG contributor in the world since 2005 and emitted about 29% of the worldwide GHG in 2015 [18]. The $PM_{2.5}$ concentrations in 310 out of 362 cities in China exceeded critical levels of 35 $\mu g\ m^{-3}$ in the first quarter of 2016 [19]. Moreover, the gasoline and diesel consumptions from 2003 to 2014 increased by 58% and 51% in China, respectively [20]. The fuel consumption in transportation was identified as a major source of CO_2 and $PM_{2.5}$ [21–23]. Additionally, the in-field burning of crop residue significantly increased GHG and $PM_{2.5}$ emissions, accounting for 107 Mt of CO_2 emissions annually from 1999 to 2008 [24] and contributing 12% of the annual mean $PM_{2.5}$ emissions in Beijing, China [25].

Previous studies [13,26–28] mainly focused on life-cycle GHG emissions mitigation of corn stover based ethanol production by comparing it with gasoline production. For instance, developing commercial-scale corn stover based ethanol plants could displace fossil fuels and reduce GHG emissions [26]. Spatari et al. [27] showed that the GHG emissions were 65% lower in 2010 for a light-duty vehicle fueled by E85 (i.e., a blended fuel comprising 15% gasoline and 85% ethanol derived from corn stover) compared with petroleum fuel. Ethanol from corn stover could reduce life-cycle GHG emissions by 90–103% relative to gasoline in the United States [28]. Recently, Zhao, et al. [13] reported that the use of pure fuel ethanol produced from corn stover in China could lead to a GHG emission reductions of 52–55% relative to gasoline. Because of different system boundaries and functional unit (FU), the results related to life-cycle GHG emission reductions, at least in their numerical forms, cannot always be compared directly with most of the reported cases. Based on some literature reviews [8–10,13,26–28], using corn stover for ethanol production is urgent and necessary considering energy and environment profits. However, there are no studies found in the available literature to assess the potential reductions in GHG and $PM_{2.5}$ emissions from corn stover based ethanol while considering corn stover geographical distributions.

In this study, the available corn stover for ethanol production and its emission reduction factors per unit corn stover were combined to assess the environmental impacts. The results can help understand the potential reductions in GHG and $PM_{2.5}$ emissions across the country. They can also assist policy makers to improve allocation of resources and achieve the best environmental effects. The methodology developed in this study could be used for assessing emission reductions from biomass residues for bioenergy utilization in China and in other countries.

Accordingly, the objectives of this study include: (1) calculating the geographical distribution of surplus quantity of corn stover across China; (2) analyzing the life-cycle GHG and $PM_{2.5}$ emissions for corn stover based ethanol; (3) assessing the total potential reductions in GHG and $PM_{2.5}$ emissions.

2. Materials and Methods

2.1. Corn Stover Surplus Quantity

2.1.1. Data Collection and Assumption

Face-to-face field surveys were conducted from June 2016 to April 2017 in nine provincial regions (Shanxi, Jilin, Anhui, Hunan, Guangxi, Chongqing, Yunnan, Ningxia, and Xinjiang) to determine the corn stover surplus that could be used for ethanol production (SEP). The selection of the nine provincial regions was based on corn production [20], provincial regulations on crop residue management [29], and geographical features of North China, Northeast China, East China, Central China, South China, Southwest China, and Northwest China.

To maximize data validity and unbiased representation, three or four prefecture-level cities in each provincial region, two counties in each city, three towns in each county, and two villages in each town were selected. Three questionnaires per village were used. Five corn stover utilization pathways, comprising retention in field, commercial utilization (e.g., sold for papermaking, electricity generation), home utilization (e.g., for daily cooking and home heating), burning in field, and unplanned utilization (e.g., abandonment), were included in the questionnaires. The percentage of different corn stover utilizations in 2015 in the sampled provincial regions is shown in Table 1.

Table 1. Percentage (%) and number of questionnaires (n) of corn stover field retention (FR), commercial utilization (CU), cooking and heating (CH), burning in field (BF), unplanned utilization (UU), and surplus that could be used for ethanol production (SEP) at different sampled sites in 2015.

Sampled Site	**FR**		**CU**		**CH**		**BF**		**UU**		**SEP** [1]
	%	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**
Shanxi	48.9	28	25.3	14	0.0	0	25.8	23	0.0	0	25.8
Jilin	11.8	32	15.5	41	21.8	71	49.5	73	1.4	8	50.9
Anhui	51.0	44	33.0	10	3.1	5	3.9	3	8.9	18	12.8
Hunan	14.6	4	0.0	0	0.0	0	71.1	10	14.3	2	85.4
Guangxi	7.8	7	8.9	6	17.4	5	62.5	15	3.5	2	66.0
Chongqing	9.0	17	16.7	33	21.8	10	51.8	27	12.1	18	52.5
Yunnan	14.3	15	28.0	26	6.1	26	40.4	56	0.5	2	52.2
Ningxia	54.5	17	36.0	92	0.0	2	0.7	7	0.7	1	9.0
Xinjiang	15.6	22	76.3	12	1.7	0	8.3	2	5.1	14	5.8
Average	25.3	-	26.6	-	8.0	-	34.9	-	5.1	-	40.0

[1] SEP is the sum of BF and UU.

The SEP at the sampled sites equaled the corn stover burning in field plus the corn stover unplanned utilization. The SEP in other provincial regions not field-surveyed was evaluated according to the administrative division, comprehensive agricultural regionalization information, and data for selected sample sites in China (Table 2).

Table 2. Percentage of corn stover surplus for ethanol production (SEP) in non-sampled provincial regions referencing the neighboring provincial regions in 2015.

Provincial Region	**SEP (%)**	**Reference** [1]
Beijing	25.8	Shanxi
Tianjin	25.8	Shanxi
Hebei	25.8	Shanxi
Inner Mongolia	22.9	Jilin, Shanxi, Ningxia, Xinjiang
Liaoning	50.9	Jilin
Heilongjiang	50.9	Jilin
Shanghai	12.8	Anhui
Jiangsu	12.8	Anhui
Zhejiang	49.1	Anhui, Hunan
Fujian	54.7	Anhui, Hunan, Guangxi
Jiangxi	85.4	Hunan
Shandong	19.3	Anhui, Shanxi
Henan	19.3	Anhui, Shanxi
Hubei	69.0	Hunan, Chongqing
Guangdong	75.7	Hunan, Guangxi
Hainan	66.0	Guangxi
Sichuan	52.4	Chongqing, Yunnan
Guizhou	63.4	Hunan, Chongqing, Yunnan
Tibet	52.2	Yunnan
Shaanxi	17.4	Ningxia, Shanxi
Gansu	7.4	Ningxia, Xinjiang
Qinghai	9.0	Ningxia

[1] For the regions with two or more reference provincial regions, SEP is the average of the reference regions.

2.1.2. Calculation of Corn Stover Surplus Quantity

The corn stover was defined to include only cornfield residues. The surplus quantity of corn stover was calculated according to the corn production, factor of cornfield residue on an air-dried basis, and corn stover surplus for ethanol production (Equation (1)):

$$Q_c = C_p \times C_{FRI} \times SEP \tag{1}$$

where Q_C is the quantity of corn stover surplus, ton; C_P denotes the corn production in 2015 [20] with the exception of Hainan Province in 2013 [30], ton; C_{FRI} is the corn stover factor (ratio of corn stover mass to grain yield produced) in 31 provincial regions of China, as described previously [31], dimensionless; and *SEP* is the corn stover surplus that could be used for ethanol production, %.

2.2. Life-Cycle Assessment

2.2.1. Scope of the Life-Cycle Assessment

A LCA was conducted using the system boundary and flow chart shown in Figure 1. Even though corn stover has traditionally been viewed as wastes, the development of corn stover based ethanol production technologies supported by governmental funding may eventually cause corn stover to evolve into a co-product of corn production. Hence, in this study, the LCA of corn stover based ethanol production started with corn planting, and included corn stover collection, corn stover transport, ethanol production, ethanol transport and use in vehicles (Figure 1).

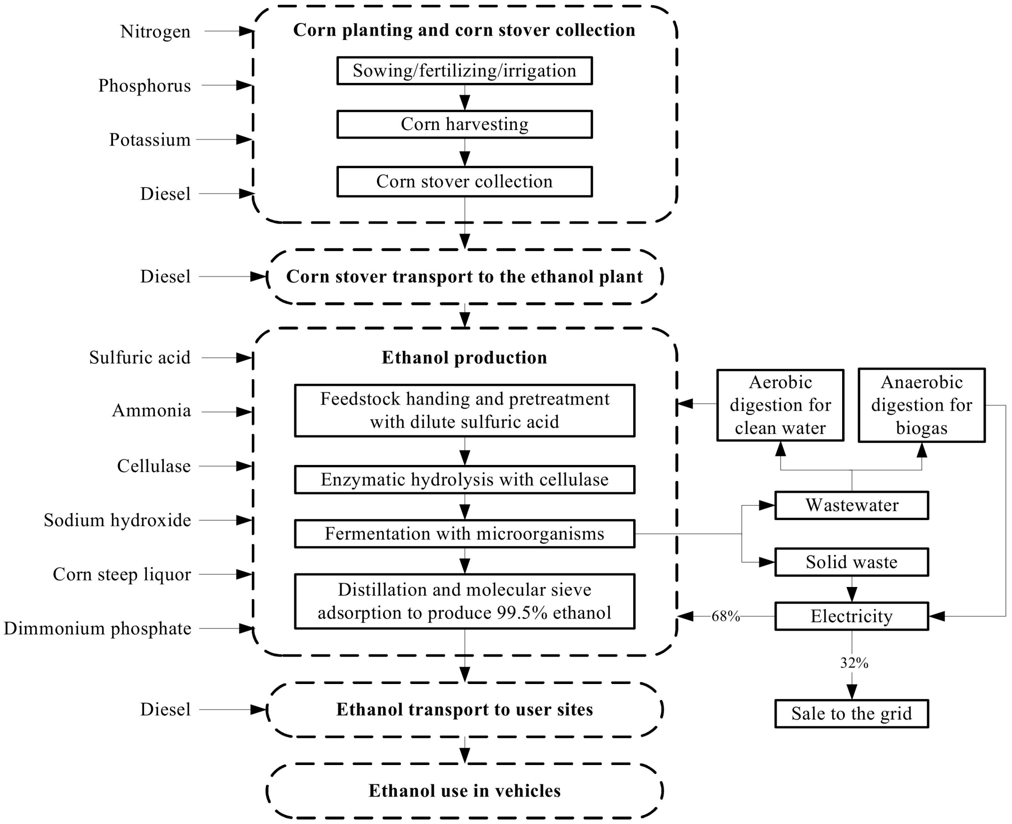

Figure 1. System boundary of the life-cycle assessment of ethanol from corn stover.

As part of the LCA, GHG emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) were weighed according to their global warming potentials of 1, 25, and 298, respectively, following IPCC's 100-year estimates [32]. It was assumed that carbon in the form of CO_2 from vehicular ethanol combustion originated from biogenic carbon that was derived from corn stover because more than 96% of all carbon in the process entered as biomass feed, with only small amounts of additional carbon coming from glucose (for enzyme production) and fermentation nutrients such as corn steep liquor [33]. Thus, CO_2 emissions from ethanol in the vehicle-use stage were negligible in this study. An FU for treatment comparison in the life-cycle inventory was based on per ton of corn stover.

The GREET (Greenhouse Gases, Regulated Emissions and Energy in Transportation) model developed by the Argonne National Laboratory of the U.S. Department of Energy was used in this study because it was a well-developed LCA tool and included numerous fuel and vehicle cycles [34,35]. For a given transportation fuel or vehicle technology combination, the GREET can be used to calculate life-cycle GHG and $PM_{2.5}$ emissions [36].

2.2.2. Data Sources

Corn Planting

In corn planting, the main material input was fertilizer and the average recommended fertilizer application in corn planting was 19.0 kg nitrogen, 9.5 kg phosphorus pentoxide, and 5.3 kg potassium oxide per ton of corn produced. The mass allocation method was used to calculate the partition of fertilizer between corn grain and corn stover [13]. After allocation, the average fertilizer use in corn stover was 9.8 kg nitrogen, 4.9 kg phosphorus pentoxide, and 2.7 kg potassium oxide per ton of dry corn stover. Direct N_2O emissions from nitrogen fertilization was calculated based on Wang et al. [37], who estimated the N_2O-N emissions as 2.0% of nitrogen by weight.

Corn Stover Collection and Transportation

To gather data of corn stover collection and transportation, the largest biomass feedstock supplier in City, China, Symbior Biocrude Ltd., was interviewed. During stover collection in Symbior Biocrude Ltd., a grinder attachment to a corn combine first cut the corn stover into pieces of about 10 cm in length. Next, a tractor-pulled raker and baler chopped the corn stover and bundled it into large round bales. On average, a bale of corn stover weighed 0.3 tons with 20.0% moisture content. Fork loaders picked up the bales and placed them on a 13-m-long truck, which could load 52 corn stover bales and consume 30 L of diesel per 100 km travel distance. Table 3 displays the power, efficiency, and diesel consumption data for the machinery used in collection.

Table 3. Technical parameters of machinery used in corn stover collection based on the field surveys.

Machinery	Power (kW)	Efficiency (ha h^{-1})	Average Diesel Consumption (L ha^{-1})
Combine with grinder	>64	0.5–0.7	10.7
Stover raker	>40	0.7–0.9	5.7
Baler	>74	1.2–1.3	9.3
Fork loader	44	1.0–1.3	5

Based on an evaluation of optimized feedstock quality and profits, the company estimated that the maximum transportation distance could be approximately 150 km to 200 km. Therefore, a value of 150 km for transportation distance by heavy-duty truck (13,000 kg payload; 0.3 L per ton-km) was used in this study.

Ethanol Production

The data reported by NREL (National Renewable Energy Laboratory of the U.S.) to analyze ethanol production technology [33] were used, as the second generation ethanol technology has not seen widespread use recently in China. The technology studied by NREL employed dilute acid pretreatment followed by enzymatic hydrolysis and co-fermentation to convert corn stover to ethanol (Figure 1). First, hydrolysis with dilute sulfuric acid converted most of the feedstock hemicellulose carbohydrates to soluble sugars. Next, the hydrolysate slurry was cooled, and ammonia was added to raise the pH. Then, while the slurry was still at an elevated temperature, enzymatic hydrolysis was initiated. Once the conversion was complete, the slurry was cooled to the fermentation temperature and inoculated with fermentative microorganisms. The fermentation broth was then separated into water, ethanol, and solids. Finally, distillation and molecular sieve adsorption were used to produce 99.5% ethanol. Water was recycled after treatment, and solids were sent to an incinerator to generate heat and electricity. Approximately 68.0% of the electricity generated from the system was used in the plant and the remaining 32% was sold to the grid, providing a co-product credit [33]. A displacement method was used to allocate output between ethanol and the electricity co-product. The key technology input and output data for the ethanol production process are shown in Table 4.

Table 4. Key technological data per ton of corn stover for ethanol production.

Inventory Item	Unit	Value
Input		
Corn stover [1]	ton	1.0
Sulfuric acid	kg	22.1
Ammonia	kg	14.0
Sodium hydroxide	kg	27.2
Cellulase	mg g^{-1} cellulose	20.0
Cellulose in corn stover	%	31.9
Cellulase	kg	6.4
Corn steep liquor [2]	kg	15.5
Diammonium phosphate [3]	kg	1.9
Output		
Ethanol	gal	87.8
Electricity	kWh	1.8

[1] Dry corn stover; [2,3] These materials were used for microorganism production. All the data are from [33].

Ethanol Transport to User Sites and Use in Vehicles

The transportation distance of ethanol to its site of use was estimated to be 150 km using a heavy-duty truck (13,000 kg payload; 0.3 L per ton-km). In this study, a fuel-cell car as used in the GREET model for E100 consumption was selected. According to the GREET, the fuel economy of E100 in a fuel-cell car was 1570.4 J m^{-1} (7.4 L per 100 km, and 22.2 kg corn stover for 7.4 L).

2.3. Potential Reductions in GHG and $PM_{2.5}$ Emissions

The total potential reductions in GHG and $PM_{2.5}$ emissions from corn stover for ethanol production in China were calculated following Equations (2) and (3), respectively:

$$Q_{GER} = Q_C \times RF_{CO_2} \tag{2}$$

$$Q_{PER} = Q_C \times RF_{PM_{2.5}} \tag{3}$$

where Q_{GER} is the total potential reductions in GHG emissions, ton; Q_{PER} is the total potential reductions in $PM_{2.5}$ emissions, ton; Q_C is the surplus quantity of corn stover available for ethanol production, ton; RF_{CO_2} is the reduction factor of GHG emissions, kg CO_2-eq per ton corn stover; $RF_{PM2.5}$ is the reduction factor of $PM_{2.5}$ emissions, kg $PM_{2.5}$-eq per ton corn stover.

The reduction factor of GHG (RF_{CO_2}) and $PM_{2.5}$ emissions ($RF_{PM2.5}$) were calculated by using emissions from a reference case minus emissions from the corn stover-based ethanol production in LCA. The reference case was used as a baseline to assess the GHG and $PM_{2.5}$ emission reductions of the ethanol pathway. Corn stover burning in field and vehicles powered by gasoline were assumed in the reference case. As for emissions from corn stover burning in field, the values of 3.5 g of CH_4, 0.1 g of N_2O, and 11.7 g of $PM_{2.5}$ emissions from 1.0 kg of corn stover field-burning in China were adopted [38,39].

In accordance with life-cycle emissions from corn stover for ethanol production, the CO_2, N_2O, CH_4, and $PM_{2.5}$ emissions from diesel consumption during collection, as well as the N_2O emissions from nitrogen fertilizers were also considered in the pathway of corn stover burning in field. The emissions from gasoline-powered vehicles were calculated based on the blended gasoline stock from crude oil for use in U.S. refineries because the data on emissions from gasoline production in China are not available.

3. Results

3.1. Corn Stover Surplus and Its Spatial Distribution Density

In 2015, the total quantity of corn stover surplus was estimated to be 86.2 Mt in China. Among the 31 provincial regions, those from Northeast to Southwest had higher total surplus quantities than Southeast and Northwest. The three provinces in Northeast region had the highest surplus quantities, which counted for 51.0% (43.9 Mt) of the total corn stover surplus in China. This was because of the highest total corn production (34.5%) and proportion of corn stover surplus for ethanol production (50.9%, Table 1) in Northeast. The Northwest region ranked the lowest, with approximately 2.2 Mt.

Corn stover densities in the Northeast provinces of Jilin, Liaoning and Heilongjiang were relatively high, ranging between 44.4 and 81.6 ton km^{-2}. They were the lowest in the Western provincial regions of Xinjiang, Qinghai and Tibet, less than 0.3 ton km^{-2} (Figure 2). However, the ranking of the total surplus quantities was not necessarily consistent with the ranking of the densities among the 31 provincial regions. For instance, the surplus corn stover in Inner Mongolia ranked the fourth (6.7 Mt), though its density was only 5.5 ton km^{-2}, ranking 17th among the 31 provincial regions.

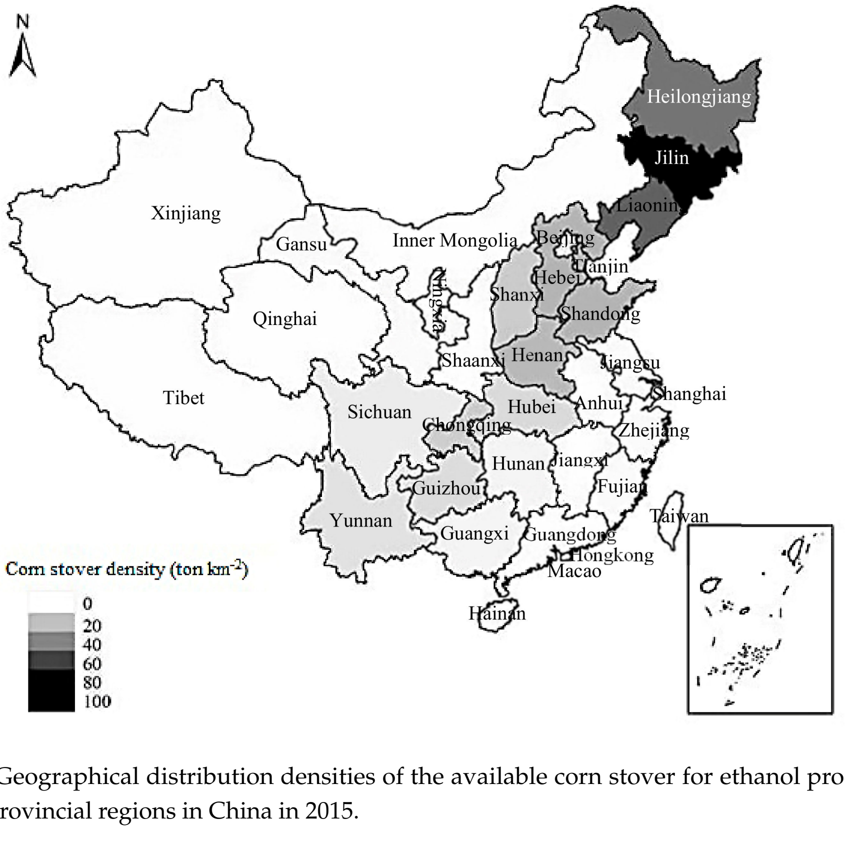

Figure 2. Geographical distribution densities of the available corn stover for ethanol production in different provincial regions in China in 2015.

3.2. Life-Cycle GHG and $PM_{2.5}$ Emissions for Corn Stover Based Ethanol

The net emissions for corn stover based ethanol were 245.5 kg CO_2-eq GHG and 25.7 g $PM_{2.5}$ per ton of corn stover (Figure 3). The GHG emissions from the ethanol production stage were the highest and reached 160.3 kg CO_2-eq (65.3%) because of the use of chemicals and nutrients. The $PM_{2.5}$ emissions from the stages of corn planting and corn stover collection were the highest and reached 16.5 g (64.2%) because of the fertilizer use in corn planting and diesel consumption in vehicles. Fertilizer production emits large quantities of air pollutants. Emission credits from co-product could offset part of the air pollution. The emission credits were 82.2 kg CO_2-eq GHG and 4.8 g $PM_{2.5}$ for the corn stover based ethanol production (Figure 3).

The emission reduction factors were 950.1 kg CO_2-eq GHG and 11,722.7 g $PM_{2.5}$ per ton of corn stover (Table 5). The GHG emission reductions were mainly due to high emissions from gasoline. The corn stover burning in field emitted the highest $PM_{2.5}$, reaching 11.7 kg per ton of corn stover. The results indicated that the potential reductions in GHG and $PM_{2.5}$ emissions were significant if corn stover were used for ethanol production.

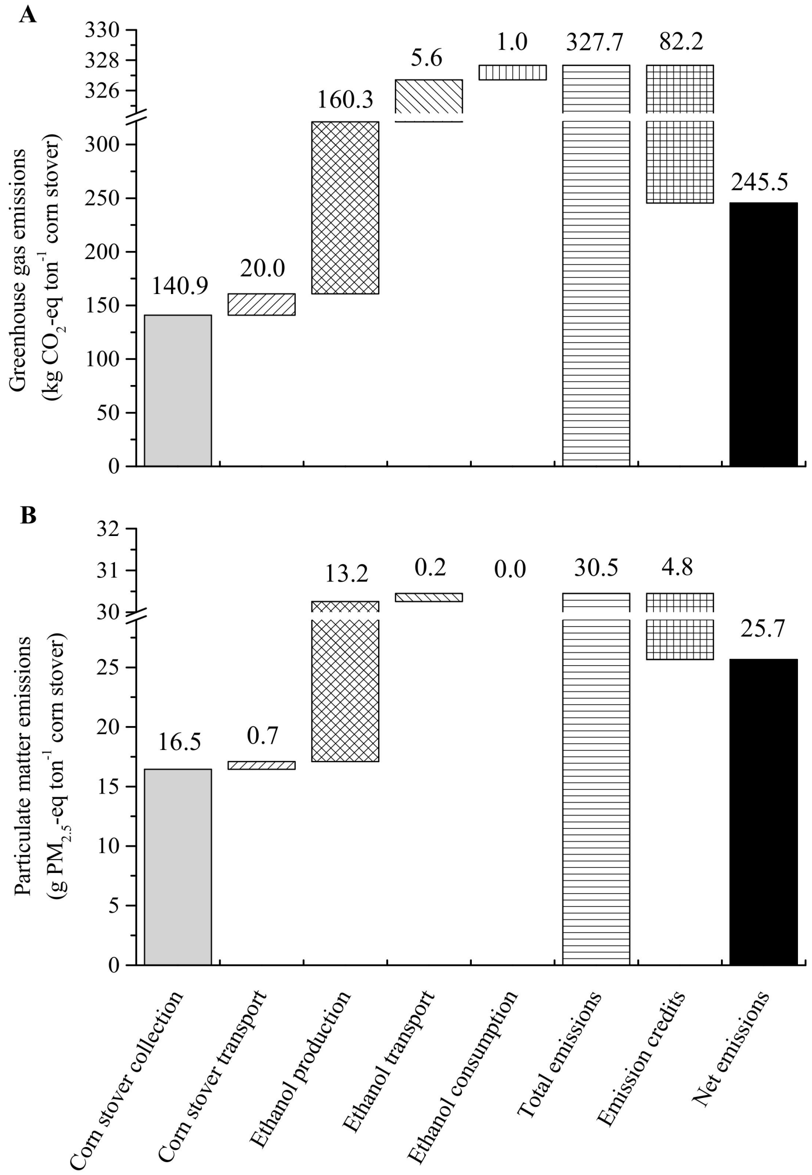

Figure 3. Emissions of greenhouse gas (**A**) and $PM_{2.5}$ (**B**) from corn stover based ethanol production by stages (Corn stover collection included corn planting and corn stover collection in field).

Table 5. Greenhouse gas (GHG) and fine particulate matter ($PM_{2.5}$) emissions from the reference case and the corn stover based ethanol production.

Pathway	GHG	$PM_{2.5}$
	(kg CO_2-eq ton^{-1} Corn Stover)	(g ton^{-1} Corn Stover)
Corn stover burning in field [1]	270.1	11,716.50
Gasoline from crude oil [1]	925.5	32
Corn stover for ethanol production	245.5	25.7
Reduction factor (RF) [2]	950.1	11,722.70

[1] Reference case; [2] The reduction factors of GHG and $PM_{2.5}$ emissions were calculated by using emissions from the reference case minus emissions from the corn stover-based ethanol production.

3.3. Potential Reductions in GHG and $PM_{2.5}$ Emissions under Four Scenarios

According to the Medium and Long-Term Development Plans for Renewable Energy released in 2007 in China [40], looking toward a target of 10.0 Mt ethanol production by 2020, the corn stover demand could be 38.5 Mt, or 44.6% of corn stover surplus (Scenario B, Table 6). Under this scenario, the potential reductions in emissions were 36.5 Mt CO_2-eq GHG and 450.9 kt $PM_{2.5}$. By comparison, under Scenario A, which assumed half the ethanol production (5.0 Mt) of Scenario B, the potential reductions were 18.3 Mt CO_2-eq GHG and 225.4 kt $PM_{2.5}$. Under Scenario C, which assumed 50.0% higher ethanol production than Scenario B, the potential reductions were 54.8 Mt CO_2-eq GHG and 676.3 kt $PM_{2.5}$. Finally, when it was assumed that all the corn stover surplus was used to produce ethanol (Scenario D), ethanol production could reach 22.4 Mt and the potential mitigations were 81.9 Mt CO_2-eq GHG and 1010.4 kt $PM_{2.5}$. The results indicated that the potential GHG and $PM_{2.5}$ emission reductions were sensitive to the quantities of corn stover surplus for ethanol production.

Table 6. Potential GHG and $PM_{2.5}$ emission reductions in corn stover based ethanol production under four scenarios in China.

Parameter	Scenario [1]			
	A	B	C	D
Target ethanol production (Mt)	5.0	10.0	15.0	22.4
Corn stover used for ethanol production (%)	26.0	26.0	26.0	26.0
Corn stover demand (Mt)	19.2	38.5	57.7	86.2
Ratio of corn stover demand to surplus quantity in 2015 (%)	22.3	44.6	66.9	100.0
GHG emission reductions compared with reference case (Mt CO_2-eq)	18.3	36.5	54.8	81.9
$PM_{2.5}$ emission reductions compared with reference case (kt)	225.4	450.9	676.3	1010.4

[1] Scenario B was based on the target for ethanol fuel production, i.e., 10 million tons, set in the *Medium and Long-Term Development Plan for Renewable Energy* by the National Development and Reform Commission, China in 2007 [40]. Scenario A was for half of the ethanol target of Scenario B. In Scenario C, the ethanol target was 50% higher than Scenario B. Scenario D was based on all the corn stover surplus quantity in this study.

3.4. Potential Reductions in GHG and $PM_{2.5}$ Emissions in a Provincial Regional Context

Based on Scenario B, the potential reductions in GHG and $PM_{2.5}$ emissions in 2015 were the highest in Northeast China, i.e., 8889.3 kt CO_2-eq and 109,680.5 t for Heilongjiang (24.3%), 6612.6 kt CO_2-eq and 81,589.3 t for Jilin (18.1%), and 3125.8 kt CO_2-eq and 38,566.9 t for Liaoning (8.6%), respectively (Table 7). In contrast, the potential reductions in GHG and $PM_{2.5}$ emissions, and the weight in the country (%) were the lowest in Shanghai (1.1 kt CO_2-eq and 13.3 t, 0.003%), Tibet (1.7 kt CO_2-eq and 20.7 t, 0.005%), and Qinghai (7.8 kt CO_2-eq and 96.3 t, 0.02%), respectively. These results were consistent with the corn stover surplus quantities in each provincial regions because the same reduction factors of GHG and $PM_{2.5}$ emissions were used in all the regions.

Table 7. Geographical distributions of corn stover surplus, availability for bioethanol production, and potential total emission reductions in GHG (Q_{GER}) and $PM_{2.5}$ (Q_{PER}) from corn stover-based bioethanol compared with the reference case in different regions and provinces in 2015.

Region and Province [1]	**Surplus Quantity (kt)**	**Available Quantity (kt)** [2]	**Q_{GER} (kt CO_2-eq)**	**Q_{PER} (t)**	**Ratio (%)** [3]
North	14,299.2	6380.8	6062.4	74,800.8	16.6
Beijing	131.0	58.5	55.5	685.3	0.2
Tianjin	276.2	123.2	117.1	1444.8	0.3
Hebei	4560.2	2034.9	1933.4	23,854.9	5.3
Shanxi	2601.9	1161.1	1103.1	13,610.9	3.0
Inner Mongolia	6729.9	3003.1	2853.3	35,204.9	7.8
Northeast	43,936.4	19,606.1	18,627.7	229,836.7	51.0
Liaoning	7372.6	3289.9	3125.8	38,566.9	8.6
Jilin	15,596.9	6959.9	6612.6	81,589.3	18.1
Heilongjiang	20,966.9	9356.2	8889.3	109,680.5	24.3
East	5076.1	2265.1	2152.1	26,553.5	5.9
Shanghai	2.5	1.1	1.1	13.3	0.0
Jiangsu	327.9	146.3	139.0	1715.1	0.4
Zhejiang	146.3	65.3	62.0	765.3	0.2
Anhui	645.2	287.9	273.5	3375.1	0.7
Fujian	110.0	49.1	46.6	575.3	0.1
Jiangxi	103.4	46.1	43.8	540.7	0.1
Shandong	3740.8	1669.3	1586.0	19,568.8	4.3
Central-South	9927.4	4430.0	4208.9	51,931.4	11.5
Henan	3768.6	1681.7	1597.8	19,713.9	4.4
Hubei	2251.1	1004.5	954.4	11,775.6	2.6
Hunan	1540.6	687.5	653.2	8059.1	1.8
Guangdong	550.6	245.7	233.4	2880.2	0.6
Guangxi	1741.5	777.1	738.3	9109.8	2.0
Hainan	75.1	33.5	31.8	392.7	0.1
Southwest	10,735.6	4790.6	4551.6	56,159.5	12.5
Chongqing	1296.4	578.5	549.6	6781.7	1.5
Sichuan	3902.0	1741.2	1654.3	20,411.9	4.5
Guizhou	1919.3	856.5	813.7	10,040.2	2.2
Yunnan	3613.9	1612.7	1532.2	18,905.0	4.2
Tibet	4.0	1.8	1.7	20.7	0.0
Northwest	2216.1	988.9	939.6	11,592.7	2.6
Shaanxi	1015.6	453.2	430.6	5312.7	1.2
Gansu	448.5	200.1	190.1	2346.1	0.5
Qinghai	18.4	8.2	7.8	96.3	0.0
Ningxia	247.1	110.3	104.8	1292.6	0.3
Xinjiang	486.5	217.1	206.3	2545.0	0.6
Total (China)	86,190.7	38,461.5	36,542.2	450,874.6	100.0

[1] It includes the municipalities and autonomous regions according to the administrative divisions in China; [2] The available quantity is 44.6% of the surplus quantity, based on Scenario B in this study; [3] The ratio is percentage (%) of each provincial region in the total (China). The ratio is the same for surplus quantity, available quantity, Q_{GER} and Q_{PER} within the same columns.

The potential reductions in emissions exhibited variations in regional distribution between 939.6 kt to 18,627.7 kt CO_2-eq GHG, and 11,592.7 t to 229,836.7 t $PM_{2.5}$, in the order of: Northwest China (2.6%) < East China (5.9%) < Central-South China (11.5%) < Southwest China (12.5%) < North China (16.6%) < Northeast China (51.0%). These results indicated that the potential of GHG and $PM_{2.5}$ emission reductions was especially high in Northeast China if corn stover was used for ethanol production.

4. Discussion

In 2015, the total corn stover surplus for bioethanol production reached 86.2 Mt. In the near future, this quantity could be higher because the proportion of corn stover for cooking and heating could be added. The use of corn stover for cooking and heating would likely decrease with the recent development of more energy options in China (e.g., coal and natural gas).

In addition, even though the Chinese government issued seven regulations between 2008 and 2015 to ban the crop residues burning in field [41], corn stover burning in field still remained widespread. As shown in this study, the average corn stover burning in field reached 34.9% of the total corn stover in 2015. Wang and Wang [42] also reported that 26.0% of crop residues were burned in field in China in 2008 and 2009.

The results of this study suggested that regulations are needed to combine the ban of burning corn stover in field with the encouragement of corn stover commercial utilization, e.g., bioenergy production. This is expected to greatly decrease the corn stover burning in field. This approach may also be applicable to other countries such as India, where more than half of the crop straw was burned openly in field [43]. It was also found in this study that the percentage of corn stover burning in field was related to the regulations on crop residue management. Chen et al. [29] reported that the regulations in South and East regions in China were not always available, and in this study, the percentages of corn stover burning in field were higher in these regions (40.4–71.1%).

In this study, the overall life-cycle GHG emissions per unit of ethanol produced from corn stover were 245.5 kg of CO_2-eq ton^{-1}, 738.7 g CO_2-eq L^{-1}, or 34.7 g CO_2-eq MJ^{-1}. The 34.7 g CO_2-eq MJ^{-1} was similar to the value of 38.0 g CO_2-eq MJ^{-1}, which was also based on the NREL bioethanol production process [44]. However, it was lower than the 65.3 g CO_2-eq MJ^{-1} reported by Zhao et al. [13] because the fertilizer quantity in this study was lower than in previously published studies. The 738.7 g CO_2-eq L^{-1} in this study was higher than a previous estimate of 330 g CO_2-eq L^{-1} [27] because of the inclusion of GHG emissions from fertilizer use in field in this study. The results demonstrated that chemical fertilizer use in the cornfield had an obvious effect on life-cycle GHG emissions. Reducing the use of chemical fertilizer or replacing it with organic fertilizer, e.g., animal manure, could decrease the life-cycle GHG emissions from bioethanol production using corn stover. It is also worth noting that the major source of GHG emissions was from the stage of ethanol production because of the use of a large amount of chemicals and nutrients. This finding was consistent with McKechnie et al. [44] and Zhao et al. [13], whose studies were based on the same ethanol conversion process as in this study.

Since 2014, the National Development and Reform Commission of China has been regulating the assessments and interventions for the control of CO_2 emissions in each province [45]. Ultimately, the control of CO_2 and $PM_{2.5}$ emissions is expected to have dramatic environmental and social impacts in China. This study combined corn stover geographical distributions and its reduction factors based on LCA, in order to assess the potential reductions in GHG and $PM_{2.5}$ emissions across China. It could be a reference to estimate the total environmental impacts from organic waste utilization in other countries. It would encourage policy makers, researchers and industry managers to promote the commercial development of corn stover for bioenergy use. Its development could not only decrease the pollutant emissions and provide the service of disposing the corn stover as agricultural waste, but also supply the lots of job opportunities and promote the local economic development.

5. Conclusions

This study revealed that the total surplus quantity of corn stover reached 86.2 Mt in 2015 in China. However, geographical distributions of the corn stover surplus among 31 different provincial regions varied greatly. The use of corn stover for ethanol production had great potential to reduce GHG and $PM_{2.5}$ emissions, especially in Northeast China. The potential reductions from 38.5 Mt corn stover, or 44.6% of corn stover surplus, to produce 10 Mt ethanol were 36.5 Mt CO_2-eq GHG and 450.9 kt $PM_{2.5}$. Chemical fertilizer application in the stage of corn planting had a negative effect on life-cycle GHG emission reductions. A large amount of chemical and nutrient use in the stage of ethanol production also greatly decreased the benefit of GHG emission reductions. New regulations that could combine the ban of in-field corn stover burning with the encouragement of corn stover ethanol production could lead to more GHG and $PM_{2.5}$ emission reductions.

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References

1. UNFCCC, The Paris Agreement. Available online: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (accessed on 31 September 2019).
2. People's Republic of China, United States of America, Joint Statement on Climate Change. Available online: https://baike.baidu.com/reference/1717477/b46eZgbzNushW8cRJOshek_dddLHbvyt5H8AYk-vNugfp178cQ9T1vL8jec-uk1MPPYJlUtjUqiaIGKrA1huByOHT-DXzQm41c1QhAwWjhur (accessed on 28 August 2019).
3. Dong, H.; Dai, H.; Dong, L.; Fujita, T.; Geng, Y.; Klimont, Z.; Inoue, T.; Bunya, S.; Fujii, M.; Masui, T. Pursuing air pollutant co-benefits of CO_2 mitigation in China: A provincial leveled analysis. *Appl. Energy* **2015**, *144*, 165–174. [CrossRef]
4. International Grains Council, Market Information of Maize Supply and Demand. Available online: http://www.igc.int/en/markets/marketinfo-sd.aspx (accessed on 16 September 2019).
5. Farine, D.; O'connell, D.; Raison, R.; May, B.; O'Connor, M.; Crawford, D.; Herr, A.; Taylor, J.; Jovanovic, T.; Campbell, P.; et al. An assessment of biomass for bioelectricity and biofuel, and for greenhouse gas emission reduction in Australia. *GCB Bioenergy* **2012**, *4*, 148–175. [CrossRef]
6. Murphy, C.W.; Kendall, A. Life cycle analysis of biochemical cellulosic ethanolunder multiple scenarios. *GCB Bioenergy* **2015**, *7*, 1019–1033. [CrossRef]
7. Jones, C.D.; Zhang, X.; Reddy, A.D.; Robertson, G.P.L.I.; Izaurralde, R.C.E. The greenhouse gas intensity and potential biofuel production capacity of maize stover harvest in the US Midwest. *GCB Bioenergy* **2017**, *9*, 1543–1554. [CrossRef]
8. Liu, H.; Pang, B.; Zhao, Y.; Lu, J.; Han, Y.; Wang, H. Comparative study of two different alkali-mechanical pretreatments of corn stover for bioethanol production. *Fuel* **2018**, *221*, 21–27. [CrossRef]
9. Zhao, Y.; Damgaard, A.; Christensen, T.H. Bioethanol from corn stover—A review and technical assessment of alternative biotechnologies. *PrECS* **2018**, *67*, 275–291. [CrossRef]
10. Zhao, Y.; Damgaard, A.; Xu, Y.; Liu, S.; Christensen, T.H. Bioethanol from corn stover – Global warming footprint of alternative biotechnologies. *Appl. Energy* **2019**, *247*, 237–253. [CrossRef]
11. Liu, C.Q.; Huang, Y.J.; Wang, X.Y.; Tai, Y.; Liu, L.Q.; Sun, C.G.; Liu, H. Emergy analysis for transportation fuels produced from corn stover in China. *J. Clean. Prod.* **2018**, *174*, 213–225. [CrossRef]
12. Xu, X.N.; Yang, Y.L.; Xiao, C.; Zhang, X.M. Energy balance and global warming potential of corn straw-based bioethanol in China from a life cycle perspective. *Int. J. Green Energy* **2018**, *15*, 296–304. [CrossRef]
13. Zhao, L.; Ou, X.; Chang, S. Life-cycle greenhouse gas emission and energy use of bioethanol produced from corn stover in China: Current perspectives and future prospectives. *Energy* **2016**, *115*, 303–313.
14. National Bureau of Statistics of China, China Statistical Yearbook 2018. Available online: http://www.stats.gov.cn/tjsj/ndsj/2018/indexch.htm (accessed on 16 September 2019).
15. Chen, X. Economic potential of biomass supply from crop residues in China. *Appl. Energy* **2016**, *166*, 141–149. [CrossRef]
16. Zuo, X.; Wang, H.; Wang, Y.; Wang, L.; Jing, L.; Wang, D. Estimation and suitability evaluation of corn straw resources in China. *Chin. J. Agric. Resour. Reg. Plan.* **2015**, *36*, 5–10.
17. Song, J.; Yang, W.; Higano, Y.; Wang, X. Dynamic integrated assessment of bioenergy technologies for energy production utilizing agricultural residues: An input–output approach. *Appl. Energy* **2015**, *158*, 178–189. [CrossRef]
18. Global Carbon Project, Global Carbon Budget. Available online: http://www.globalcarbonproject.org/carbonbudget/index.htm (accessed on 14 November 2016).
19. Greenpeace, Ranking of PM2.5 Pollution in Provincial Regions in 2016. Available online: http://huanbao.bjx.com.cn/news/20160420/726494.shtml (accessed on 15 December 2017).
20. National Bureau of Statistics of China, China Statistical Yearbook 2016. Available online: http://www.stats.gov.cn/tjsj/ndsj/2016/indexch.htm (accessed on 29 August 2018).
21. Zheng, B.; Zhang, Q.; Borken-Kleefeld, J.; Huo, H.; Guan, D.; Klimont, Z.; Peters, G.P.; He, K. How will greenhouse gas emissions from motor vehicles be constrained in China around 2030? *Appl. Energy* **2015**, *156*, 230–240. [CrossRef]
22. Wang, X.; Bi, X.; Sheng, G.; Fu, J. Chemical composition and sources of PM10 and PM2.5 aerosols in Guangzhou, China. *Environ. Monit. Assess.* **2006**, *119*, 425–439. [CrossRef] [PubMed]

23. XinhuaNews, The Debate of the Vehicle Emission Contribution to PM2.5. Available online: http://auto.ifeng.com/xinwen/20140103/1006551.shtml (accessed on 1 January 2014).
24. Zhao, J.; Zhang, G.; Yang, D. Estimation of carbon emission from burning of grain crop residues in China. *JAES* **2011**, *30*, 812–816.
25. Zhang, R.; Jing, J.; Tao, J.; Hsu, S.C.; Wang, G.; Cao, J.; Lee, C.S.L.; Zhu, L.; Chen, Z.; Zhao, Y.; et al. Chemical characterization and source apportionment of PM2.5 in Beijing: Seasonal perspective. *Atmos. Chem. Phys.* **2013**, *13*, 7053–7074. [CrossRef]
26. Kim, S.; Dale, B.E. Life cycle assessment of various cropping systems utilized for producing biofuels: Bioethanol and biodiesel. *Biomass Bioenergy* **2005**, *29*, 426–439. [CrossRef]
27. Spatari, S.; Zhang, Y.; Maclean, H.L. Life cycle assessment of switchgrass and corn stover-derived ethanol fueled automobiles. *Environ. Sci. Technol.* **2005**, *39*, 9750–9758. [CrossRef]
28. Wang, M.; Han, J.; Dunn, J.B.; Cai, H.; Elgowainy, A. Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use. *Environ. Res. Lett.* **2012**, *7*, 045905. [CrossRef]
29. Chen, C.; Yang, Y.; Hu, L.; Xie, G. Review on the development of crop residue management policies in provincial regions in China. *J. China Agric. Univ.* **2017**, *22*, 1–16.
30. National Bureau of Statistics of China, China Statistical Yearbook 2014. Available online: http://www.stats.gov.cn/tjsj/ndsj/2014/indexch.htm (accessed on 28 September 2015).
31. Wang, X.; Xue, S.; Xie, G.H. Value-taking for residue factor as a parameter to assess the field residue of field crops. *J. China Agric. Univ.* **2012**, *17*, 1–8.
32. Eggleston, S.; Buendia, L.; Miwa, K.; Ngara, T.; Tanabe, K. *IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme*; The Institute for Global Environmental Strategies (IGES): Hayama, Japan, 2006.
33. National Renewable Energy Laboratory, Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol. Available online: http://www.nrel.gov/docs/fy11osti/47764.pdf (accessed on 30 May 2011).
34. Wang, M. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model Version 1.5. Available online: http://GREET.es.anl.gov/publications (accessed on 24 April 2016).
35. Wang, M. Technical Report: GREET 1.5—Transportation Fuel-Cycle Model—Volume 1: Methodology, Development, Use and Results. Available online: http://GREET.es.anl.gov/publications (accessed on 25 September 2014).
36. Wang, M.; May, W.; Huo, H. Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types. *Environ. Res. Lett.* **2007**, *2*, 024001. [CrossRef]
37. Wang, M.; Saricks, C.; Lee, H. Fuel-Cycle Energy and Emission Impacts of Ethanol-Diesel Blends in Urban Buses and Farming Tractors. Available online: https://digital.library.unt.edu/ark:/67531/metadc737237/#prefix_0 (accessed on 2 January 2015).
38. Li, X.; Wang, S.; Duan, L.; Hao, J.; Li, C.; Chen, Y.; Yang, L. Particulate and trace gas emissions from open burning of wheat straw and corn stover in China. *Environ. Sci. Technol.* **2007**, *41*, 6052–6058. [CrossRef] [PubMed]
39. Wang, S.; Zhang, C. Spatial and temporal distribution of air pollutant emissions from open burning of crop residues in China. *Sci. Online* **2008**, *3*, 329–333.
40. National Development and Reform Commission, Medium and Long Term Developmen Plan for Renewable Energy. Available online: http://www.ndrc.gov.cn/zcfb/zcfbghwb/200709/t20070904_579685.html (accessed on 16 September 2017).
41. Chen, C.; Yang, Y.; Xie, G.H. Study of the development of crop straw management policy in China. *J. China Agric. Univ.* **2016**, *21*, 1–11.
42. Wang, X.; Wang, L. Environmental Protection Departments about the Fog Haze in Harbin: Straw is a Important Factor. Available online: http://www.chinanews.com/gn/2013/10-21/5403825.shtml (accessed on 21 October 2013).
43. Trivedi, A.; Verma, A.R.; Kaur, S.; Jha, B.; Vijay, V.; Chandra, R.; Vijay, V.K.; Subbarao, P.M.V.; Tiwari, R.; Hariprasad, P.; et al. Sustainable bio-energy production models for eradicating open field burning of paddy straw in Punjab, India. *Energy* **2017**, *127*, 310–317. [CrossRef]

44. McKechnie, J.; Pourbafrani, M.; Saville, B.A.; MacLean, H.L. Exploring impacts of process technology development and regional factors on life cycle greenhouse gas emissions of corn stover ethanol. *Renew. Energy* **2015**, *76*, 726–734. [CrossRef]
45. National Development and Reform Commission, The Target Responsibility of Assessment Method about Reduction from Per Unit GDP of CO_2 Emission. Available online: http://www.ndrc.gov.cn/gzdt/201408/t20140815_622318.html (accessed on 28 August 2014).