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Study on the Vertical Linkage of Greenhouse Gas Emission Intensity Change of the Animal Husbandry Sector between China and Its Provinces

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Received: 30 May 2018; Accepted: 13 July 2018; Published: 16 July 2018



Abstract: China's carbon intensity (CI) reduction target in 2030 needs to be allocated to each province in order to be achieved. Thus, it is of great significance to study the vertical linkage of CI change between China and its provinces. The existing research on the vertical linkage focuses more on energy-related economic sectors in China; however, attention has not been paid to China's animal husbandry (AH) sector, although the role of the China's AH sector in greenhouse gas (GHG) reduction is increasingly important. This study firstly established a vertical linkage of change in greenhouse gas emission intensity of the animal husbandry sector (AHGI) between China and its 31 provinces based on the logarithmic mean Divisia index (LMDI) decomposing method from the perspective of combining emission reduction with economic development, and quantified the contributions of each province and its three driving factors of environmental efficiency (AHEE), productive efficiency (AHPE), and economic share (AHES) to reducing China's AHGI during the period of 1997–2016. The main results are: (1) The AHGI of China decreased from 5.49 tCO₂eq/10⁴ yuan in 1997 to 2.59 tCO₂eq/10⁴ in 2016, showing a 75.25% reduction. The AHGI in 31 provinces also declined and played a positive role in promoting the reduction of national AHGI, but there were significant inter-provincial differences in the extent of the contribution. Overall, the provinces with higher emission levels contributed the most to the reduction of China's AHGI; (2) The AHPE and AHEE factors in 31 provinces cumulatively contributed to the respective 68.17% and 11.78% reduction of China's AHGI, while the AHES factors of 31 provinces cumulatively inhibited the 4.70% reduction. Overall, the AHPE factor was the main driving factor contributing to the reduction of China's AHGI. In the future, improving the level of AHEE through GHG emissions reduction technology and narrowing the inter-provincial gap of the level of AHPE are two important paths for promoting the reduction of China's AHGI.

Keywords: LMDI; provincial contribution; emission reduction; decomposition; driving factor

1. Introduction

In 2015, at the “Paris Climate Conference”, the international community reached a legally-binding target of limiting the global temperature increase to no more than 2 °C [1]. To attain this target, global greenhouse gas (GHG) emissions must be reduced by 70% by 2050 [2]. Moreover, the implementation of effective emission reduction depends on the emission reduction policies and cooperation of different countries and their economic sectors [3]. China is the world's largest emitter of GHG and largest developing country [4]. The Chinese government had integrated emission reduction with economic development and promised the world that by 2030 the CO₂ emission intensity of its GDP would be

reduced by 60–65% compared to 2005 levels [5]. Meanwhile, this carbon intensity (*CI*) reduction target was allocated to each province in order to be achieved [6–8].

However, China's daunting *CI* reduction target is only intended for CO₂ emissions, with no clear quantitative target for non-CO₂ *GHG* emission reduction [4]. In fact, non-CO₂ *GHG* emissions are an important contributor to global warming [9], and the animal husbandry (*AH*) sector has been universally recognized as the primary source of global non-CO₂ *GHG* (CH₄ and N₂O) emissions [9–13]. Non-CO₂ emissions directly from the *AH* sector contribute approximately 19% to the current climate warming [14], but there is also very large potential for emission reduction [10,15–18]. China's *AH* sector emitted 445 million tons (2005) of non-CO₂ *GHG* (CO₂ equivalents), accounting for approximately 6% of China's total *GHG* emissions and 30% of the total non-CO₂ *GHG* emissions [19]. With the continuous rise in the per capita income level and the continuous progress in urbanization in China, the demand for livestock food in the residents' diet will continue to grow [20–24]. Thus, the *AH* sector will play a more important role in reducing *GHG* emissions in China. China's *CI* reduction targets need to be allocated to each province to achieve. Therefore, it is of great significance to conduct a study from the perspective of combining emissions reduction with economic development to uncover the vertical linkage of change in greenhouse gas emission intensity of animal husbandry sector (*AHGI*) between China and its provinces, and evaluate the driving factors of change in *AHGI*, which will provide an important basis for formulating provincial *AHGI* reduction targets for China.

Macro studies on global *GHG* emission intensity of *AH* sector have been reported. Caro's study found that it was vastly different among countries of the intensity of *GHG* emission per unit of economic output value in *AH* sector in 2010, with the highest intensity occurring in developing countries, and particularly Africa [11]. Bennetzen's study showed that *GHG* emissions per unit livestock product has decreased by approximately 44% since 1970 in global. The decoupling of livestock production and emissions had shown very large regional differences. While developing countries have contributed to the doubling of global livestock production, they have also contributed more *GHG* emissions [25,26]. However, more literature has focused on the study of the carbon footprint of animal products from a small scale perspective [27–32].

Existing studies on the vertical linkage and its drivers of *CI* between China and its provinces have mainly focused on energy-related CO₂ emission intensity [7,33–35], with the logarithmic mean Divisia index (*LMDI*) approach being the most commonly used decomposition method. Wang et al. [7] used the *LMDI* method to investigate the contribution given by China's 30 provinces to the decline of national *CI* from 1997 to 2008. The results showed that Liaoning, Heilongjiang, and Hebei have made greater contributions to the decline of national *CI*, the contribution of a province to the decline of national *CI* laid mainly in the promotion of its energy efficiency. Zhang et al. [33] applied the *LMDI* technique to explore the *CI* drivers in 29 Chinese provinces from 1995 to 2012. The results indicated that the overall *CI* of China decreased rapidly and energy intensity is the most significant driver for the decrease of *CI*. Tan et al. [34] examined the role of activities related to the electric power industry in reducing China's *CI* from 1998 to 2008 utilizing the *LMDI* technique. The results revealed that the provinces with higher emission levels contributed the most to China's improvements in *CI*. Wang et al. [35] established panel data models to explore the influencing factors of *CI* in China. The results showed that the economic level of activity was negatively correlated to *CI* on both national and regional levels. However, attention has not been paid to China's *AH* sector. The existing research literature related to China's *AH* sector have either focused more on the macro horizontal perspective on the regional characteristics of emissions and intensity in various provinces [36–39] and the decomposition of the drivers for carbon emissions [39–43], or on the micro perspective on the differences in the carbon footprint between different feeding methods [44,45] and different animal products [46–48]. Meng et al. [36] estimated the *AH*'s *GHG* emissions of China's different livestock division by life circle assessment method. The results revealed that there were higher emissions of CO₂ equivalent of livestock in agricultural areas than in pastoral areas, but the emission intensity was lower than in pastoral areas. Yao et al. [37] used the same method to obtain a conclusion that high livestock carbon emissions areas were mostly

located in prairie areas or major grain producing areas of China. Luo et al. [38] explored the spatial and temporal heterogeneity of CO₂ emission intensity in China's agricultural sector and found that Central China had the highest agricultural CO₂ emission intensity than Western and Eastern China. Tian et al. [39,41] studied regional characteristics and driving factor of agricultural carbon emissions in China with *LMDI* model. The results showed that the traditional agricultural provinces, especially the major crop production areas were the main emission source regions. The efficiency factor, labor factor, and industry structure factor had strong inhibitory effects on China's agricultural carbon emissions, while the economy factor had a strong positive effect. Yao et al. [43] conducted a decomposition study on the factors affecting the changes of *AH* carbon emissions based on the *LMDI* method and found that *AH* production efficiency improvement was the most important factor to restrain the sustained growth of the *AH* carbon emissions. Xiong et al. [40,42] used the same decomposition method to draw conclusions that the economy factor was the critical factor to promote the increase in agricultural carbon emissions in Xinjiang province of China, while the main inhibiting factor was the efficiency factor. These research results have enriched the body of work on *GHG* emissions reduction in China's *AH* sector from different perspectives. However, the above-mentioned studies have mostly treated both the *AH* sector and crop farming sector as part of the agricultural sector and neglected the particularity of the *AH* sector. In fact, first of all, the *AH* sector differs from the crop farming sector in its production methods, the economic benefits, the generation mechanism of *GHG*, and the emission reduction strategies; secondly, studying the *GHG* emissions and intensity of the *AH* sector from the horizontal perspective of provinces cannot reveal the vertical linkage between the partial and overall changes. More importantly, vertical linkage is an important basis for the Chinese government to formulate *AHGI* reduction targets for all provinces.

Our work is different from the above research in the following respects: First, this study estimated the *GHG* emissions (CO₂ equivalent) per unit of *AH* economic output value in China and its 31 provinces from 1997 to 2016. Second, we established a vertical linkage of change in *AHGI* between china and its 31 provinces from the perspective of combining emissions reduction with economic development, and separated the factors affecting the change of *AHGI* into environmental efficiency, productive efficiency and economic share. We used the *LMDI* decomposition method to support our study, because it was proven to be a feasible tool in achieving complete decomposition without residuals, allowing subgroup estimations to be aggregated in a consistent manner and performing attribution analyses on the impact of subcategory estimates [49]. Third, we quantified the contributions of each province and its three driving factors to the change of China's *AHGI* during the period of 1997–2016. This study aims to provide a reference for formulating provincial *AHGI* reduction targets for the Chinese government in a more scientific and reasonable way.

2. Materials and Methods

2.1. Estimation of *AHGI*

This study adopted the *GHG* emissions (CO₂ equivalent) per unit of the *AH* economic output value as the *AHGI* indicator. The formula is shown as follows:

$$AHGI = AHGE / AHGDP \quad (1)$$

where *AHGI*, *AHGE*, and *AHGDP* denote greenhouse gas emission intensity of animal husbandry sector (in tCO₂eq/10⁴ yuan), the sum of greenhouse gas emissions from animal husbandry sector (in tCO₂eq) and economic output value of animal husbandry sector (10⁴ yuan), respectively. The *AHGI* of each province is calculated similarly.

According to the "Guidelines for Compiling Low-carbon Development and Provincial Greenhouse Gas Inventory" issued by the Department of Climate Change of the National Development and Reform Commission of China (NDRCC) in 2013 [50], the provincial *GHG* inventory for *AH* includes two parts: CH₄ and N₂O emissions in animal manure management and CH₄ emissions from animal enteric

fermentation in this study. Due to the vast territory of China, the climate and soil conditions in different geographical regions have different effects on CH₄ and N₂O emissions during the storage and management of animal manure, so the emissions factors of different emission sources also adopt the recommended values of the sub-regions in China by the guidelines. The formula is shown as follows:

$$AHE_{CH_4,manure} = (\sum AP_i \times EF_{CH_4,manure,i}) \times 10^{-3} \quad (2)$$

$$AHE_{N_2O,manure} = (\sum AP_i \times EF_{N_2O,manure,i}) \times 10^{-3} \quad (3)$$

$$AHE_{CH_4,enteric} = (\sum AP_i \times EF_{CH_4,enteric,i}) \times 10^{-3} \quad (4)$$

$$AHGE = [(AHE_{CH_4,manure} + AHE_{CH_4,enteric}) \times 25 + AHE_{N_2O,manure} \times 298] \quad (5)$$

where $AHE_{CH_4,manure}$ represent the sum of the CH₄ caused by the manure management, in t CH₄/year; $AHE_{N_2O,manure}$ represent the sum of the N₂O emissions caused by the manure management, in t N₂O/year; $AHE_{CH_4,enteric}$ represents the sum of the CH₄ emissions caused by enteric fermentation, in t CH₄/year; AP_i is the amount of annual feeding of animal i in head; i include cattle, buffalo, dairy cows, horses, donkeys, mules, camels, goats, sheep, pigs and poultry in China; Non-ruminant animals, especially poultry, which have small body weights, produce low CH₄ emissions. Therefore, CH₄ emissions from non-ruminant animals are not included in animal enteric fermentation emissions; $EF_{CH_4,manure,i}$ is the CH₄ emission factor of manure management of animal i in kg CH₄/head/year, as shown in Table A1; and $EF_{N_2O,manure,i}$ is the N₂O emission factor of manure management of animal i in kg N₂O/head/year, as shown in Table A2; $EF_{CH_4,enteric,i}$ is the CH₄ emission factor of enteric fermentation of animal i , in kg CH₄/head/year. The guidelines give the methane emission factors for enteric fermentation of different animals in different feeding modes (large-scale farming, farmer raising, and grazing) in China. However, it is difficult to obtain the provincial data of livestock activity by distinguishing different feeding methods, so the CH₄ emission factor for animal enteric fermentation in this study uniformly adopted IPCC recommendations [51] as shown in Table 1, in kg CH₄/head/year. In order to facilitate the summation of total greenhouse gas emissions and comparative analysis in each province, we converted CH₄, N₂O to CO₂ equivalent. 25 and 298 are the relative molecular warming forcing of CH₄ and N₂O in a 100-year horizon, respectively [52]. $AHGE$ represent the sum of greenhouse gas emissions from animal husbandry sector, in tCO₂eq. The $AHGE$ of each province is calculated similarly. The total amount of $AHGE$ in China is equal to the sum of total $AHGE$ in 31 provinces.

Table 1. The CH₄ emission factor for animal enteric fermentation (kg CH₄/head/year).

Livestock	Emission Factor	Livestock	Emission Factor	Livestock	Emission Factor
Buffalo	55	Mule	10	Sheep	5
Dairy cow	61	Camel	46	Goat	5
Cattle	47	Horse	18	Pig	1
Donkey	10				

2.2. Decomposition of AHGI

2.2.1. Decomposing Process

As the total $AHGE$ and $AHGDP$ from China are generated by the AH sectors of the 31 provinces across the country, this study firstly established a vertical linkage of the $AHGI$ calculation between the national and provincial AH sectors. The calculation is shown as follows:

$$AHGI = \frac{AHGE}{AHGDP} = \frac{\sum_{i=1}^{31} AHGE_i}{\sum_{i=1}^{31} AHGDP_i} \quad (6)$$

The existing studies have shown that changes in China's *CI* have been impacted not only by the changes of *CI* of provinces but also by changes of the *GDP* share of the provinces in the national *GDP* [7,34]. As China's *AH* sector is one of the economic production sectors, changes in its intensity should also comply with the above assertion. Therefore, the factors that drive the changes in *AHGI* in the country are divided into two categories: the *AHGI* of each province and its share of *AHGDP* in the national *AHGDP*. Formula (6) is decomposed as follows:

$$AHGI = \sum_{i=1}^{31} \frac{AHGE_i}{AHGDP_i} \frac{AHGDP_i}{AHGDP} \quad (7)$$

However, the changes of *AHGI* in various provinces are also impacted by different factors. The differences in resource endowments, development methods, technical levels, and supporting policies for the development of *AH* in various provinces in China determine the inter-provincial differences in the level of *AH* production [53]. However, this regional difference can be summarized as the difference in the level of *GHG* emissions and economic benefits of each province's *AH* sector from the perspective of the *AHGI* calculation formula. The most perfect scenario for the development of *AH* sector is to reduce the amount of *GHG* emissions while increasing the economic benefits of livestock. This is also a sustainable path for *AH* sector to mitigate and adapt to climate change [54,55]. Therefore, this study classifies the driving factors that drive the changes of *AHGI* in 31 provinces into two categories: the animal husbandry environmental efficiency (*AHEE*) factor (*GHG* emissions per unit of production factors; the lower the former is, the higher the environmental efficiency) and the animal husbandry productive efficiency (*AHPE*) factor (the input of production factors per unit of *AH* output value; the lower the former is, the higher the productive efficiency). Formula (7) is, therefore, further broken down as follows:

$$AHGI = \sum_{i=1}^{31} \frac{AHGE_i}{AHBS_i} \frac{AHBS_i}{AHGDP_i} \frac{AHGDP_i}{AHGDP} = \sum_{i=1}^{31} AHEE_i AHPE_i AHES_i \quad (8)$$

where $AHBS_i$ denotes the input of production factors in the *AH* sector (it can be replaced with the breeding scale of livestock) in the *i*th province of China. To make it easier for comparing different types of livestock in different provinces, the equivalent standardized cattle index is introduced to estimate the total provincial livestock population. The estimation method and parameters are cited from [56], one cattle is a standard unit, and the reference parameters for converting other livestock to standard cattle units are shown in Table 2. $AHEE_i$, $AHPE_i$ and $AHES_i$ are the three drivers of *AHGI* in each province, indicating the *i*th province's *AHEE* (*GHG* emissions per unit of livestock), *AHPE* (livestock input per unit of *AHGDP*), and *AHES* (the provincial proportion of the *AHGDP* in the national *AHGDP*).

Table 2. The reference parameters for converting other livestock to standard cattle units.

Livestock	Parameters	Livestock	Parameters	Livestock	Parameters
Buffalo	1.3	Mule	1	Pig	0.3
Dairy cow	2.6	Camel	1.75	Poultry	0.01
Horse	0.8	Goat	0.2		
Donkey	0.6	Sheep	0.25		

2.2.2. Calculating Method

After decomposing the *AHGI* into the above three driving factors, as shown in Equation (8), next we will present the method used to calculate. Referring to Ang [49], the change of *AHGI* can be decomposed using an additive *LMDI* method as follows:

$$\ln \frac{AHGI_T}{AHGI_0} = \Delta AHGI = AHGI_T - AHGI_0 = \Delta AHEE + \Delta AHPE + \Delta AHES \quad (9)$$

where T represents the end of the period; 0, the start of the period; $\Delta AHGI$, the change of *AHGI* in China; $\Delta AHEE$, the contribution of *AHEE* factor; $\Delta AHPE$, the contribution of *AHPE* factor; and $\Delta AHES$, the contribution of *AHES* factor. $\Delta AHEE$, $\Delta AHPE$ and $\Delta AHES$ can be calculated by:

$$\Delta AHEE = \sum_{i=1}^{31} w_i^{AH*} \ln(AHEE_{i,T} / AHEE_{i,0}) \quad (10)$$

$$\Delta AHPE = \sum_{i=1}^{31} w_i^{AH*} \ln(AHPE_{i,T} / AHPE_{i,0}) \quad (11)$$

$$\Delta AHES = \sum_{i=1}^{31} w_i^{AH*} \ln(AHES_{i,T} / AHES_{i,0}) \quad (12)$$

where w_i^{AH*} in the above equations is the logarithmic weighting scheme specified in the following:

$$w_i^{AH*} = L(w_{i,0}^{AH}, w_{i,T}^{AH}) / \sum_{i=1}^{31} L(w_{i,0}^{AH}, w_{i,T}^{AH}) \quad (13)$$

$$L(w_{i,0}^{AH}, w_{i,T}^{AH}) = (w_{i,T}^{AH} - w_{i,0}^{AH}) / \ln(w_{i,T}^{AH} / w_{i,0}^{AH}) \quad (14)$$

$$w_i^{AH} = AHEE_i AHPE_i AHES_i / \sum_{i=1}^{31} AHEE_i AHPE_i AHES_i \quad (15)$$

2.3. Data Collection and Processing

This study involves 31 provinces in mainland China and the study period spans from 1997 to 2016. Considering the feeding cycles which are more than one year of cattle, buffalo, dairy cows, horses, donkeys, mules, goats, and sheep [51], the data for the annual total livestock raised is denoted by the year-end inventory data. The feeding cycle for poultry (55 days) and pig (200 days) is less than one year [37], and the data for the annual total is expressed by the current year's slaughter volume [53]. The time-series livestock activity data of each province used in this paper are obtained from the China Rural Statistical Yearbook (1998–2017). The time-series livestock economic output data of every province are obtained from the China Statistical Yearbook (1998–2017) and then converted to outputs in constant 1997 price. All abbreviations used in this study are described in Table A3.

As China's *CI* reduction target is a long-term target, until 2030, this study took 1997 as the baseline period and 2016 as the comparison period as the basis for this research.

3. Results and Discussion

3.1. Changes of *AHGI* in China and Its Provinces

From a national perspective, the *AHGI* of China decreased from 5.49 tCO₂eq/10⁴ yuan in 1997 to 2.59 tCO₂eq/10⁴ in 2016, showing a 75.25% reduction within this period, as shown in Figure 1. This is in line with the finding by Caro [11] that the *AHGI* in global developing countries has been on the decline.

From a provincial perspective, compared 2016 with 1997, the *AHGI* were all decreasing in 31 provinces, but the extent of the decrease varied significantly among the provinces. Figure 2 shows that the *AHGI* in 15 provinces (including Hainan, Heilongjiang, Yunnan, Anhui, Henan, Guizhou, Shanxi, Hebei, Shaanxi, Guangxi, Xinjiang, Inner Mongolia, Jilin, Shandong and Sichuan) declined faster than 75.25% (the aggregate reduction in *AHGI* of China), while the *AHGI* in other 16 provinces declined slower than 75.25%. Hainan's *AHGI* declined from 6.68 tCO₂eq/10⁴ yuan to 1.76, which was the largest decline (133.28%) of all the provinces. Liaoning's *AHGI* declined from 3.11 tCO₂eq/10⁴ yuan to 2.54, which was the smallest decline (19.91%) of all the provinces.

According to the above changing trends of the *AHGI* in China and its provinces during the period of 1997–2016, this paper argues that these reductions of the *AHGI* are due to two reasons. On the one hand, the *AHGE* has been growing slowly with the transformation of China's *AH* production from an extensive mode to an intensive mode during the study period. On the other hand, the *AHGDP* has been growing rapidly due to advancement of livestock feeding and management techniques, and standardization, scale, and organizational level of *AH* production. However, there are significant inter-provincial differences in resource endowments, development methods, technical levels, and supporting policies for the development of *AH*, which made the extent of reduction different among the 31 provinces.

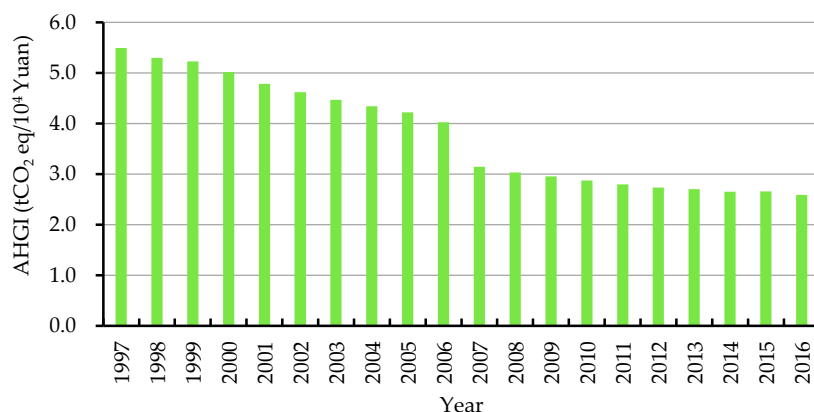


Figure 1. Changes of *AHGI* in China during the period 1997–2016.

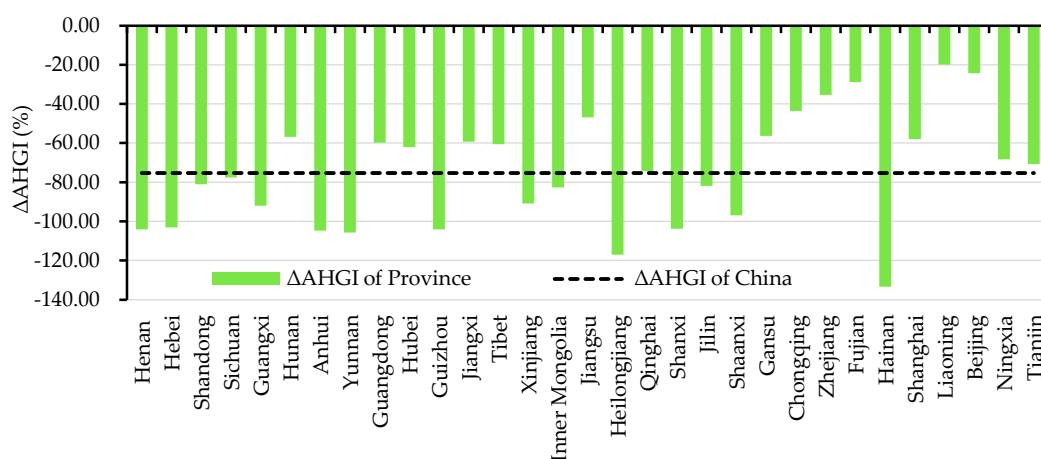


Figure 2. Changes of *AHGI* in 31 provinces, comparing 2016 with 1997.

It was reported that 445 million tCO₂eq were emitted from animal enteric fermentation and manure management in the Second National Communication on Climate Change (NCCC) issued by the Chinese government in 2005, using 21 and 310 as the values for Global Warming Potential (GWP)

of CH₄ and N₂O [19]. Our estimates of 503 million tCO₂eq emissions for the corresponding year are comparable to these data and differences can be attributed to different GWP (this paper used IPCC Fourth Assessment Report value (25 and 298 of CH₄ and N₂O)) [52]. However, this will not affect the overall research results and, thus, the estimated value of AHGI used in this study is reliable.

3.2. Analysis of Provincial Contributions to the Reduction of China's AHGI

Compared 2016 with 1997, China's AHGI showed a 75.25% reduction. The decomposition results (Table 3, Figure 3) of provincial contributions from the LMDI model showed that all provinces played a positive role in promoting the 75.25% reduction of China's AHGI, but there were significant differences among provinces in the extent of the contribution. The top 10 contributing provinces were Henan (−7.11%), Hebei (−5.58%), Shandong (−5.55%), Sichuan (−5.29%), Guangxi (−4.81%), Hunan (−4.29%), Anhui (−4.24%), Yunnan (−3.31%), Guangdong (−3.23%), and Hubei (−2.82%), while the bottom ten contributing provinces, in descending order, were Tianjin (−0.06%), Ningxia (−0.14%), Beijing (−0.34%), Liaoning (−0.35%), Shanghai (−0.58%), Hainan (−0.59%), Fujian (−1.01%), Zhejiang (−1.01%), Chongqing (−1.12%), and Gansu (−1.25%). Considering the largest and smallest contributors, Henan contributed approximately 119 times as much as Tianjin.

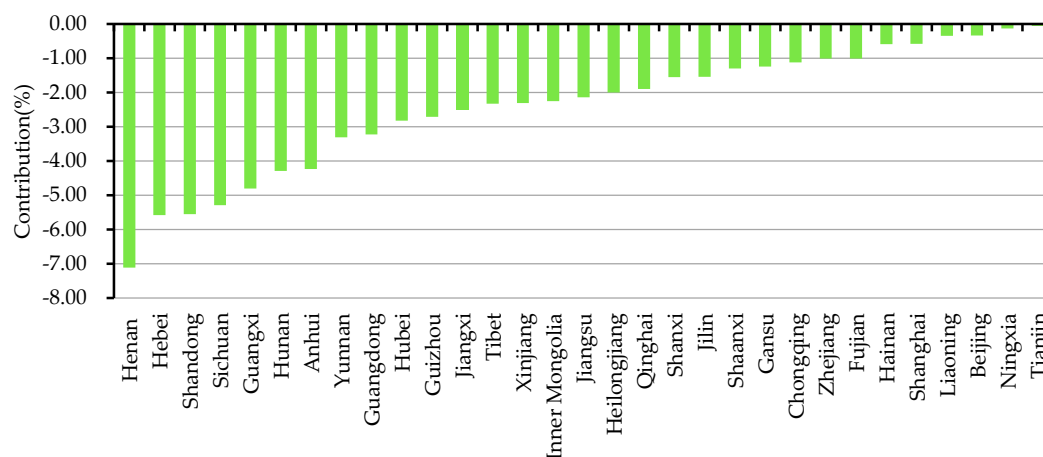


Figure 3. Provincial contributions to the reduction of China's AHGI, comparing 2016 with 1997.

The study period witnessed a decline of the AHGI in all provinces, which contributed positively to the reduction in national AHGI. However, the results of linear regression between the reduction of AHGI in 31 provinces and the contributions of 31 provinces to the country showed that the R² value was only 0.1543 (Figure 4). This showed that there was an inconsistency between the extent of the actual reduction of AHGI in each province and its contributions to the country. Taking Hainan and Hunan as an example, the actual decline in AHGI in Hainan (133.28%) is the highest in 31 provinces, but Hainan's contribution (0.59%) to the reduction of China's AHGI is ranked the reciprocal sixth position among all provinces. The decline in AHGI in Hunan (56.74%) is only ranked 24th, but its contribution (4.29%) is ranked sixth among all provinces. The reason is that the proportion of AH scale, GHG emissions, and share of the output value in Hainan are relatively small relative to the entire country (0.75%, 0.75%, and 1.11% in 2016, respectively). This is reflected in the LMDI decomposition model of this study as a smaller weighting factor. Consequently, the actual decline in AHGI in Hainan has less impact on the decline in national AHGI. Likewise, the proportion of the above-mentioned three factors in Hunan are relatively large in the country (5.21%, 5.68%, and 6.27% in 2016), which makes Hunan have a greater impact on the decline in national AHGI. Similar provinces include Sichuan, Guangdong, Shaanxi, and Shanxi. This indicates that the proportion of the provincial AH scale, GHG emissions, and share of economic output value in the country are important for measuring their contributions.

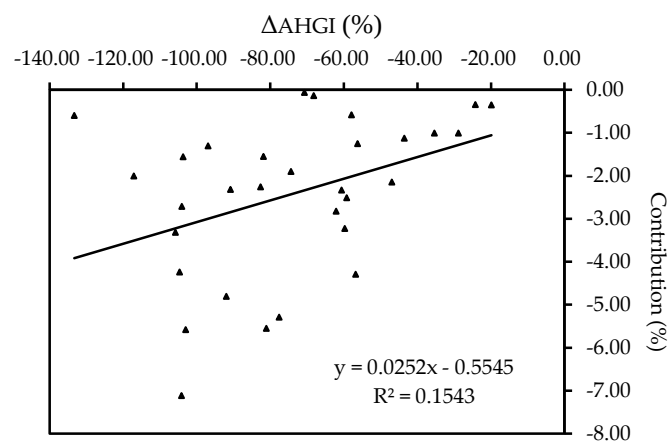


Figure 4. The scatter diagram of the regression variables between the change of *AHGI* in 31 provinces and the contributions of the 31 provinces to the country.

In terms of the regional characteristics of animal husbandry production, among the top 10 contributing provinces, Henan, Hebei, Shandong, Sichuan, Hunan, Anhui, and Hubei are the major grain-producing regions in China, and they are also the major livestock breeding provinces in the agricultural areas of China. There are abundant feeding resources from crops, and the standardization, scale, and organizational level of *AH* production are high in these provinces. They are currently China's main base for producing livestock such as live pigs, beef cattle, and poultry [53,57], and shoulder the important function of supplying animal-based food to the country; the top ten provinces cumulatively contributed to a reduction of 46.22% in China's *AHGI*, accounting for 61.42% of the total contributions by 31 provinces. Meanwhile, for these provinces in 2016, it accounted for approximately 55.16%, 55.01%, and 61.05% of the scale of livestock breeding, *AHGE*, and *AHGDP*, respectively, of the corresponding total amount in the country.

Among the bottom ten contributing provinces, Beijing, Tianjin, Shanghai, and Chongqing are the four municipalities directly governed by the Chinese government. Zhejiang, Fujian, Hainan, and Liaoning are the coastal provinces of Eastern China. The above eight provinces and municipalities are the major consumers of animal-based food in China. They are densely populated, with relatively high levels of urbanization and industrialization, and their *AH* production is dominated by modern urban *AH* [37] and the proportion of *AHGDP* in the *GDP* is relatively low; in contrast, Gansu and Ningxia are in the northwest agro-pastoral ecotone of China, with a relatively fragile ecological environment, and strong resource and environment constraints for the development of *AH*, and the total output from *AH* is not large [24,58]. The bottom ten provinces cumulatively contributed to a reduction of only 6.45% in China's *AHGI*, accounting for 8.57% of total provincial contributions. Meanwhile, for these provinces in 2016, it accounted for approximately 14.39%, 12.97% and 13.07% of the scale of livestock breeding, *AHGE*, and *AHGDP*, respectively, of the corresponding total amount in the country.

The remaining 11 provinces cumulatively contributed to a reduction of 22.58% in China's *AHGI*, accounting for 30.01% of the provincial total contributions. Among these provinces, Inner Mongolia, Xinjiang, Qinghai, and Tibet are the traditional pastoral areas, with a long development history of *AH*. With rich resources in natural grassland, the focus is primarily on the development of grassland *AH*. They are currently China's major breeding base for cattle, sheep, horses, and other herbivorous livestock [58]; on the other hand, Jiangxi, Heilongjiang, Jiangsu, and Jilin are the main grain-producing regions in China and are rich in feed resources, the focus is primarily on the development of *AH* in agricultural areas. For these provinces in 2016, it accounted for approximately 30.45%, 32.02%, and 25.88% of the scale of livestock breeding, *AHGE*, and *AHGDP*, respectively, of the corresponding total amount in the country.

The discussion above showed that there was an inconsistency between the extent of the actual reduction of *AHGI* in each province and their contributions to the country, China's progress in reducing *AHGI* was mainly made by provinces with a large *GHG* emissions from *AH*. The conclusion drawn by this study that provinces contributed to the reduction in national *CI* is consistent with the conclusion drawn by Tan's research [34] on the Chinese power industry and Wang's research [7] on China's economic development. The revelation for us is that the government should comprehensively consider the actual decline of *AHGI* in all provinces and its contributions to the reduction in national *AHGI* in formulating provincial *AHGI* reduction targets for China. Each province should not be required to have the same decline in *AHGI* as in the national *AHGI*. In addition, priority should be given to assessing the emission reduction responsibilities and impact in large *AH* provinces, because while these provinces emit a larger share of *AHGE*, they also supply a larger share of animal-based food and create a larger share of *AHGDP* for the country. More importantly, these provinces are also major contributors in reducing the *AHGI* of China.

3.3. Analysis of Driving Factors' Contributions to the Reduction of China's *AHGI*

The decomposition results of three driving factors' contributions from the *LMDI* model (Table 3, Figure 5) indicate that there is a complex linkage among the three driving factors: *AHEE*, *AHPE*, and *AHES*. Three driving factors comprehensively determine the reduction of China's *AHGI* through two different contributions of positive promotion and negative inhibition, but the way the three driving factors exert impact and the extent of their contributions vary significantly among provinces. Overall, the *AHPE* factors of all provinces are the main factors contributing to the reduction of China's *AHGI*, cumulatively contributing to 68.17%, followed by the *AHEE* factors (11.78%). The *AHES* factors of various provinces have the nature of a "double-edged sword", having cumulatively inhibited the 4.70% reduction of China's *AHGI*.

Table 3. The decomposition results of vertical linkage of changes in *AHGI* between China and its provinces based on the *LMDI* model.

Province	The Decomposition Results of Three Driving Factors (%)				Province	The Decomposition Results of Three Driving Factors (%)			
	$\Delta AHEE$	$\Delta AHPE$	$\Delta AHES$	Total		$\Delta AHEE$	$\Delta AHPE$	$\Delta AHES$	Total
China	−11.78	−68.17	4.70	−75.25	Jiangsu	−0.15	−1.05	−0.94	−2.15
Henan	−2.17	−6.93	1.99	−7.11	Heilongjiang	−0.34	−3.29	1.63	−2.00
Hebei	−0.52	−4.96	−0.09	−5.58	Qinghai	0.07	−1.82	−0.15	−1.90
Shandong	−1.25	−4.62	0.32	−5.55	Shanxi	−0.29	−1.25	−0.01	−1.55
Sichuan	−0.47	−5.67	0.85	−5.29	Jilin	−0.15	−1.97	0.57	−1.55
Guangxi	−1.17	−3.40	−0.23	−4.81	Shaanxi	−0.23	−1.13	0.06	−1.31
Hunan	−0.27	−2.96	−1.05	−4.29	Gansu	0.02	−1.36	0.10	−1.25
Anhui	−1.43	−2.54	−0.27	−4.24	Chongqing	−0.16	−0.58	−0.38	−1.12
Yunnan	−0.53	−4.74	1.96	−3.31	Zhejiang	−0.08	−0.26	−0.66	−1.01
Guangdong	−0.26	−2.08	−0.88	−3.23	Fujian	−0.44	−0.03	−0.54	−1.01
Hubei	−0.52	−2.11	−0.19	−2.83	Hainan	−0.30	−0.72	0.43	−0.59
Guizhou	−0.44	−2.90	0.63	−2.71	Shanghai	0.07	−0.24	−0.41	−0.58
Jiangxi	−0.66	−1.29	−0.56	−2.51	Liaoning	−0.07	−0.47	0.19	−0.35
Tibet	0.10	−1.90	−0.53	−2.33	Beijing	0.04	−0.11	−0.27	−0.34
Xinjiang	−0.22	−3.00	0.91	−2.31	Ningxia	0.06	−0.44	0.25	−0.14
Inner Mongolia	0.02	−4.14	1.86	−2.26	Tianjin	−0.02	−0.20	0.16	−0.06

Note: Positive and negative values in the table represent the contribution of two different properties, the positive value is the contribution to inhibit the reduction of China's *AHGI*, while negative value is the contribution to promote the reduction of China's *AHGI*.

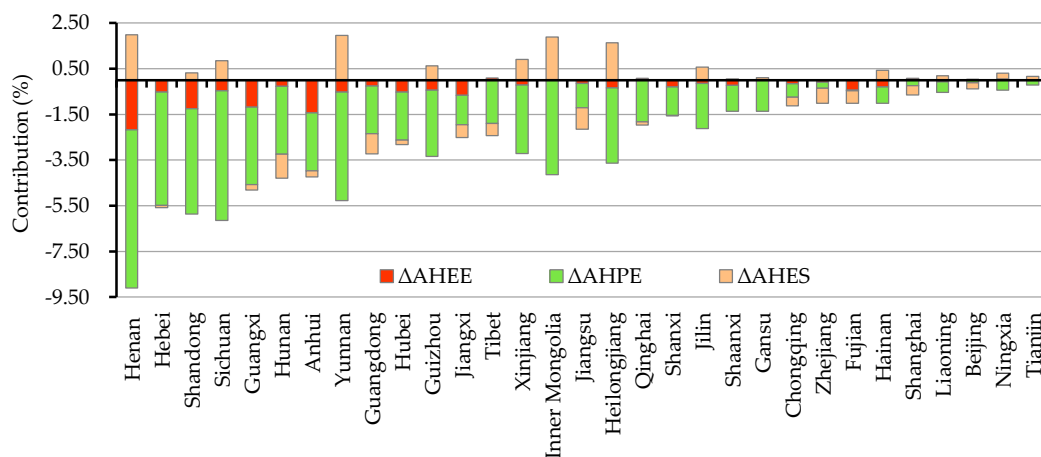


Figure 5. Driving factors' contributions to the reduction of *AHGI* in each province, comparing 2016 with 1997.

3.3.1. AHPE Factor

With the transformation of China's *AH* production from an extensive mode to an intensive mode and the continuous improvement in the productivity of *AH*, the livestock input for China's 10,000 yuan of *AHGDP* dropped from the 5.98 standard cattle in 1997 to 3.17 standard cattle in 2016, and the level of *AHPE* increased about 63.47%. The livestock input for 10,000 yuan of *AHGDP* in all provinces of China also decreased (Figure 6). As a result, the *AHPE* factors of all provinces contributed positively to the reduction of *AHGI*. Among them, Henan's contribution (6.93%) was the highest, and Tianjin's contribution (0.20%) was the lowest. Overall, the *AHPE* factors of all provinces cumulatively contributed to a reduction of 68.17% in *AHGI* of China. However, due to the vast territory of China, there are significant regional differences among provinces in terms of the economic benefits of livestock products. Taking 2016 as an example, the livestock input for 10,000 yuan of *AHGDP* for China's frontier grassland pastoral areas (Tibet (28.59), Qinghai (15.20), Gansu (7.72), Xinjiang (7.20), Inner Mongolia (4.75), Ningxia (4.63), Guizhou (4.18), Yunnan (4.14), and Guangxi (3.73)) was higher than the national average (3.17) due to the comprehensive impact of the productivity level of *AH*, the distance to the consumer market of livestock products, and the national dietary habits [24]. On the other hand, the livestock input for 10,000 yuan of *AHGDP* for China's central and eastern regions (Henan (2.55), Anhui (2.47), Hubei (2.62), (Jiangsu (2.40), Zhejiang (2.35), and Tianjin (1.46)), which are close to the consumer market, have a larger scale of *AH*, and a higher intensity, was lower than the national average. This finding shows that the *AHPE* factor of each province is the leading factor in promoting the reduction of China's *AHGI*, but there are still large gaps among provinces. Overall, the productive efficiency level of China's frontier grassland pastoral areas is lower than that of central and eastern provinces.

3.3.2. AHEE Factor

The *GHG* emissions per unit standard cattle in China dropped from 0.92 tCO₂eq in 1997 to 0.82 tCO₂eq in 2016, and the level of *AHEE* increased about 11.51%. However, the changes of *AHEE* levels were different in 31 provinces (Figure 6), as a result, the *AHEE* factors of each province have both positive and negative contributions in reducing the China's *AHGI*. Among 31 provinces, the *GHG* emissions per unit standard cattle in these seven provinces (Tibet (1.16 increased to 1.20), Qinghai (1.05 increased to 1.08), Inner Mongolia (0.895 increased to 0.899), Ningxia (0.81 increased to 0.89), Gansu (0.89 increased to 0.90), Beijing (0.62 increased to 0.70), and Shanghai (0.59 increased to 0.75)) increased slightly, which cumulatively inhibited the 0.38% reduction of China's *AHGI*. On the one hand, Shanghai and Beijing are currently China's cities with relatively developed economy and urbanization among the seven provinces. As the demand of urban residents for milk consumption

continues to grow, the proportion of dairy cows in their livestock breeding structure has been increasing, resulting in an increase in emissions. On the other hand, Tibet, Qinghai, Inner Mongolia, Ningxia, and Gansu are China's traditional grassland pastoral regions, so their livestock breeding focuses mainly on cattle, sheep, horses, and other ruminant livestock. The methane emissions generated by the enteric fermentation of these animals are relatively high [12,59]. As these livestock breeding scales increase, so will the amount of emissions. The GHG emissions per unit standard cattle in the remaining 24 provinces have been on the decline, which cumulatively promoted the 12.16% reduction of China's AHGI. Overall, the AHEE factors of all provinces only cumulatively promoted the 11.78% reduction of China's AHGI. This indicates that the reduction of China's AHGI during the study period depended more on the substantial increase in the AHPE of all the provinces than on the improvement of AHEE.

3.3.3. AHES Factor

The AHGDP of China continued to grow from 713.33 billion yuan in 1997 to 1707.90 billion yuan in 2016, which is a relative increase of 87.31%. The 15 provinces of Henan, Yunnan, Inner Mongolia, Heilongjiang, Xinjiang, Sichuan, Guizhou, Jilin, Hainan, Shandong, Ningxia, Liaoning, Tianjin, Gansu, and Shaanxi all saw an increase in their AHES (Figure 6). However, the increase in AHES of these provinces was significantly faster than the increase in AHEE, which inevitably led to a rapid increase in carbon emissions when they expanded the scale of AH production. Therefore, the AHES factors of these provinces all inhibited the reduction of China's AHGI. However, the AHES in the remaining 16 provinces was on the decline. As the AHES declined, so did the GHG emissions. Therefore, the AHES factors of these provinces all promoted the reduction of China's AHGI. However, due to the difference in the base of AHGDP in each province, the increase and decrease based on the AHGDP were also different. As a result, the contribution from the AHES factors of different provinces varied. Overall, the cumulative negative contribution from the AHES factors of 15 provinces, including Henan, was 11.88%, while the AHES factors of the other 16 provinces, including Anhui, cumulatively made a positive contribution of 7.18%. In all, the AHES factors of all provinces cumulatively inhibited a 4.70% reduction of China's AHGI. This means that, in terms of contributions by each province to the reduction in China's AHGI, the AHES factor is a weight with the nature of a "double-edged sword", and can decrease or increase the contribution value of each province. If a province can expand its scale of AH production and also improve the level of AHEE, there will be a greater increase in the AHGDP of the province, and a greater positive contribution to the reduction in national AHGI. If not, then the result will be the opposite.

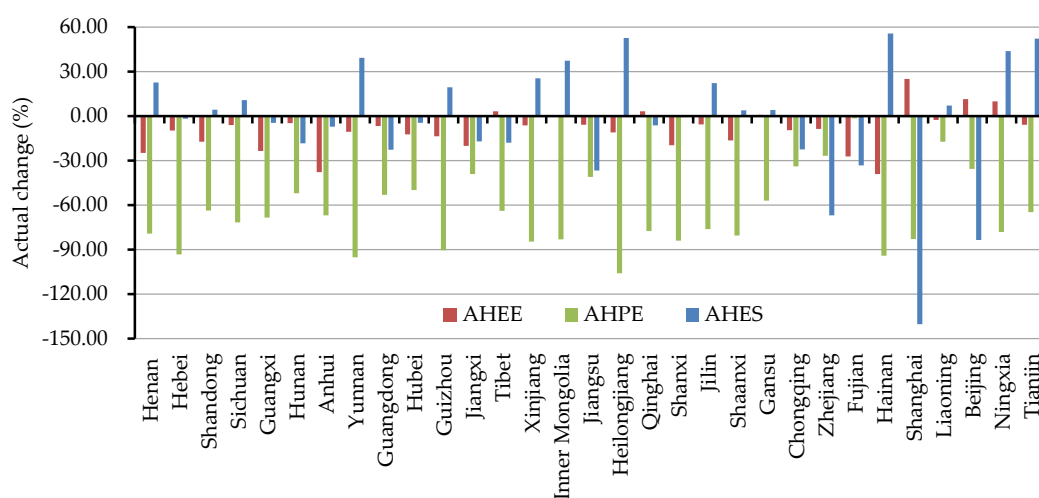


Figure 6. Actual change of three driving factors in each province of China, comparing 2016 with 1997.

Currently, China is the foremost producer of *GHG* emissions and largest developing country in the world. China is also a major producer of livestock products in the world. China's *AH* sector not only shoulders responsibility for supplying livestock products to more than 1.3 billion people, but also takes care of the livelihoods of more than 200 million farmers and herdsmen. With the continuous rise in the per capita income level and the continuous progress of urbanization in China, the demand for livestock food in the residents' diet will continue to increase. Therefore, it is an objective need and an inevitable trend for various provinces in China to expand the scale of breeding and pursue economic benefits of *AH*. In terms of the driving factors that contribute to the reduction of China's *AHGI* during the research period, *AHPE* factors played a major role. However, in terms of the reduction responsibilities of the *AH* sector in China, the development of *AH* should take into account both economic and environmental benefits. The most perfect scenario for the development of *AH* sector is to reduce the amount of *GHG* emissions while increasing the economic benefits of livestock [54,55]. This is also a sustainable path for China's *AH* sector to mitigate and adapt to climate change. With reference to Caro's results [11], the *AHGI* of China in 2010 ($2.87 \text{ tCO}_2\text{eq}/10^4 \text{ yuan}$) was much lower than that of Vietnam ($17.97 \text{ tCO}_2\text{eq}/10^4 \text{ yuan}$) and India ($16.16 \text{ tCO}_2 \text{ eq}/10^4 \text{ yuan}$), both of which have higher emission intensities in Asia, but it is 3.78 times that of the United States ($0.76 \text{ tCO}_2\text{eq}/10^4 \text{ yuan}$). This shows that although the *AHGI* has been continuously on the decline, there is still a large gap compared with the developed countries, and there is still more room for greater emissions reduction in the future. On the one hand, Wang's research shows that the greatest technical emission reduction potential for China's *AH* sector will be 253 Mt of CO_2 emission by 2020 [60], accounting for 56.85% of total *GHG* emissions in 2005 from *AH*. This shows that the technical means will be important measures to reduce *GHG* emissions for China's *AH* sector in the future. On the other hand, Herrero's research indicates that *GHG* emissions can be effectively reduced in *AH* sector by using feed additives to improve the animal's forage digestibility and strengthening the storage and management of animal manure and other technical means [15]. Therefore, in the future, all provinces should focus more on improving the level of *AHEE*, and further reduce the *GHG* emissions of livestock by improving the raising of livestock and manure management technologies so as to promote the conversion from advantage in production scale to advantage in contribution to emissions reduction. In addition, there is a large gap among all provinces in China in terms of *AHPE*. Therefore, narrowing the inter-provincial gap of *AHPE* is also an important path for promoting the reduction of China's *AHGI*.

3.4. Advantages and Limitations of This Study

This study focused on *AHGI* reduction in China and its provinces. Compared with previous studies, this study went deeper in the following three aspects. First, on the decomposition scale, it was different from the existing decomposition studies on the *GHG* emissions from *AH* [39,41–43], which have been done only from the horizontal provincial scales. This study firstly established a vertical linkage of change in *AHGI* between china and its 31 provinces and clearly revealed the linkage between partial changes and overall changes. This is more in line with China's current need to allocate *GHG* reduction tasks from top to bottom. Second, in terms of driving factors, the existing studies have mostly explained the impact on *GHG* emissions of *AH* [39,41–43]. Based on the *AHGI* calculation formula, we separated the factors affecting the change of China's *AHGI* into environmental efficiency, productive efficiency, and economic share. Our research effectively combined emissions reduction and economic development, thus, it can provide a more specific basis for each province to formulate *GHG* emission reduction measures for the *AH* sector. Third, in terms of research findings, previous studies [36–39] found that provinces such as Henan, Shandong, Hebei, and Sichuan have always been major contributors to *GHG* emissions from the *AH* sector in China. Our findings indicated that these provinces were not only major contributors to *GHG* emissions from the *AH* sector in China, they were also the main contributors to the reduction of China's *AHGI*. This is of great significance for a comprehensive and objective understanding of the responsibilities of the provinces with large *GHG* emissions for their emissions reduction tasks.

However, although there are some advantages in the study, it also needs for further development. First, we only discussed the decomposition results of provincial contributions to the reduction of China's *AHGI* comparing 2016 with 1997. However, we did not further divide the study period into different time periods for detailed analysis and discussion. Future studies should strengthen the comparative analysis at different time periods. In addition, we only revealed the linkage of *AHGI* change between China and its 31 provinces, but did not delve more deeply into the issues of fairness and efficiency of contribution values in each province. In future research, the *LMDI* decomposition method and the performance evaluation method should be combined to answer the issues of fairness and efficiency of each province's contribution value. Three major factors, which are the reduction of greenhouse gas emissions, economic growth and the supply of livestock food, should be included in the performance evaluation system together.

4. Conclusions

This study established a vertical linkage of *GHG* emission intensity change of the animal husbandry sector between China and its 31 provinces based on *LMDI* decomposing method from the perspective of combining emission reductions with economic development. In addition, the study quantified the contributions of each province and its three driving factors of environmental efficiency, productive efficiency, and economic share to reducing China's animal husbandry *GHG* emission intensity during the period of 1997–2016. The final conclusions are as follows.

- (1) The *AHGI* of China decreased from 5.49 tCO₂eq/10⁴ yuan in 1997 to 2.59 tCO₂eq/10⁴ in 2016, showing a 75.25% reduction. Compared 2016 with 1997, the *AHGI* in 31 provinces also declined and played a positive role in promoting the reduction of the national *AHGI*, but there were significant differences among provinces in the extent of contribution. Henan, the largest contributor, contributed to a 7.11% reduction of China's *AHGI*, and Tianjin was the smallest contributor (0.06%). The top ten provinces (Henan, Hebei, Shandong, Sichuan, Guangxi, Hunan, Anhui, Yunnan, Guangdong and Hubei) cumulatively contributed to a reduction of 46.22% in China's *AHGI*, accounting for 61.42% of the total contributions by 31 provinces; while the bottom ten provinces (Tianjin, Ningxia, Beijing, Liaoning, Shanghai, Hainan, Fujian, Zhejiang, Chongqing and Gansu) cumulatively contributed to a reduction of only 6.45% in China's *AHGI*, accounting for 8.57% of total provincial contributions. Overall, there was an inconsistency between the extent of the actual reduction of *AHGI* in each province and its contributions to the country. China's progress in reducing *AHGI* was mainly made by provinces with a large *GHG* emissions from *AH*.
- (2) Three driving factors (environmental efficiency, productive efficiency, and economic share) comprehensively determine the reduction of China's *AHGI* through two different contributions of positive promotion and negative inhibition, but the way in which the three driving factors exert their impact and the extent of their contributions vary significantly among provinces. The productive efficiency and environmental efficiency factors in 31 provinces cumulatively contributed to the respective 68.17% and 11.78% reduction of China's *AHGI*, while the economic share factors of 31 provinces cumulatively inhibited the 4.70% reduction of China's *AHGI*. Overall, the productive efficiency factors are the main driving factors contributing to the reduction of China's *AHGI*. The reduction of China's *AHGI* during the study period depended more on the substantial increase in the *AH*'s productive efficiency than on the improvement of *AH*'s environmental efficiency. The economic share factor was a weight with the nature of a "double-edged sword", which can decrease or increase the contribution value of each province to the reduction of China's *AHGI*. In the future, improving the level of *AHEE* through *GHG* emission reduction technology and narrowing the inter-provincial gap of the level of *AHPE* are two important paths for promoting the reduction of China's *AHGI*. In terms of improving the level of *AHEE*, all provinces need to do this. However this is even more urgent in the seven provinces, including Tibet, Qinghai, Inner Mongolia, Ningxia, Gansu, Beijing and Shanghai. In terms of narrowing the inter-provincial gap of the level of *AHPE*, the gap is mainly reflected between the frontier grassland pastoral areas in the western and the agricultural

areas in Central and Eastern China. The key provinces that need to improve the level of *AHPE* are located in grassland pastoral areas, including Tibet, Qinghai, Gansu, Xinjiang, Inner Mongolia, Ningxia, Guizhou, Yunnan and Guangxi.

Author Contributions: T.C. and D.Y. designed the research; T.C., D.Y., and F.X. performed the research; R.W. analyzed the data; T.C. drafted the manuscript, which was revised by D.Y. and X.Z. All authors have read and approved the final manuscript.

Funding: This research was funded by Grant Program of Clean Development Mechanism Fund of China (CDMF) grant number [No. 2014092].

Acknowledgments: We acknowledge the Grant Program of Clean Development Mechanism Fund of China (CDMF) (No. 2014092).

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

Appendix A.

Table A1. The CH₄ emission factor for animal manure management (kg CH₄/head/year).

Region	Dairy Cow	Cattle	Buffalo	Horse	Donkey	Mule
North China	7.46	2.82	-	1.09	0.60	0.60
Northeast China	2.23	1.02	-	1.09	0.60	0.60
East China	8.33	3.31	5.55	1.64	0.90	0.90
Central and Southern China	8.45	4.72	8.24	1.64	0.90	0.90
Southwest China	6.51	3.21	1.53	1.64	0.90	0.90
Northwest China	5.93	1.86	-	1.09	0.60	0.60
Region	Camel	Sheep	Goat	Pig	Poultry	
North China	1.28	0.15	0.17	3.12	0.01	
Northeast China	1.28	0.15	0.16	1.12	0.01	
East China	1.92	0.26	0.28	5.08	0.02	
Central and Southern China	1.92	0.34	0.31	5.85	0.02	
Southwest China	1.92	0.48	0.53	4.18	0.02	
Northwest China	1.28	0.28	0.32	1.38	0.01	

Note: North China: Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia; Northeast China: Heilongjiang, Jilin, Liaoning; East China: Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong; Central and Southern China: Henan, Hubei, Hunan, Guangxi, Guangdong, Hainan; Southwest China: Chongqing, Sichuan, Guizhou, Yunnan, Tibet; Northwest China: Shaanxi, Gansu, Ningxia, Qinghai, Xinjiang.

Table A2. The N₂O emission factor for animal manure management (kg N₂O/head/year).

Region	Dairy Cow	Cattle	Buffalo	Horse	Donkey	Mule
North China	1.846	0.794	-	0.330	0.188	0.188
Northeast China	1.096	0.931	-	0.330	0.188	0.188
East China	2.065	0.846	0.875	0.330	0.188	0.188
Central and Southern China	1.710	0.805	0.860	0.330	0.188	0.188
Southwest China	1.884	0.691	1.197	0.330	0.188	0.188
Northwest China	1.447	0.545	-	0.330	0.188	0.188
Region	Camel	Sheep	Goat	Pig	Poultry	
North China	0.330	0.093	0.093	0.227	0.007	
Northeast China	0.330	0.057	0.057	0.266	0.007	
East China	0.330	0.113	0.113	0.175	0.007	
Central and Southern China	0.330	0.106	0.106	0.157	0.007	
Southwest China	0.330	0.064	0.064	0.159	0.007	
Northwest China	0.330	0.074	0.074	0.195	0.007	

Note: The provinces included in different regions are the same as Table A1.

Table A3. Abbreviations.

Item	Descriptions
GHG	Greenhouse gas
AH	Animal husbandry
CI	Carbon intensity
LMDI	The logarithmic mean Divisia index
AHGI	Greenhouse gas emission intensity of animal husbandry sector (in tCO ₂ eq/10 ⁴ yuan)
AHGE	The sum of greenhouse gas emissions from animal husbandry sector (in tCO ₂ eq)
AHGDP	Economic output value of animal husbandry sector (10 ⁴ yuan)
AHBS	The input of production factors in the animal husbandry sector (it can be replaced with the breeding scale of livestock by converting to standard cattle units)
AHEE	The animal husbandry environmental efficiency (GHG emissions per unit of livestock)
AHPE	The animal husbandry productive efficiency (livestock input per unit of AHGDP)
AHES	The animal husbandry economic share (the provincial proportion of the AHGDP in the national AHGDP)

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