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# Multiple Cropping System Expansion: Increasing Agricultural Greenhouse Gas Emissions in the North China Plain and Neighboring Regions

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**Abstract:** The increase of agricultural greenhouse gas (GHG) emissions has become a significant issue for China, affecting the achievement of its Nationally Determined Contributions under the Paris Agreement. Expansion of the large-scale multiple cropping system as a consequence of climate warming could be a major driving force of this increase. In this study, life cycle assessment was employed to identify agricultural GHG emissions due to the expansion of the multiple cropping system in the North China Plain and neighboring regions. We found that agricultural greenhouse gas emissions have increased from 41.34 to 120.87 Tg CO<sub>2</sub>-eq/yr over the past 30 years, and the expansion of the multiple cropping system has contributed to 13.89% of this increment. Furthermore, the increases in straw handling and agricultural inputs which are related to multiple cropping systems have also played an important role. Results of our study demonstrate that the expansion of the multiple cropping system contributes considerably to increases in agricultural GHG emissions in the North China Plain and neighboring regions. Therefore, it can be concluded that the sustained northward expansion of the multiple cropping system will further elevate agricultural GHG emissions in China, and this should be considered while formulating policies to reduce GHG emissions from agriculture.

**Keywords:** greenhouse gas emissions; multiple cropping system; life cycle assessment; China

## 1. Introduction

China is the largest emitter of greenhouse gases (GHGs) and has promised to achieve the peak of carbon dioxide emissions around 2030 in its Nationally Determined Contributions (NDCs) under the Paris Agreement. As such, the Chinese government has employed a series of actions in line with global plans to reduce GHG emissions from energy supply, transport, and traditional secondary industries [1,2]. However, GHG emissions from agriculture increased substantially from 0.61 to 0.92 Pg CO<sub>2</sub>-equivalence (CO<sub>2</sub>-eq) from 1994 to 2012 [3,4]. Tian et al. also reported that agricultural GHG emissions show a clear upward trend with an average annual growth rate of 3.10% in China from 1995 to 2010 [5]. This increase in agricultural GHG emissions has become an important sustainability issue to ensure that China meets its Nationally Determined Contributions under the Paris Agreement [6,7]. The agricultural GHG emissions, which include fertilizer, pesticide, plastic sheeting, diesel, electricity, and soil carbon emissions, increased by 4.08% in China from 1993 to 2008 [8]. Agriculture is a non-point source of GHG emissions, which is closely related to the sown area and multiple cropping systems (MCSs) [9].

Multiple cropping systems play a vital role for securing the food supply of Asia, particularly in densely populated China where farmland areas have been reduced [10]. The changing climate has prolonged the growing season by about ten days in most of northern China, and the boundary of MCSs

has shifted northward by 26 to 127 km [4,11,12], enabling annual agricultural practices to shift from single to double cropping [13–15]. Crops in the temperate climate zones of northern China benefit from increasing temperatures [16]. The climatically-mediated potential agricultural productivity is predicted to increase by 9.36% if single cropping (e.g., spring maize) is replaced with double cropping (e.g., winter wheat and summer maize) in northeastern China over the decades spanning 2011–2040 [17]. Yang et al. argued that if the climate resources were fully utilized in China by developing MCSs, the total yields of maize, wheat, and rice could increase by 2.2% from 2011 to 2100 [12]. There are now high expectations to increase cropping intensity to boost crop yields in northeastern and northern China. However, these large-scale changes in MCS patterns could alter agricultural GHG emissions, which may threaten corresponding mitigation efforts in the agricultural sector. Unfortunately, the information on GHG emissions obtained from MCSs is lacking.

The assessment methods used to account for agriculture GHG emissions are quite different. The latest national GHG inventory of China in 2012 followed the methodologies provided in the Intergovernmental Panel on Climate Change (IPCC) *Guidelines for National Greenhouse Gas Inventories and Uncertainty Management* [4,18]. The IPCC method assigns the responsibility for the emissions from agricultural inputs, such as fertilizer and diesel, to the industrial and energy sectors, which cannot reflect the emissions of the entire agricultural production process. However, the life cycle assessment (LCA) method describes the global warming potential of the entire process of agricultural production, which has been widely adopted in studies on the agricultural sector. Biswas et al. used LCA to calculate GHG emissions from wheat production in Western Australia [19]. Athena and Regina certified the first carbon neutrality coffee in Costa Rica based on comprehensive data collection and the LCA method [20]. Li et al. reported, based on the LCA, that for every 1% increase in agricultural output, agricultural carbon emissions have increased by 0.69% [21]. Therefore, the LCA is a good method to assess GHG emissions from the expansion of MCSs due to climate change [9,22].

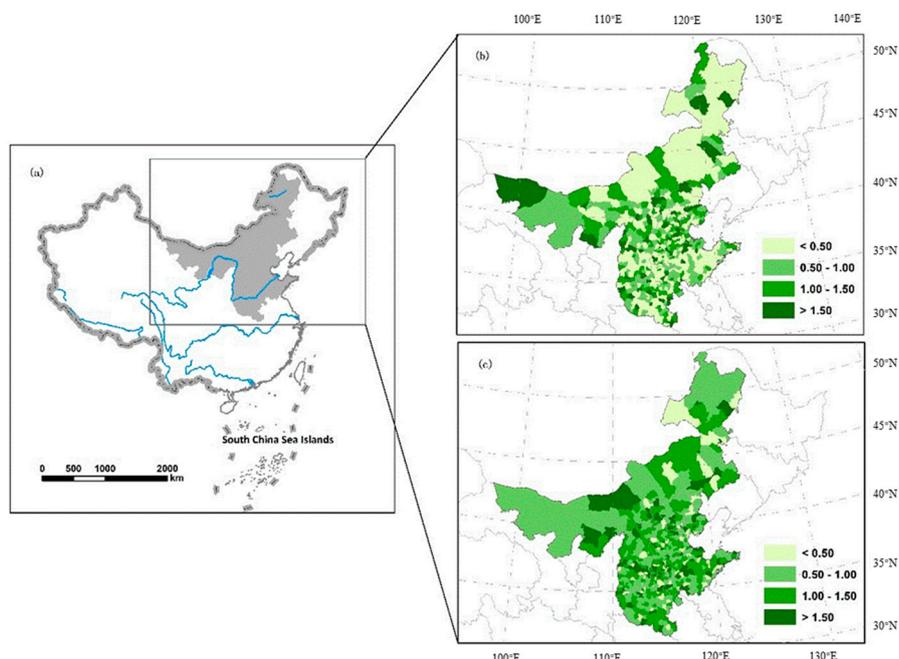
Known as China's granary, the North China Plain (NCP) is one of the largest planting areas, providing more than half of the cereal consumed in China [23]. Wheat-maize double cropping has expanded in this region, supported by climate change [15,16]. However, little is known of the contribution of MCSs to GHG emissions in the NCP. Therefore, the objectives of this study were to (i) estimate GHG emissions related to the expansion of MCSs and (ii) determine the GHG emissions increase attributed to MCSs.

## 2. Data and Methodology

### 2.1. Study Region and Data

The NCP and neighboring regions are the most obvious areas for the development of MCS in China. These areas are dominated by double cropping of winter wheat and summer maize, and include Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Henan, and Shandong Provinces (Figure 1). The climate regime is temperate with continental monsoons. The frost-free period is about four to eight months, and heat conditions vary substantially meridionally. Annual precipitation is approximately 400–800 mm, which occurs mainly in the humid summer months of June, July, and August. Soil types are mainly cinnamon and black, similar to ustalf and mollisol, respectively, in U.S. soil classification, and dryland farming methods predominate. The major crops include wheat, maize, soybean, and cotton. Data from 508 rural counties from the China Rural Statistical Yearbooks 1982–2012 included wheat, maize, soybean, and cotton plantations, sown areas, the multiple cropping index (MCI), yield, fertilizers, electric power, pesticides, plastic mulch, and diesel. The changes in the MCI indicate the dynamics of MCSs that have arisen from enhanced climate resources. For example, the climatically mediated potential agricultural productivity is predicted to increase by 9.36% upon replacing single cropping (e.g., spring maize) with double cropping (e.g., winter wheat and summer maize) in northeastern China from 2011 to 2040 [17]. If the climatic resources were fully utilized in China by developing MCSs, the yields of maize, wheat, and rice could increase by 2.20% from 2011 to 2100 [12]. However,

comparison of the spatiotemporal differences between the beginning and end of a single year using the MCI is difficult and unreliable [24]. Therefore, we compared the average MCI of the first (1982–1986) and last (2008–2012) five-year periods of the study period to quantify the changes in the MCS expansion patterns (Figure 1).



**Figure 1.** Study region and distributions of the MCI: (a) Overview of the study region, the MCI between (b) 1982–1986, and (c) 2008–2012.

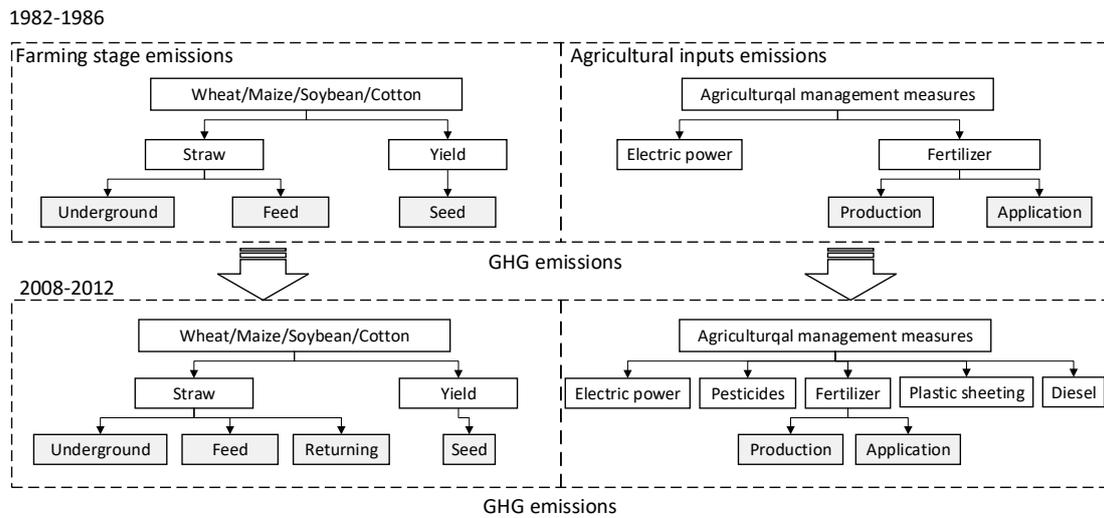
Table 1 presents the sown areas and yields of wheat, maize, soybean, and cotton in two phases. In comparison to 1982–1986, the yields of wheat, maize, soybean, and cotton increased over the 30 year study period by 116.27%, 228.91%, 51.95%, and 14.24%, respectively. The total sown area of the four crops was  $20.18 \times 10^6$  ha/yr between 1982–1986, which increased to  $27.58 \times 10^6$  ha/yr between 2008–2012, representing an increase of 36.67%. Although the sown areas of wheat and maize increased, the sown areas of soybean and cotton decreased slightly over time. The MCI at a county level increased markedly between 1982–1986 and 2008–2012, with mean values of 1.00 and 1.13, respectively.

## 2.2. LCA System Boundary of MCS GHG Emissions

The LCA system boundary of MCS GHG emissions included GHGs for specific farming stages and agricultural management measures [33]. According to the IPCC methodology [34], farming stage emissions involve two parts, emissions from seed and those from straw handling. In the past 20 years, returning straw to the field has become an important measure to improve soil fertility in China [35]; however, returning straw increased  $N_2O$  emissions by 27.73% in northern China [33]. The use and production of fertilizers, pesticides, plastic mulch (maintaining heat and moisture during spring sowing), diesel, and electric power for agricultural machinery is embedded in crop management practices. However, the  $CO_2$  emissions from the combustion of agricultural waste were carbon neutral [9,36,37]. The LCA system boundary did not include the emissions of  $CO_2$  and trace gases (i.e.,  $CH_4$  and  $N_2O$ ) from the burning of straw (Figure 2).

**Table 1.** Activity levels and emission factors by farming stage.

Parameter	1982–1986				2008–2012				Reference
	Wheat	Maize	Soybean	Cotton	Wheat	Maize	Soybean	Cotton	
Seeds per ha (kg/ha)	268.800 <sup>a</sup>	52.5000 <sup>b</sup>	45.000 <sup>c</sup>	18.000 <sup>d</sup>	268.800 <sup>a</sup>	52.500 <sup>b</sup>	45.000 <sup>c</sup>	18.000 <sup>d</sup>	<sup>a</sup> : Li et al., 2009 [25]; <sup>b</sup> : Li, 2004 [26]; <sup>c</sup> : Li, 2004 [27]; <sup>d</sup> : Shang, 2011 [28]
EF <sub>seed</sub> (kgCO <sub>2</sub> -eq/kg)	1.160	1.220	1.160	1.160	1.160	1.220	1.160	1.160	Liu et al. 2010 [14]
Straw feed ratio	0.126	0.340	0.207	0.002	0.126	0.199 <sup>e</sup>	0.207	0.002	Liu, 2005 [29]; <sup>e</sup> : Wang, 2011 [30]
CH <sub>4</sub> conversion factor	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	NDRC, 2011 [31]
Straw returning ratio	0.000	0.000	0.000	0.000	0.237	0.436 <sup>e</sup>	0.189	0.026	Liu, 2005 [29]; <sup>e</sup> : Wang, 2011 [30]
Straw ratio	1.170	1.040	1.600	3.000	1.170	1.040	1.600	3.000	Guo and Huang, 2016 [32]
Dry weight ratio	0.870	0.860	0.860	0.830	0.870	0.860	0.860	0.830	NDRC, 2011 [31]
Root crown ratio	0.166	0.170	0.130	0.200	0.166	0.170	0.130	0.200	NDRC, 2011 [31]
Carbon content <sub>straw</sub>	0.485	0.471	0.485	0.485	0.485	0.471	0.485	0.485	IPCC, 2014 [18]
Nitrogen content <sub>straw</sub>	0.005	0.006	0.018	0.005	0.005	0.006	0.018	0.005	NDRC, 2011 [31]
Sown area (10 <sup>6</sup> ha)	9.990	5.475	2.002	2.709	12.335	11.200	1.707	2.333	China Rural Statistical Yearbook, 1982–2009
Yield (Tg)	31.709	20.393	2.154	2.283	68.577	67.075	3.273	2.608	China Rural Statistical Yearbook, 1982–2009



**Figure 2.** The system boundary of the LCA according to agricultural practices in the NCP and neighboring regions.

### 2.3. Calculation of GHG Emissions

#### 2.3.1. CO<sub>2</sub> Emissions from Seeds

Carbon emissions from seeds was calculated according to Equation (1).

$$E_{Seed,CO_2} = \sum (Sown\ area_{crop} * Seed\ per\ ha_{crop} * EF_{seed}) \quad (1)$$

where  $E_{Seed, CO_2}$  is the CO<sub>2</sub> emissions from seeds,  $Sown\ area_{crop}$  is the sown area of the crop,  $Seed\ per\ ha_{crop}$  is the quantity of seeds per hectare of the crop, and  $EF_{seed}$  is the related emission factor. The seed activity data and emission factors of wheat, maize, soybean, and cotton were adopted according to local research results (see Table 1).

#### 2.3.2. N<sub>2</sub>O Emissions from Soil

The N<sub>2</sub>O emissions from soil include direct and indirect emissions from fertilizer and straw. Direct N<sub>2</sub>O emissions result from nitrogen fertilizer and straw returning. Meanwhile, indirect N<sub>2</sub>O emissions come from atmospheric deposition, leaching, and runoff of nitrogen from soil [24]. These values are based on the IPCC Guideline [34]. The soil N<sub>2</sub>O emissions were determined as:

$$E_{soil, N_2O} = E_{direct, N_2O} + E_{indirect, N_2O} \quad (2)$$

where  $E_{soil, N_2O}$  is the total N<sub>2</sub>O emissions from the cropland, including direct emissions ( $E_{direct, N_2O}$ ) and indirect emissions ( $E_{indirect, N_2O}$ ).

The cropland nitrogen inputs mainly contained nitrogen fertilizer  $E_{fertilizer\ application, N_2O}$  and straw returning (including nitrogen returned to the upper ground and underground root nitrogen)  $E_{straw\ returning, N_2O}$  can be represented as follows:

$$E_{direct, N_2O} = (E_{fertilizer\ application, N_2O} + E_{straw\ returning, N_2O}) \quad (3)$$

$$E_{fertilizer\ application, N_2O} = A_{fertilizer\ application, N_2O} * EF_{fertilizer\ application} \quad (4)$$

where  $A_{fertilizer\ application, N_2O}$  is the activity level of fertilizer application and  $EF_{fertilizer\ application}$  is the emission factor corresponding to fertilizer application.

$$\begin{aligned} E_{straw\ returning, N_2O} &= E_{upper\ ground\ straw\ returning, N_2O} + E_{underground\ root, N_2O} \\ &= Yield * Root\ crown\ ratio * Dry\ weight\ ratio * Straw\ ratio \\ &\quad * Nitrogen\ content_{straw} + (Yield + Yield * Dry\ weight\ ratio \\ &\quad * straw\ ratio) * Root\ crown\ ratio * Nitrogen\ content_{straw} \end{aligned} \quad (5)$$

where  $E_{upper\ ground\ straw\ returning, N_2O}$  represents emissions from nitrogen content in the upper ground due to straw returning and  $E_{underground\ root, N_2O}$  represents emissions from nitrogen content in the underground root.

Indirect  $N_2O$  emissions are calculated as:

$$\begin{aligned} E_{indirect, N_2O} &= (E_{deposition, N_2O} + E_{leaching, N_2O}) \\ &= (E_{direct, N_2O} * 10\%) * 0.01 + (E_{direct, N_2O} * 20\%) * 0.0075 \end{aligned} \quad (6)$$

where  $E_{deposition, N_2O}$  represents  $N_2O$  emissions from atmospheric deposition and  $E_{leaching, N_2O}$  represents  $N_2O$  emissions from atmospheric leaching. Atmospheric nitrogen mostly comes from the volatilization of  $NH_3$  and  $NO_x$ . We adopted the recommended value of 10%. According to provincial inventories [4], nitrogen leaching and runoff from soil accounts for 20% of the total nitrogen inputs into cropland. We used the emission factors of 0.01 and 0.0075 recommended by IPCC [34], respectively. The activity data of cropland  $N_2O$  emissions mainly include the sown area, yield, fertilizer application, root crown ratio, dry weight ratio, straw ratio, straw nitrogen content, straw feed ratio, and straw returning ratio (Tables 1 and 2).

### 2.3.3. $CH_4$ Emissions from Straw Feed

The  $CH_4$  emissions from straw feed were related to animal enteric fermentation [34].

$$E_{straw\ feed, CH_4} = \sum (Yield * Dry\ weight\ ratio * Straw\ ratio * Straw\ feed\ ratio * Y_m) \quad (7)$$

where  $E_{straw\ feed, CH_4}$  represents the emissions of  $CH_4$  from straw feed;  $Y_m$  is the  $CH_4$  conversion factor, available from the guideline of provincial inventory [4], and the value of  $7 \pm 0.5\%$  corresponds to the conversion factor for emissions from other cattle and buffaloes which are primarily fed low-quality straw and by-products (Table 1).

### 2.3.4. $CO_2$ Emissions from Agricultural Inputs

The GHG emissions from agricultural inputs, including fertilizer production, electric power, pesticides, plastic mulch, and diesel, are calculated as follows:

$$E_{input, CO_2} = \sum (A_{input} * EF_{input}) \quad (8)$$

where  $A_{input}$  is the activity level of the agricultural inputs, and  $EF_{input}$  is the emission factor of the agricultural input. Table 2 lists the activity level data from the statistical yearbook and EF for agricultural inputs.

$CH_4$  and  $N_2O$  emissions can be converted into  $CO_2$  equivalents ( $CO_2_{eq}$ ) using the global warming potential (GWP). Over a 100 year timescale, the GWPs of  $CH_4$  and  $N_2O$  have been estimated to be 34 and 298, respectively [39].

**Table 2.** Activity levels and emission factors of agricultural inputs.

Parameter	Activity (1982–1986)				Activity (2008–2012)				Unit	EF	Unit	Reference
	Wheat	Maize	Soybean	Cotton	Wheat	Maize	Soybean	Cotton				
Fertilizer application	2.10	1.15	0.42	0.57	5.95	5.41	0.82	1.13	Tg	0.0056 <sup>a</sup> /0.0057	kgN <sub>2</sub> O-N/kg	NDRC, 2011 [31]
Fertilizer production	2.10	1.15	0.42	0.57	5.95	5.41	0.82	1.13	Tg	0.8956	kgCO <sub>2</sub> -eq/kg	West et al., 2002 [38]
Electric power	31.60	17.32	6.33	8.57	0.01	0.01	0.00	0.00	10 <sup>9</sup> KW	1.03025/0.89355 <sup>b</sup>	Kg/KW.h	NDRC, 2004 [3], 2012 [4]
Pesticides					0.16	0.14	0.02	0.03	Tg	6.5800	kgCO <sub>2</sub> -eq/kg	Li et al. 2013 [21]
Plastic mulch					0.12	0.11	0.02	0.02	Tg	5.1800	kgCO <sub>2</sub> -eq/kg	Li et al., 2011 [8]
Diesel					3.30	3.00	0.46	0.62	Tg	3.3200	kgCO <sub>2</sub> -eq/kg	Li et al., 2013 [21]

Note: <sup>a</sup> EF in Shanxi and Inner Mongolia is 0.0056; <sup>b</sup> EF is 1.03025 between 1982–1986 and 0.89355 between 2008–2012, respectively.

#### 2.4. Contribution of MCS to the GHG Emission Ratio

To determine the contribution of MCSs to GHG emissions, we assumed that the MCI retained the state between 1982–1986 (mean value of MCI of 508 counties is 1.00), instead of the state between 2008–2012 (mean value of MCI of 508 counties is 1.13). Furthermore, to eliminate the change in cultivated land area between 1982–1986 and 2008–2012, the change in GHGs was calculated in terms of the sown area and the carbon emissions per unit area. Therefore, the change in GHGs caused by the MCI replacement could be treated as the contribution of MCSs. The contribution ratio of MCI to GHG emissions is calculated as:

$$C_{MCS} = \Delta GHG_{MCS} / GHG_{MCS2} \quad (9)$$

$$\Delta GHG_{MCS} = (MCI_2 - MCI_1) \times Area_{cultivated2} \times GHG_{unit\ area2} \quad (10)$$

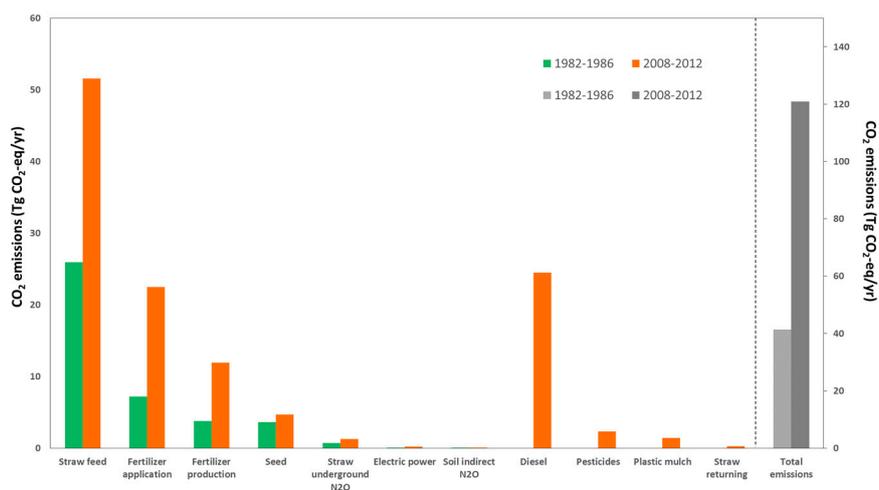
$$GHG_{unit\ area2} = GHG_{MCS2} / Area_{sown2} \quad (11)$$

where  $C_{MCS}$  is the contribution ratio of MCSs to GHG emissions,  $\Delta GHG_{MCS}$  is the change in GHGs caused by the MCI replacement,  $GHG_{unit\ area2}$  is the GHG emissions per unit area between 2008–2012,  $GHG_{MCS2}$  is the GHG emissions between 2008–2012,  $MCI_2$  and  $MCI_1$  are the MCI values between 2008–2012 and 1982–1986, respectively, and  $Area_{cultivated2}$  and  $Area_{sown2}$  are the cultivated area and sown area between 2008–2012, respectively.

### 3. Results

#### 3.1. Agricultural GHG Emissions in the NCP and Neighboring Regions

The average GHG emissions from wheat, maize, soybean, and cotton were 120.87 Tg CO<sub>2</sub>-eq/yr between 2008–2012, representing an increase of 192.38% as compared with the 41.34 Tg CO<sub>2</sub>-eq/yr produced between 1982–1986 (Table 3, Figure 3). Straw feed was the largest GHG emissions source, producing 25.93 and 51.59 Tg CO<sub>2</sub>-eq/yr for the two respective periods. Indirect N<sub>2</sub>O emissions from soil was the smallest GHG emissions source, producing 0.02 and 0.07 Tg CO<sub>2</sub>-eq/yr, respectively. Furthermore, the GHG emissions from diesel, pesticides, plastic mulch, and straw returning were 24.51, 2.35, 1.43, and 0.29 Tg CO<sub>2</sub>-eq/yr, respectively, and these were newly added emission sources between 2008–2012.



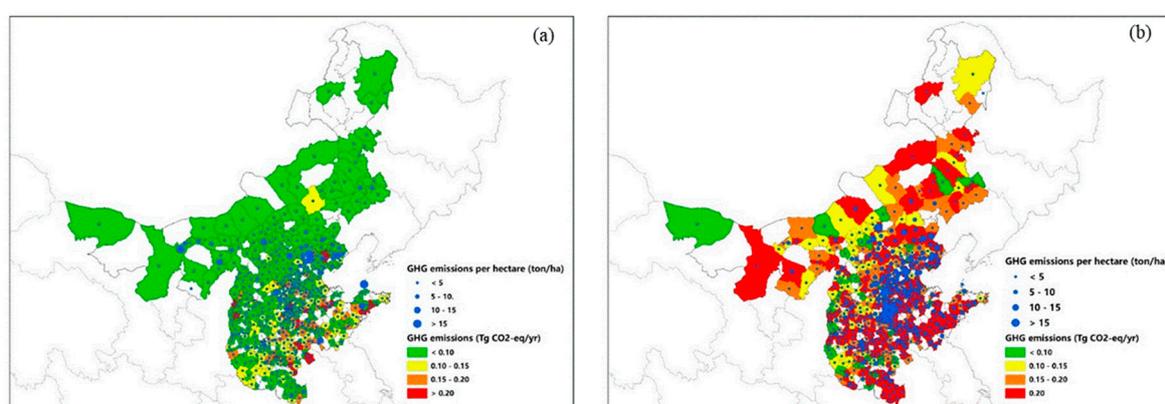
**Figure 3.** Agricultural GHG emissions in the NCP and neighboring regions between 1982–1986 and 2008–2012.

**Table 3.** Total carbon emissions in 508 counties in the NCP and neighboring regions between 1982–1986 and between 2008–2012 (Tg CO<sub>2</sub>-eq/yr).

Emissions	1982–1986				2008–2012				Total Emissions 1982–1986	Total Emissions 2008–2012
	Wheat	Maize	Soybean	Cotton	Wheat	Maize	Soybean	Cotton		
Straw underground N <sub>2</sub> O	0.09	0.06	0.55	0.01	0.20	0.21	0.83	0.02	0.71	1.26
Straw feed	9.68	14.76	1.46	0.03	20.93	28.41	2.22	0.03	25.93	51.59
Straw returning	-	-	-	-	0.00	0.26	0.03	0.00	-	0.29
Fertilizer application	3.56	1.95	0.71	0.97	10.07	9.14	1.39	1.90	7.19	22.50
Fertilizer production	1.88	1.03	0.38	0.51	5.33	4.84	0.74	1.01	3.80	11.92
Electric power	0.03	0.02	0.01	0.01	0.11	0.10	0.01	0.02	0.07	0.24
Seeds	3.11	0.35	0.10	0.06	3.85	0.72	0.09	0.05	3.62	4.71
Pesticides	-	-	-	-	1.05	0.95	0.15	0.20	-	2.35
Plastic mulch	-	-	-	-	0.64	0.58	0.09	0.12	-	1.43
Diesel	-	-	-	-	10.96	9.96	1.52	2.07	-	24.51
Soil indirect N <sub>2</sub> O	0.01	0.01	0.00	0.00	0.03	0.03	0.00	0.01	0.02	0.07
Total emissions	18.36	18.18	3.21	1.59	53.17	55.2	7.07	5.43	41.34	120.87

### 3.2. Spatial and Temporal Evolution of GHG Emissions

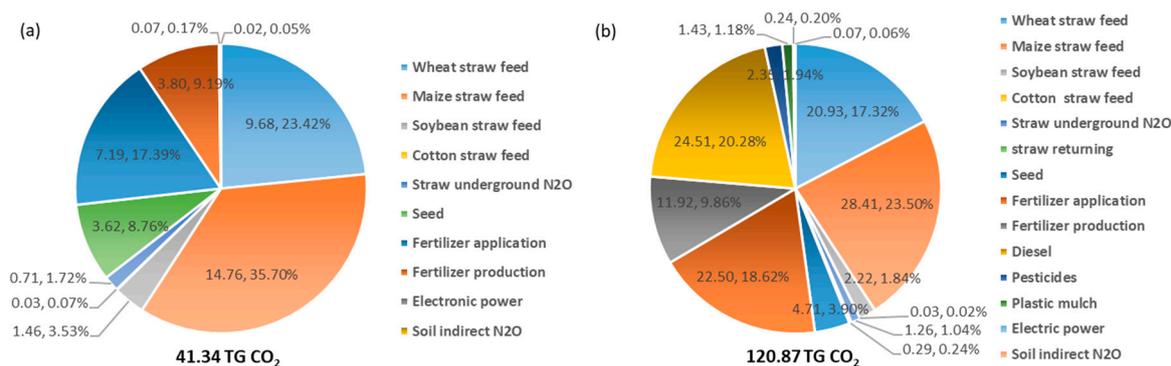
Figure 4 presents the evolution of the temporal dynamics and spatial patterns of GHG emissions in the 508 studied counties over the past 30 years. The proportion of counties producing more than 0.20 Tg CO<sub>2</sub>-eq/yr increased from 3.79% to 56.30% and those with GHG emissions of more than 5 ton per hectare increased from 7.48% to 33.46% between 1982–1986 and between 2008–2012. From 1982 to 1986, the GHG emissions in the northern region of the NCP, including Inner Mongolia, northern Hebei, and north of Shanxi, were relatively low whereas higher emissions were mainly observed in the southern areas, such as Beijing, Tianjin, south of Hebei, and Shandong. The higher emissions region expanded northward significantly from 2008 to 2012. From 1982–1986 to 2008–2012, counties with increased GHG emissions accounted for 93.11% of the region. The 35 counties with reduced GHG emissions were counties with reduced sown areas and they accounted for 97.14% of the total reduced GHG emissions.



**Figure 4.** The spatial and temporal evolution of GHG emissions from 508 counties between (a) 1982–1986 and (b) 2008–2012.

### 3.3. Analysis of the Driving Factors of Agricultural GHG Emissions

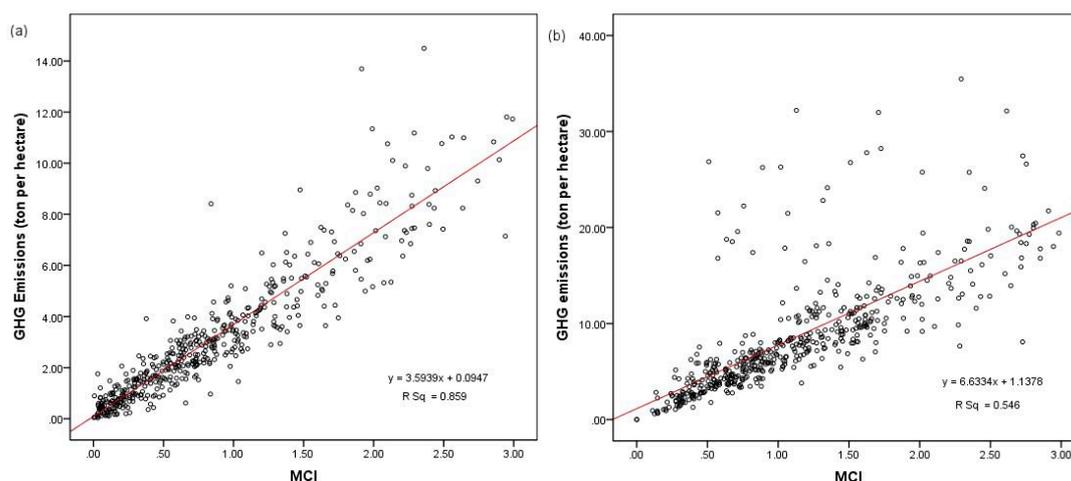
Dividing MCS GHG emissions by farming stage and agricultural inputs helped clarify the large range of GHG emissions (Figure 5). Straw accounted for 64.44% of the total GHG emissions between 1982–1986 and 43.96% between 2008–2012. In particular, the GHG emissions from straw feed increased from 25.93 to 51.59 Tg CO<sub>2</sub>-eq/yr, but which accounted for 62.72% of total GHG emissions between 1982–1986, which decreased to 42.68% between 2008–2012. The reason was that new GHG emission sources appeared between 2008–2012, such as diesel, pesticides, plastic mulch, and straw returning. Agricultural inputs were another important driving factor of agricultural GHG emissions, which accounted for 26.75% (including fertilizer and electric power) between 1982–1986 and up to 52.08% (including fertilizer, electric power, pesticides, plastic mulch, and diesel) between 2008–2012. China's agricultural material GHG emissions have shown a clear upward trend since 1995 [5]. From 1982 to 1986, fertilizer application and production were the main sources of GHG emissions among the agricultural inputs, accounting for 26.58% of the total GHG emissions. From 2008 to 2012, they remained the largest source of emissions among agricultural inputs, followed by diesel, accounting for 28.48% of total GHG emissions.



**Figure 5.** Proportion of emissions from various emission sources, determined based on LCA, between (a) 1982–1986 and (b) 2008–2012.

### 3.4. Contribution of MCSs to GHG Emissions

GHG emissions were positively correlated with MCIs between 1982–1986 (Person correlation coefficient = 0.606,  $P < 0.05$ ,  $N = 508$ ) and between 2008–2012 (Person correlation coefficient = 0.306,  $P < 0.05$ ,  $N = 508$ ). A significant positive linear trend ( $R^2 = 0.859$ ,  $P < 0.05$ , Figure 6a) was found between the GHG emissions and MCI from 1982 to 1986. Likewise, we also found that GHG emissions increased linearly with increasing MCI ( $R^2 = 0.546$ ,  $P < 0.05$ , Figure 6b) from 2008 to 2012. This relation suggests a strong influence of MCI on GHG emissions.



**Figure 6.** Scatter plots of GHG emissions and MCI between (a) 1982–1986 and (b) 2008–2012. The red lines represent the linear fit.

The contribution of MCSs was measured according to Equations (9–11) based on the change in the MCI for GHG emissions between 1982–1986 and 2008–2012. The calculated contribution ratio was 13.89%, indicating that the change in the MCI may have driven about one seventh of the total GHG emissions increase.

## 4. Discussion

This study focused on the relationship between MCS expansion and agricultural GHG emissions in NCP and the neighboring regions in China. During the past 30 years, agricultural GHG emissions increased from 41.34 to 120.87 Tg CO<sub>2</sub>-eq/yr (Figure 3), along with the significant northward expansion of the MCSs and higher emissions area (Figures 1 and 4). Among the driving factors, the contribution of the expansion MCSs accounted for about 13.89% of the total emissions increase (Table 3). These results are in agreement with the findings of Ha et al. [36] and Riano and Garcia-Gonzalez [39],

who reported that the carbon footprint of winter wheat and summer maize in the NCP was 2.32 (0.42–4.23) kg CO<sub>2</sub>-eq/kg, which is comparable with the value of 2.15 kg CO<sub>2</sub>-eq/kg determined in this study. Furthermore, The National Development and Reform Commission (NDRC) reported that the agricultural sector had GHG emissions of 0.61 Pg CO<sub>2</sub>-eq in 1994, 0.82 Pg CO<sub>2</sub>-eq in 2005, and 0.92 Pg CO<sub>2</sub>-eq in 2012 [3,4]. Correspondingly, the average agricultural GHG emissions was about 0.19 Pg CO<sub>2</sub>-eq in the NCP and neighboring regions between 2008–2012, accounting for about one-fifth of the national agricultural GHG emissions. In view of the crucial role of MCSs in China's food security system, it is safe to deduce that sustained northward expansion of MCSs will further elevate the emissions of agricultural GHG.

There are different accounting calibers to account for agricultural GHG emissions [22]. Dace et al. proposed that the system boundary of agricultural GHG emissions included land management, livestock farming, soil fertilization, and crop production [40]. Meanwhile, the IPCC agricultural sector inventory methodology does not include the CO<sub>2</sub> emissions of straw and agricultural inputs, because CO<sub>2</sub> released into the atmosphere is reabsorbed during the next crop growth period. Furthermore, the emissions from the production of agricultural inputs are calculated for the industrial and energy sector [18]. Therefore, we adopted the LCA method to identify the impacts of the expansion of MCSs at all stages in the production cycle and enable the evaluation of GHG emissions for comparative purposes. The LCA system boundary for agricultural GHG emissions included farming stage emissions and agricultural input emissions, which include the use of fertilizers, pesticides, plastic mulch, diesel, and electric power (Figure 2). According to the evolution of agricultural practices in the NCP and neighboring regions, the system boundary of the LCA was a more comprehensive assessment method.

## 5. Conclusion

Expansion of the multiple cropping system due to climate change increased the GHG emissions in the North China Plain and neighboring regions over the past 30 years and the contribution from the northward expansion of MCSs was about 13.98%. In view of the crucial role played by MCSs in China's food security system, it is expected that the sustained expansion of MCSs will further elevate the emissions of agricultural GHGs upon climate change. This study also revealed that straw handling and agricultural inputs are important sources of agricultural GHG emissions. During the past 20 years, returning straw to the field has become an important measure used to improve soil fertility in China, however, this practice is the main source of N<sub>2</sub>O emissions. Furthermore, fertilizers, electric power, pesticides, plastic mulch, and diesel are used widely, and the agricultural GHG emissions from agricultural inputs increased from 14.84% to 33.37% over the past 30 years. Overall, it is safe to conclude that while industrial/agricultural product replacement and modern agricultural technology have greatly improved agricultural productivity, they have also elevated the agricultural GHG emissions in China. Therefore, the increase in GHG emissions related to the expansion of MCSs could affect the ability of China to meet its Nationally Determined Contributions under the Paris Agreement, and should be considered while formulating policies related to reductions of agricultural emissions in China.

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## References

1. Li, F.F.; Xu, Z.; Ma, H. Can China achieve its CO<sub>2</sub> emissions peak by 2030? *Ecol. Indic.* **2018**, *84*, 337–344. [[CrossRef](#)]
2. Wang, H.M.; Dai, H.C.; Dong, L.; Xie, Y.; Geng, Y.; Yue, Q.; Ma, F.M.; Wang, J.; Du, T. Co-benefit of carbon mitigation on resource use in China. *J. Clean. Prod.* **2018**, *174*, 1096–1113. [[CrossRef](#)]

3. National Development and Reform Commission (NDRC). The People's Republic of China Initial National Communication on Climate Change. 2004. Available online: [http://unfccc.int/essential\\_background/library/items/3599.php?such=j&symbol=CHN/COM/1%20B#beg](http://unfccc.int/essential_background/library/items/3599.php?such=j&symbol=CHN/COM/1%20B#beg) (accessed on 2 April 2019).
4. National Development and Reform Commission (NDRC). Second National Communication on Climate Change of the People's Republic of China. 2012. Available online: [http://unfccc.int/essential\\_background/library/items/3599.php?rec=j&preref=7666#beg](http://unfccc.int/essential_background/library/items/3599.php?rec=j&preref=7666#beg) (accessed on 5 April 2019).
5. Tian, Y.; Zhang, J.B.; He, Y.Y. Research on Spatial-Temporal Characteristics and driving factor of agricultural carbon emissions in China. *J. Integr. Agric.* **2014**, *13*, 1393–1403. [[CrossRef](#)]
6. Ma, D.; Chen, W.Y. China's carbon emission peak path—Based on China TIMES model. *J. Tsinghua Univ. (Sci. Technol.)* **2017**, *57*, 1070–1075.
7. Lin, B.Q.; Fei, R.L. Regional differences of CO<sub>2</sub> emissions performance in China's agricultural sector: A malmquist index approach. *Eur. J. Agron.* **2015**, *70*, 33–40. [[CrossRef](#)]
8. Li, B.; Zhang, J.B.; Li, H.P. Research on spatial-temporal characteristics and affecting factors decomposition of agricultural carbon emission in China. *China Popul. Resour. Environ.* **2011**, *21*, 80–86.
9. Li, Z.J.; Sui, P.; Wang, X.L.; Yang, X.L.; Long, L.; Cui, J.X.; Yan, L.L.; Chen, Y.Q. Comparison of net GHG emissions between separated system and crop-swine integrated system in the North China Plain. *J. Clean. Prod.* **2017**, *149*, 653–664. [[CrossRef](#)]
10. Ju, H.; Marijn, V.; Lin, E.D.; Xiong, W.; Li, Y.C. The impacts of climate change on agricultural production systems in China. *Clim. Chang.* **2013**, *120*, 313–324. [[CrossRef](#)]
11. Yang, X.G.; Liu, Z.J.; Chen, F. The possible effect of climate warming on northern limits of cropping system and crop yield in China. *Agric. Sci. China* **2011**, *10*, 585–594. [[CrossRef](#)]
12. Yang, X.G.; Chen, F.; Lin, X.M.; Liu, Z.J.; Zhang, H.L.; Zhao, J.; Li, K.N.; Ye, Q.; Li, Y.; Lv, S.; et al. Potential benefits of climate change for crop productivity in China. *Agric. For. Meteorol.* **2015**, *208*, 76–84. [[CrossRef](#)]
13. Cook, R.J. Toward cropping system that enhance productivity and sustainability. *Proc. Natl. Acad. Sci. USA* **2006**, *103*, 18389–18394. [[CrossRef](#)] [[PubMed](#)]
14. Liu, Y.; Wang, E.L.; Yang, X.G.; Wang, J. Contributions of climatic and crop varietal changes to crop production in the North China Plain, since the 1980s. *Glob. Chang. Biol.* **2010**, *16*, 2287–2299. [[CrossRef](#)]
15. Jeong, S.J.; Ho, C.H.; Piao, S.L.; Kim, J.W.; Ciais, P.; Lee, Y.B.; Jhun, J.G.; Park, S.K. Effects of double cropping on summer climate of the North China Plain and neighbouring regions. *Nat. Clim. Chang.* **2014**, *4*, 615–619. [[CrossRef](#)]
16. Piao, S.L.; Ciais, P.; Huang, Y.; Shen, Z.H.; Peng, S.S.; Li, J.S.; Zhou, L.P.; Liu, H.Y.; Ma, Y.C.; Ding, Y.H.; et al. The impacts of climate change on water resources and agriculture in China. *Nature* **2010**, *467*, 43–51. [[CrossRef](#)] [[PubMed](#)]
17. Guo, J.P. Advances in impacts of climate change on agricultural production in China. *J. Appl. Meteorol. Sci.* **2015**, *26*, 1–11.
18. Des, P.L. *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*; Intergovernmental Panel on Climate Change (IPCC): Geneva, Switzerland, 2014; pp. 1–94.
19. Biswas, W.K.; Barton, L.; Carter, D. Global warming potential of wheat production in Western Australia: A life cycle assessment. *Water Environ. J.* **2008**, *22*, 206–216. [[CrossRef](#)]
20. Athena, B.; Regina, B. The world's first neutral coffee: Lessons on certification and innovation from a pioneer case in Costa Rica. *J. Clean. Prod.* **2018**, *189*, 485–501.
21. Li, Y.; Ge, Y.X.; Liang, Y. Relationship between agricultural carbon emissions and agricultural gross value of output. *Chin. J. Agric. Resour. Reg. Plan.* **2013**, *34*, 60–65.
22. Goglio, P.; Smith, W.N.; Grant, B.B.; Desjardins, R.L.; Gao, X.; Hanis, K.; Tenuta, M.; Campbell, C.A.; McConkey, B.G.; Nemecek, T.; et al. A comparison of methods to quantify greenhouse gas emissions of cropping systems in LCA. *J. Clean. Prod.* **2018**, *172*, 4010–4017. [[CrossRef](#)]
23. Godfray, H.C.J.; Beddington, J.R.; Crute, I.R.; Haddad, L.; Lawrence, D.; Muir, J.F.; Pretty, J.; Robinson, S.; Thomas, S.M.; Toulmin, C. Food security: The challenge of feeding 9 billion people. *Science* **2010**, *327*, 812–818. [[CrossRef](#)]
24. Dong, J.W.; Xiao, X.M.; Kou, W.L.; Qin, Y.W.; Zhang, G.L.; Li, L.; Jin, C.; Zhou, Y.T.; Wang, J.; Biradar, C.; et al. Tracking the dynamics of paddy rice planting area in 1986–2010 through time series Landsat images and phenology-based algorithms. *Remote Sens. Environ.* **2015**, *160*, 99–113. [[CrossRef](#)]

25. Li, X.; Mu, Y.Y.; Fu, W.G. Empirical analysis of factors affecting wheat production in China in recent ten years. *Rural Econ.* **2009**, *10*, 32–34.
26. Li, C.H. *Analysis on Market of Maize Seed in China*; China Agricultural University: Beijing, China, 2004; pp. 53–54.
27. Li, L.J. *Involving Regularities in Recent 50 Years and Future Trends in 2020 on Farming System in China*; China Agricultural University: Beijing, China, 2004; pp. 204–206.
28. Shang, Y.Y. *The Study on the Cost and Economic Benefits of BT Cotton in Our Country*; Huazhong Agricultural University: Wuhan, China, 2011; pp. 1–52.
29. Liu, J.S. *Analyses on the Distribution Pattern of the Crop-Straw Resource and the Status Quo of Its Application in China*; China Agricultural University: Beijing, China, 2005; pp. 1–34.
30. Wang, R.F.; Zhang, J.W.; Dong, S.T.; Liu, P. Present situation of maize straw resource utilization and its effect in main regions of China. *Chin. J. Appl. Ecol.* **2011**, *22*, 1504–1510.
31. National Development and Reform Commission (NDRC). The Provincial Greenhouse Gas Inventories. Available online: [http://www.chinadmd.com/file/puexsrrwv3owooir3arvepc\\_1.html](http://www.chinadmd.com/file/puexsrrwv3owooir3arvepc_1.html) (accessed on 18 April 2019).
32. Guo, D.S.; Huang, C.H. Spatial and temporal distribution of crop straw resources in past 10 years in China and its use pattern. *Southwest China J. Agric. Sci.* **2016**, *29*, 948–954.
33. Zhao, R.; Zhao, X.; Pu, C.; Liu, S.; Xue, J.; Zhang, X.; Chen, F.; Zhang, H. Meta-analysis on effects of residue retention on soil N<sub>2</sub>O emissions and influence factors in China. *Trans. Chin. Soc. Agric. Eng.* **2015**, *31*, 1–6.
34. Intergovernmental Panel on Climate Change (IPCC). *IPCC Guidelines for National Greenhouse Gas Inventories*; IGES: Hayama, Japan, 2006.
35. Wang, Y.J.; Wang, H.Y.; Gao, C.Y.; Wang, L.; Bi, Y.Y. Quantitative estimation method and its application to rice, wheat and corn straw residues left in field. *Trans. Chin. Soc. Agric. Eng.* **2015**, *31*, 244–250. (In Chinese)
36. Ha, N.; Feike, T.; Back, H.; Xiao, H.F.; Bahrs, E. The effect of simple nitrogen fertilizer recommendation strategies on product carbon footprint and gross margin of wheat and maize production in the North China Plain. *J. Environ. Manag.* **2015**, *163*, 146–154. [[CrossRef](#)]
37. Snyder, C.S.; Bruulsema, T.W.; Jensen, T.L.; Fixen, P.E. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. *Agric. Ecosyst. Environ.* **2009**, *133*, 247–266. [[CrossRef](#)]
38. West, T.O.; Marland, G. A Synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: Comparing tillage practices in the United States. *Agric. Ecosyst. Environ.* **2002**, *91*, 217–232. [[CrossRef](#)]
39. Riano, B.; Garcia-Gonzalez, M.C. Greenhouse gas emissions of an on-farm swine manure treatment plant-comparison with conventional storage in anaerobic tanks. *J. Clean. Prod.* **2015**, *103*, 542–548. [[CrossRef](#)]
40. Dace, E.; Muizniece, I.; Blumberga, A.; Kaczala, F. Searching for solutions to mitigate greenhouse gas emissions by agricultural policy decisions—Application of system dynamics modeling for the case of Latvia. *Sci. Total Environ.* **2015**, *527*, 80–90. [[CrossRef](#)] [[PubMed](#)]



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