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Temporal trends and spatial patterns of energy use efficiency and greenhouse gas emissions in crop production of Anhui Province, China

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ABSTRACT

The aim of this study is to establish an energy use efficiency and GHG emissions (EUE-GHG) model to promote ecological agriculture, not only examining these indicators on crop production in Anhui Province from 1990 to 2014, but also comparing them among 16 provincial cities in 2014. The results reveal that energy use efficiency decreased significantly from 3.75 to 1.87 during 1990–2005, and then increased to 2.08 in 2014, while the GHG emissions increased rapidly from 2919.51 CO_2-eq in 1990 –8993.46 CO_2-eq in 2014. These two important indicators were mainly determined by the great energy consumption from the use of agricultural machines and the use of chemical fertilizers. Regard to spatial perspective, the central and northern cities, including Fuyang, Bengbu, Suzhou, Huaibei, and Hefei, had the smaller EUEs and the higher GHG emissions than those in the southern cities, due to their large consumption of agricultural resources and the economic reasons. Several mitigation policies are then proposed by considering the local realities so that valuable policy insights can be shared by the stakeholders in other Chinese regions.

1. Introduction

Rapid agricultural development requires higher inputs such as fertilizer, pesticide, agricultural machines, seeds and fuels, resulting in higher energy consumption and corresponding greenhouse gas (GHG) emissions [1–3]. Currently, agriculture accounts for approximately 14% of total global anthropogenic GHG emissions [4]. With the increasing global population, projected food demand may double by 2050, which means that associated energy consumption and GHG emissions from this sector will also increase [5]. As the largest developing country, China's agricultural sector is essential to support its economic growth and meet with the food demand of its large population. Energy consumption in the agricultural sector had increased from 42.33 million tons in 2000 to 80.55 million tons in 2013, accounting for 22.4% of the world's total agricultural energy consumption [2]. Correspondingly, total annual GHG emissions from agricultural sector also increased quickly, from 404.2 thousand tons in 1978 to 831.6 thousand tons (CO_2 equivalent) in 2012 [6,7].

In order to respond such a challenge, a number of governmental activities have been initiated so that more renewable energy sources can be applied in the agricultural sector [8]. However, renewable energy is not easily available in many places. Therefore, current agricultural policies focus on how to reduce the overall consumption of fossil fuels, while keeping high agricultural outputs, so that the corresponding GHG emissions can be mitigated [9,10]. Academically, many studies have been undertaken from different perspectives and at different levels (including both national or regional levels), such as energy input-output analysis or energy flows relating with crops of vegetables, sugar beet, tomato, apple, olive, sugarcane, etc [11–18]. In general, in order to achieve higher outputs, it is common to use more fossil fuels. Unfortunately, increased fossil fuels inputs do not lead to the most optimal outputs due to increasing production costs and irrational management [19].

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Moreover, such an increasing use of fossil fuels may lead to various environmental concerns, such as GHG emissions, air pollutants and wastewater issues [20]. Under such a circumstance, it is critical to improve energy use efficiency (EUE) in the agricultural sector, which is defined as energy need by per unit output [21], so that sustainable agricultural development can be obtained [22,23].

Academically, many studies have been published, focusing on the agricultural EUE. Popular research methods include life cycle assessment (LCA) [24–26], data envelopment analysis (DEA) [27–29], and process analysis (PA) [30,31]. Each method has its own advantages and disadvantages. For instance, the DEA method has been widely used to evaluate the environmental and economic performances in the agricultural sector [32–34], especially for agricultural energy efficiency analysis [35]. Similarly, LCA has its unique advantage on quantifying the environmental impacts of materials and energy flows in crop's life cycle so that the key processes can be recognized [25]. However, no single method can address all the elements of agricultural production. Therefore, it would be necessary to integrate different methods together so that the complete picture of energy use efficiency and related greenhouse gas emissions can be presented to the decision makers. Such a combination can ensure that appropriate mitigation policies be released and key concerns be addressed. From spatial point of view, EUE related studies have been conducted at the national level [36,37], and at the regional level [38–45]. With regard to China, EUE-related studies have also been conducted in different sectors, such as in the industrial sector [46–49], and in the agricultural sector [50,51], even for some special crops [52–54]. However, few studies have been conducted on examining energy consumption and the corresponding GHG emissions for the whole agricultural sector at the regional level. Such studies are crucial since different Chinese regions have different agricultural activities and climatic conditions and need to adopt different mitigation strategies.

In terms of accounting GHG emissions, there are many available methods. For example, the IPCC (Intergovernmental Panel on Climate Change) method should be noted as a practical and first-order method. Such a method uses default emission factors and evaluates the anthropogenic effect on GHG emissions [4]. Many GHGs studies have been published by using the IPCC method [55–57]. However, such a method cannot provide accurate results due to the regional disparity on emission factors. Many default emission factors are quite rough and cannot reflect the different situations in different regions. Another key method is the process-based method, in which the GHG emissions are evaluated according to the processes of agricultural activities, such as DNDC [58], NGAUGE [59], SIMSdairy [60], MOTOR [61] and Cool Farm Tool [62]. In addition, life cycle analysis (LCA) is proved to be a proper method analyzing the environmental impacts including climate change through the life-cycle of the activities or products [63,64]. It is a systematic method on analyzing the environmental impacts more comprehensively and more objectively. Concerning the importance of nutrients in agriculture, many studies began to analyze the nutrient flows and its corresponding GHG emissions in agriculture through LCA [65–69]. This nutrient-based LCA is a more micro-based method with time-consuming data collection. In general, agricultural GHG emissions have been investigated by using different methods. Several studies indicate that great regional disparity does exist due to different climate zones, crops, management practices. Consequently, it is critical to further conduct such a study at regional level so that more policy insights can be obtained for mitigating the overall agricultural GHG emissions.

Under such a circumstance, this study selects Anhui Province in the central part of China as one case region. This province is a typical agricultural province and has many common features that other agricultural provinces have. Thus, the policy implications from this study may provide valuable insights to other agricultural provinces so that they can initiate their efforts on reducing agricultural energy consumption and the corresponding GHG emissions. Based on the partial LCA focusing on planting and breeding, and the use of DEA and PA based energy indices, a combined EUE-GHG model for crop production is developed so that changes of agricultural energy consumption, EUE, and the corresponding GHG emissions in Anhui province can be quantified for the period of 1990–2014. In addition, the spatial features within this province is also presented so that more city-specific mitigation policies can be raised. The whole paper is organized as below. After this introduction section, Section 2 describes research methods, including a short introduction of the study region, the establishment of the combined model and data collection. Section 3 presents research results and Section 4 discusses policy implications. Finally, Section 5 draws research conclusions.

2. Methods and data

2.1. Study area

Anhui province locates in the central China and crosses the basins of the Yangtze River and the Huai River [70]. There are 16 cities (including Hefei City, Huaibei City, Bozhou City, Suzhou City, Bengbu City, Fuyang City, Huainan City, Chuzhou City, Lu'an City, Ma'anshan City, Wuhu City, Xuancheng City, Tongling City, Chizhou City, Anqing City, and Huangshan City) in this province, with Hefei City as the capital. Anhui had a total population of 60.83 million at the end of 2014, including 30.93 million rural population (50.80% of the total). The total area is 140,100 km^2, including a total cultivation land of 59,200 km^2 (with a land share of 42.26%) [71]. Major agricultural crops include wheat, rice, maize, beans, potatoes, cotton, etc. Also, a large number of livestock such as pigs, cattle, sheep, and poultry are being raised, resulting in a big challenge on managing increasing excrement. Due to the lack of environmental infrastructure in the rural areas, over 70% of the excrement is discharged into the local agricultural fields directly, exceeding the absorption ability of the local crops [72]. In addition, in order to increase agricultural production volumes, a large amount of materials and fossil fuels have been consumed, such as fertilizers, pesticides, gasoline, kerosene, diesel, coal, etc., leading to increasing concerns on soil degradation and contamination, agricultural water pollution and air pollution [71]. Therefore, it is necessary to improve the overall resource efficiency of its agricultural sector so that corresponding environmental emissions and GHG emissions can be reduced.

2.2. EUE-GHG model

In this study, both EUE and GHG emissions from crop production are quantified by using the EUE-GHG assessment model. The model is established by utilizing the partial LCA focusing on the whole crop production system. In order to set up a clear research boundary, only energy consumed by crop production is considered, including energy consumed by those agricultural machines, electricity used for crop production, different types of fertilizer and pesticide, energy consumed for irrigation, sowing, and manure management. In terms of crop types, 11 crop categories are considered, including rice, wheat, maize, beans, potatoes, cotton, peanut, rapeseed, sesame, vegetables, and fruits. Similarly, four livestock categories are considered in this study, including pigs, cattle, sheep, and poultry. The energy embodied in crop and crop residue are determined as the energy outputs, and the GHGs emissions are closely related with the energy inputs. It includes the same categories as energy inputs except for seeds, which emit negligible CO_2. Accordingly, the diagram of these energy flows and GHGs emissions in crop production is illustrated in Fig. 1.

The model assesses EUE by measuring energy inputs and outputs (energy flows or energy budget). Fossil fuels are regarded as primary energy sources (GJ), while GHG emissions are evaluated by multiplying the corresponding CO_2 emission coefficients with the energy inputs (energy consumption). GHG emissions are characterized in kg CO_2-equivalents (CO_2-eq) on a 100-year time scale, using factors recommended by the related studies shown in Table 1.

This study uses the energy equivalents to evaluate energy inputs and outputs (energy flows), which is shown in Equation (1). The detailed calculation method is listed in Table 2.

$$E_m = Q_m e_m \quad (1)$$

where E_m is the energy input/output of type m (GJ ha^{-1}); Q_m illustrates the quantity of the energy input/output of type m (t ha^{-1}); e_m is the energy equivalent (GJ t^{-1}).

After evaluating energy inputs and outputs, this study estimates several important energy indicators, such as EUE, NE, and EP. EUE can be evaluated by the energy ratio (Equation (2)) between its output and input. Other two indicators are also important for reflecting energetic efficiency of crop production. These three indicators are calculated by using Equations (2)–(4), respectively [44,45,73,74].

$$EUE = E^{out} / E^{in} \quad (2)$$

$$NE = E^{out} - E^{in} \quad (3)$$

$$EUE = E^{g} / E^{in} \quad (4)$$

where *NE* represents net energy (GJ ha^{-1}); *EUE* represents energy use efficiency; *EP* represents energy productivity. E^{in} and E^{out} illustrate total energy input and total energy output, respectively (GJ ha^{-1}), while E^g represents energy embodied in the harvested grain (GJ ha^{-1}).

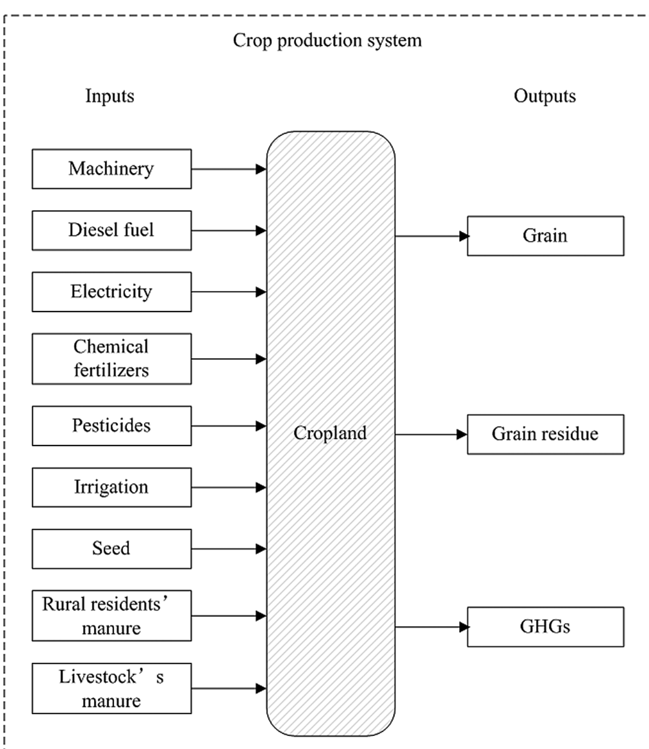

Fig. 1. The diagram of energy flows and GHGs emissions in crop production.

GHG emissions from energy inputs in crop production can be calculated by multiplying the agricultural inputs (machinery, fuels, electricity, chemical fertilizers, pesticides, and manure) by their corresponding CO_2 coefficients (listed in Table 3). Equation (5) lists how to calculate the corresponding GHG emission.

$$C_n = Q_n c_n \quad (5)$$

where C_n is the energy input of type n (CO_2-eq ha^{-1}), Q_n illustrates the quantity of the energy input of type n (GJ ha^{-1}), c_n is the CO_2 coefficient of the energy input of type n (CO_2-eq GJ^{-1}).

Energy consumption from irrigation process is converted to electricity, thus the corresponding GHG emission caused by irrigation is included into that of electricity. Similarly, data related with energy flows and GHG emissions are converted into suitable units and expressed in GJ ha^{-1} and CO_2-eq ha^{-1}.

The study period ranges from 1990 to 2014. In order to simplify the assessment results, the years 1990, 1995, 2000, 2005, 2010, and 2014 were selected to show the trend of both energy consumption and corresponding GHG emissions. The year 2014 was selected as the most recent year due to the data availability.

2.3. Data collection

In this study data were collected from official statistical yearbooks, literature, questionnaires, and face-to-face interviews. Further information on the data sources including data of Anhui and the factors of energy and CO_2 emissions are presented in Table 1. Other basic data related with energy flows and CO_2 emissions in the farming system of 16 cities in Anhui are presented in Table 4.

The statistical data were gained from local statistical yearbooks [56,85–89], covering agriculture inputs (eg., the amounts of machines, consumption of fuels and electricity, uses of chemical fertilizers and pesticides, total agricultural production areas), and agricultural outputs (eg., harvest amounts of different crops). Data related with energy equivalents, CO_2 coefficients, the weight of one agricultural machine, and ratios of straw to grain were collected from published literature. In addition, local agricultural data, including the amounts of seed per sown area, annual manure discharged per rural resident, were collected from questionnaire surveys. The questionnaire was designed and issued for local rural residents, aiming to get information on their daily life and agricultural production and covering 2 cities, 6 counties, 12 towns, and 36 villages in Anhui. Totally, 633 questionnaires were sent out and 632 questionnaires were collected, with a response rate of 99.8%. The entire questionnaire surveys were coordinated by the local agricultural officials, who helped explain the targets and the technical details to the investigated rural residents. With their help, valuable information and data were gained for this study. Finally, in order to receive more specific data (eg. annual manure discharged per livestock) and other useful information on agricultural production, face-to-face interviews were conducted with the local agricultural enterprises, farmers, rural residents, and agricultural experts.

3. Results

3.1. Energy use efficiency

Fig. 2 shows the changes of NE, EUE, EP, energy inputs and energy outputs during 1990–2014. It is clear that three different

Table 1
Data of energy flows and CO_2 emissions in the farming system of Anhui.

Parameter	Description	Value/Source
Energy input		
$Q_i^m (i = 1,2,3,4,5)$	Amount of machinery (large tractor, small tractor, diesel engines, combine harvester, and farm transporter)	unit [a]
$q_i^m (i = 1,2,3,4,5)$	Weight per machine (large tractor, small tractor, diesel engines, combine harvester, and farm transporter)	[1950, 1100, 200, 50, 1500] kg [15,75]
$e_i^m (i = 1,2,3,4,5)$	Energy equivalent of machine (large tractor, small tractor, diesel engines, combine harvester, and farm transporter)	[93.61, 93.61, 62.70, 87.63, 64.80] MJ kg^{-1} [11,39,76]
Q^d	Consumption of diesel fuel	t [a]
ρ^d	Density of diesel fuel	0.84 kg L^{-1} [b]
e^d	Energy equivalent of diesel fuel	47.80 MJ L^{-1} [19]
Q^e	Consumption of electricity	kwh [a]
e^e	Energy equivalent of electricity	3.60 MJ kwh^{-1} [77]
$Q_i^c (i = 1,2,3)$	Application of chemical fertilizers (nitrogen fertilizer, phosphate fertilizer, potassium fertilizer)	t [a]
$e_i^c (i = 1,2,3)$	Energy equivalent of chemical fertilizers (nitrogen fertilizer, phosphate fertilizer, potassium fertilizer)	[66.60, 11.10, 13.70] MJ kg^{-1} [78,79]
Q^p	Application of pesticides	t [a]
e^p	Energy equivalent of pesticides	120 MJ kg^{-1} [80]
Q^w	Amount of irrigation	ha [a]
e^w	Energy equivalent of irrigation	0.4 MJ ha^{-1} [81]
$Q_i^s (i = 1,2,3,...,11)$	Sown area of seed (rice, wheat, maize, beans, potatoes, cotton, peanut, rapeseed, sesame, vegetables, and fruits)	ha [a]
$q_i^s (i = 1,2,3,...,11)$	Amount of seed (rice, wheat, maize, beans, potatoes, cotton, peanut, rapeseed, sesame, vegetables, and fruits) per sown area	[55.50, 225.00, 30.00, 55.00, 1312.50, 52.50, 180.00, 1.13, 5.25, 10.00, 10.00] kg ha^{-1} [80],[c]
$e_i^s (i = 1,2,3,...,11)$	Energy equivalent of seed (rice, wheat, maize, beans, potatoes, cotton, peanut, rapeseed, sesame, vegetables, and fruits)	[15.37, 14.70, 15.30, 21.25, 6.23, 3.60, 21.25, 3.60, 26.00, 3.69, 4.01] MJ kg^{-1} [11,14,17,39,79]
$Q_i^l (i = 1,2,3,4)$	Amounts of pigs, cattle, poultries, and rural residents	unit [a]
$q_i^l (i = 1,2,3,4)$	Manure discharged by per pig, cattle, poultry, and rural resident per annum	[1.93, 10.10, 0.87, 0.05, 0.44] t [80,81][c, d]
r^l	Proportion of manure applied to fields	% [82]
e^l	Energy equivalents of manure discharged by pigs, cattle, poultries, and rural residents	0.3 MJ kg^{-1} [78]
Energy output		
$Q_i^g (i = 1,2,3,...,11)$	Harvest of grain (rice, wheat, maize, beans, potatoes, cotton, peanut, rapeseed, sesame, vegetables, and fruits)	[a]
$e_i^g (i = 1,2,3,...,11)$	Energy equivalent of grain (rice, wheat, maize, beans, potatoes, cotton, peanut, rapeseed, sesame, vegetables, and fruits)	[14.87, 14.70, 14.70, 20.25, 3.60, 11.80, 20.25, 25.00, 25.00, 3.19, 3.51] MJ kg^{-1} [11,14,17,39,79]
$s_i^r (i = 1,2,3,...,9)$	Ratio of straw to grain (rice, wheat, maize, beans, potatoes, cotton, peanut, rapeseed, and sesame)	0.9, 1.1, 1.2, 1.0, 0.5, 3.0, 0.8, 2.5, 2.2 [80,82,83]
$e_i^r (i = 1,2,3,...,9)$	Energy equivalent of grain residue (rice, wheat, maize, beans, potatoes, cotton, peanut, rapeseed, and sesame)	[13.40, 9.25, 17.50,18.00, 17.00, 12.50, 11.23, 12.50, 12.50] MJ kg^{-1} [11,14,17,39,79] [c]
CO_2 emission		
c^m	CO_2 coefficient of machinery	0.071 CO_2-eq MJ^{-1} [41]
c^d	CO_2 coefficient of diesel fuel	2.76 CO_2-eq L^{-1} [41]
c^e	CO_2 coefficient of electricity	0.608 CO_2-eq kwh^{-1} [45]
$c_i^c (i = 1,2,3)$	CO_2 coefficient of chemical fertilizers (nitrogen fertilizer, phosphate fertilizer, potassium)	[1.30, 0.20, 0.20] CO_2-eq kg^{-1} [84]
c^p	CO_2 coefficient of pesticides	5.10 CO_2-eq kg^{-1} [84]
c^l	CO_2 coefficient of pigs, cattle, poultries, and rural residents	0.008 CO_2-eq kg^{-1} [84]

[a] SBAP [74].
[b] General knowledge.
[c] Questionnaire of rural residents.
[d] Interviews with breeding enterprises.

stages exist, i.e. 1990–1995, 1996–2005, and 2006–2014. According to the proposed model, the values of NE, EUE and EP are calculated by using energy inputs and energy outputs. Thus, the evolution trend of energy inputs and outputs determines the trend of other three energy indicators. Both the evolution trends of EUE and EP are similar because crop residues are calculated by the grains and the ratios of straws to grains, and such ratios are fixed.

Both energy input and output increased quickly during the first stage. But the value of energy input increased faster and is much higher than the value of energy output, leading to the increase of the total NE and the decrease of the total EUE. During the second stage (1996–2005), the value of energy input still increased faster than the value of energy output, leading to the rapid decline of all the three energy indicators. However, during the third stage (2006–2014), the value of energy input slightly increased, while the value of energy output increased faster, leading to the increased values of all the three energy indicators.

In order to uncover the drivers of these dynamic changes, these indicators were further analyzed. Fig. 2(a) shows that the total energy input increased from 44.54 GJ ha^{-1} in 1990 to 132.97 GJ ha^{-1} in 2014. Especially during 1996–2005, energy input had increased drastically, with an annual increase of 5.83 GJ ha^{-1}. For the periods of 1990–1995 and 2006–2014, energy inputs had increased steadily, with annual increases of 3.23 GJ ha^{-1} and 3.51 GJ ha^{-1}, respectively. The largest energy input is for driving agricultural machines, due to two reasons. Firstly, with the agricultural modernization and more rural residents moving from rural areas to urban areas, especially during 1995–2005, more agricultural machines were used to replace manual farming. Secondly, due to the flexibility and multiple functions of the small agricultural

Table 2
Equations for calculating energy inputs and outputs in the farming system.

Flow	Description	Equation
Energy input		
E^m	Machinery	$E^m = \sum_{i=1}^{5} Q_i^m q_i^m e_i^m (i = 1,2,3,4,5)$
E^d	Diesel fuel	$E^d = \frac{Q^d}{\rho^d} e^d$
E^e	Electricity	$E^e = Q^e e^e$
E^c	Chemical fertilizers	$E^c = \sum_{i=1}^{3} Q_i^c e_i^c (i = 1,2,3)$
E^p	Pesticides	$E^p = Q^p e^p$
E^w	Irrigation	$E^w = Q^w e^w$
E^s	Seed	$E^s = \sum_{i=1}^{11} Q_i^s q_i^s e_i^s (i = 1,2,3,...,11)$
E^l	Manure	$E^l = \sum_{i=1}^{4} Q_i^l q_i^l r^l e^l (i = 1,2,3,4)$
Energy output		
E^g	Grain	$E^g = \sum_{i=1}^{11} Q_i^g e_i^g (i = 1,2,3,...,11)$
E^r	Residue	$E^r = \sum_{i=1}^{11} Q_i^g s_i^r e_i^r (i = 1,2,3,...,9)$

machines, such as the small tractors, the total use of such machines increased drastically, with an annual growth rate of 2.86%. Besides, chemical fertilizers, especially the nitrogen fertilizer, became the second largest input, which should be better managed. The great shares of chemical fertilizer have also been reported in other related studies [19,79]. As Anhui has a large cultivated area, the application of chemical fertilizer is very high, particularly during 1990–2000. In order to meet the increasing food demand, the local farmers were urged to produce more crops and had to increase the use of chemical fertilizers. Also, the local farmers can easily get the chemical fertilizers and believe that they are cleaner than the organic fertilizers. Unfortunately, the lack of technical guidance on appropriate use of chemical fertilizers led to the fact that much fertilizer was wasted without exerting its full functions. Another issue is the manure returned to the agricultural field. In fact, many cattle and pig farms and the related beef and pork processing enterprises locate in the suburb and rural areas in Anhui, where the sewage plants and waste treatment facilities are not available or very backward. Moreover, the staffs' environmental awareness is weak and appropriate waste treatment technologies are also lacking. Consequently, most manure was directly dumped to the field, without being considered as the alternative resource for methane generation.

Another key finding is that total energy efficiency first decreased and then increased, illustrated in Fig. 2(b). This indicates that in order to increase the overall agricultural outputs the stakeholders in Anhui did not pay more attention on energy efficiency. However, with the gradual implementation of more energy efficient equipment and technologies and better management, the overall energy efficiency was steadily improved.

Significant spatial differences on energy inputs and outputs also exist. Fig. 3(a) shows that the central and northern cities of Anhui Province, including Huainan, Fuyang, Bengbu, Suzhou, Huaibei, and Bozhou, had the higher energy inputs and outputs (per cultivated area) than those in the southern cities. This was mainly due to two reasons. Firstly, some central and northern cities, especially Huainan and Huaibei, have less cultivation areas than those in the southern cities. Secondly, the overall economic development in the central and northern cities is much faster than those southern cities, resulting in more agricultural investment, particularly the wide use of agricultural machines and corresponding more diesel consumption. Among all the southern cities, Tongling had the largest energy input and output. This was mainly due to its smallest cultivated area, which is only about 1/15 of the average cultivated area of other cities in Anhui.

Based on the calculation of the energy indices, the energy input and output directly determined the values of NP, EUE, and EP, which had the similar spatial characteristics. Thus, the main reasons causing the spatial changes of energy input and output are also the reasons causing the changes of these energy indicators. Firstly, it indicates Fuyang had the 2nd largest energy output, while the energy input was small. This results in the highest NP, EUE, and EP values in this city, shown in Fig. 3(b). This city has the 3rd largest cultivated area. In order to improve its agriculture, the municipal government of Fuyang prepared many innovative policies, including the promotion of ecological farming, the adjustment of agricultural planting structure, the demonstration projects of high-efficient agriculture, the wide application of modern agricultural machines, and more financial support on agricultural technologies. All these policies and measures had encouraged more efficient and ecological farming of Fuyang. Ma'anshan city also deserves attention. This city is close to Jiangsu province (one of the richest Chinese provinces) and enjoys much better economic benefits by providing different materials and comprehensive services to Jiangsu province. The much improved economic situation in Ma'anshan can ensure a large investment on agricultural development, leading to its lowest energy input and higher EUE value. Anqing is also an important city because of its high EUE value and its key role in the provincial economic development. As the mountain area occupied most of its rural area, the main crops being suitable planted in Anqing are rice, cotton and rape seed, and the machinery and the diesel fuel are also consumed less. Furthermore, the city government of Anqing significantly improved the farmers' agricultural technologies by inviting many agricultural experts to train their farmers. As a consequence, energy input in this city is far more less than many other cities, and the NE, EUE, and EP values are correspondingly higher, following Fuyang and Ma'anshan.

As the key coal extraction cities, both Huainan and Huanbei boomed their economy by intensive coal mining activities. Both cities have adequate power supply, leading to higher power consumption on agricultural production. Also, farmers in Huainan prefer to use chemical fertilizer and pesticides, rather than pursuing organic planting. Meanwhile, both cities have less cultivated areas, with only 144,440 ha and 168,180 ha respectively. All the above reasons resulted in that these two cities had the lowest energy efficiency indicators. In addition, many northern cities like Bengbu, Chuzhou, and Suzhou had the low EUEs. Their farmers have paid less attention on agricultural production. Thus, local governments in these cities have to seek more incentives on encouraging their farmers to engage in improving the overall energy efficiency.

3.2. Greenhouse gases emissions

Total GHG emissions from crop production in Anhui Province had increased from 2919.51 CO_2-eq in 1990–8993.46 CO_2-eq in 2014, illustrated in Fig. 4. The changes of the corresponding GHG emissions had similar trends as those energy inputs. Such GHG emissions were mainly determined by the use of agricultural machines, with a rate of over 50% of the total GHG emissions. Also, the operation of many agricultural machines consumes electricity, and

Table 3
Equations for accounting CO_2 emissions in the farming system.

Flow	Description	Equation
C^m	Machinery	$C^m = E^m c^m$
C^d	Diesel fuel	$C^d = \frac{Q^d}{\rho^d} c^d$
C^e	Electricity	$C^e = Q^e c^e$
C^c	Chemical fertilizers	$C^c = \sum_{i=1}^{3} Q_i^c c_i^c (i = 1,2,3)$
C^p	Pesticides	$C^p = Q^p c^p$
C^l	Manure	$C^l = \sum_{i=1}^{4} Q_i^l q_i^l r^l c^l (i = 1,2,3,4)$

Table 4
Agricultural characteristics including cultivation, breeding, and rural living in the farming system of 16 cities in Anhui.

Item		Hefei	Huaibei	Bozhou	Suzhou	Bengbu	Fuyang	Huainan	Chuzhou	Lu'an	Ma'anshan	Wuhu	Xuancheng	Tongling	Chizhou	Anqing	Huangshan
Machinery (unit)	Large tractor	9832	15,816	22,816	46,124	11,892	29,870	4748	27,189	16,436	3429	3381	1838	514	729	4361	374
	Small tractor	206,020	103,743	166,702	168,497	311,801	117,438	102,823	415,217	284,432	38,872	54,792	55,253	5562	37,929	104,009	15,875
	Diesel engines	38,129	11,433	40,732	38,847	25,654	44,193	9820	48,663	48,725	11,908	18,220	16,882	1757	9410	30,445	4681
	Combine harvester	15,204	4559	16,242	15,490	10,229	17,622	3915	19,404	19,429	4748	7265	6731	701	3752	12,140	1867
	Farm transporter	16,806	17,275	245,977	183,524	4167	109,523	7754	14,782	27,959	4366	4981	10,688	1450	2459	10,285	3197
	Diesel fuel (t)	68,599	25,749	81,125	112,806	58,338	47,711	36,225	43,899	101,201	13,936	39,853	13,238	4639	21,349	57,079	8678
	Electricity (10^4 kwh)	152,679	25,232	93,491	94,496	86,578	138,534	89,379	97,368	137,846	53,180	124,405	115,625	21,286	40,571	181,666	22,949
Chemical fertilizers	Nitrogen fertilizer (t)	107,082	27,689	64,710	106,632	109,570	91,724	55,768	114,154	154,180	27,047	75,877	44,989	8957	24,122	84,720	18,652
	phosphate fertilizer (t)	45,630	4679	29,083	27,327	33,771	22,842	25,430	47,522	27,157	6322	28,129	13,973	4857	1820	37,462	1262
	Potassium fertilizer (t)	40,353	4765	30,755	37,941	25,732	26,586	10,949	24,558	33,498	4731	24,471	11,021	3602	8033	36,200	2426
	Pesticides (t)	5531	2923	8035	23,799	6305	8258	6033	5853	14,993	3732	2718	3912	717	5585	12,185	3395
	Irrigation area (ha)	456,770	142,130	449,240	416,160	232,310	401,920	122,080	486,690	585,750	147,850	196,580	200,720	23,900	95,000	324,860	49,740
	Cultivated area (ha)	560,850	168,180	599,150	571,420	377,360	650,060	144,440	715,800	716,710	175,160	268,010	248,320	25,850	138,420	447,830	68,860
Sown area (ha)	Rice	345,601	309	3789	8002	110,425	68,602	91,483	361,093	437,338	101,894	159,522	155,942	17,004	99,933	380,950	38,092
	Wheat	108,722	121,127	406,863	357,859	240,064	486,603	100,576	282,293	241,929	44,193	27,867	50,184	8406	6289	40,598	306
	Maize	16,530	61,596	199,074	287,754	81,866	260,412	1912	40,418	25,377	3165	6197	6918	1784	6148	11,201	9795
	Beans	12,349	54,931	221,088	136,671	32,438	163,668	11,067	26,703	17,009	3766	5967	9957	1054	3431	14,016	7749
	Potato	7827	681	28,999	27,917	5077	22,665	1964	11,577	8388	2101	4804	9206	372	1564	13,193	8317
	Cotton	32,649	792	13,877	19,982	9044	11,753	912	8425	11,326	8733	37,673	8827	3696	26,799	71,565	456
	Peanut	19,311	695	6573	45,265	60,145	7522	1983	24,040	9335	2119	2557	4370	309	913	4795	501
	Rape seed	87,741	747	1660	8696	2983	13,447	2233	43,577	65,011	33,415	48,222	41,904	7582	36,864	131,835	25,069
	Sesame	2316	304	2322	2135	1792	18,982	684	4908	2458	1312	1215	1886	129	1345	3488	1406
	Vegetable	86,737	13,324	98,791	77,030	68,260	142,307	28,142	46,154	64,223	24,257	58,423	36,829	4530	15,289	74,605	23,163
	Fruit	24,478	2697	22,663	36,373	19,255	19,788	6478	15,167	7474	6470	4682	6316	1143	1499	4623	2110
Harvest (t)	Rice	2,483,779	2494	23,295	59,952	749,348	410,401	720,445	2,452,560	3,155,156	792,647	1,162,582	994,773	120,273	623,550	2,313,119	267,255
	Wheat	475,308	921,105	3,144,283	2,387,874	1,527,264	3,381,400	637,704	1,531,298	1,242,218	223,927	126,559	221,267	24,634	18,792	118,628	650
	Maize	82,794	227,697	989,365	1,168,938	402,967	1,323,223	6028	183,214	124,852	20,816	34,032	43,025	10,057	22,053	50,495	27,641
	Beans	28,365	92,243	287,961	211,308	51,646	264,519	21,174	48,411	46,203	8611	17,632	19,347	2535	7564	37,822	15,831
	Potato	46,429	4891	97,055	134,371	22,065	99,224	8182	85,755	60,409	16,557	41,834	51,011	2208	7894	63,712	35,506
	Cotton	31,588	1002	19,642	26,003	15,591	14,528	1829	9350	18,700	10,414	46,255	9361	3697	32,883	101,595	548
	Peanut	75,636	2548	45,556	223,285	397,541	23,135	9099	86,986	34,585	5519	7143	13,801	835	2313	14,333	1222
	Rape seed	238,879	1600	4108	17,151	5100	32,429	5185	107,249	134,042	84,328	127,993	95,515	17,796	94,906	274,404	36,863
	Sesame	3875	357	3460	3274	2393	24,851	1205	6399	3988	1981	1888	4411	203	2059	4710	1556
	Vegetable	2,003,670	484,696	2,907,794	3,197,168	2,635,469	5,291,768	868,212	1,421,711	1,380,619	679,831	1,438,032	755,934	111,051	385,318	1,546,629	401,827
	Fruit	617,001	106,029	841,674	1,717,880	962,035	769,463	225,447	562,703	205,305	174,703	185,140	202,614	29,666	48,283	114,822	44,490
Livestock (head)	Pig	4,349,867	1,111,958	4,595,034	7,802,542	3,001,384	8,404,634	796,814	5,199,720	6,183,055	561,745	1,281,639	1,578,611	169,906	1,162,912	4,548,333	1,732,075
	Cattle	157,721	24,525	273,416	337,143	501,236	645,612	113,727	302,244	296,898	21,057	68,473	66,697	5286	26,016	195,050	35,957

Sheep	230,590	713,228	3,294,829	6,192,217	2,076,194	3,797,282	418,365	982,226	1,422,721	163,370	64,815	114,501	6767	30,900	144,311	10,576
Poultry	218,176,300	26,879,200	36,510,200	85,620,000	84,960,000	77,120,800	30,810,000	88,930,000	141,694,000	37,700,700	62,834,600	118,900,000	11,316,600	25,130,000	100,024,600	8,787,200
Rural residents (person)	4,414,378	1,249,551	5,714,719	5,596,901	2,693,104	9,248,909	1,322,734	3,523,741	6,251,054	1,461,157	2,029,872	2,291,158	307,336	1,315,125	5,090,844	1,110,002

The statistical data were gained from local statistical yearbooks as noted in data collection.

such electricity is mainly from coal-burning based power plants, leading to higher embodied GHG emissions. Consequently, the embodied GHG emissions from the electricity contributed the second largest GHG emissions. In addition, nitrogen fertilizer contributed much more GHG emissions than the phosphate fertilizer and the potassium fertilizer. Many studies [90–94] indicate that the GHG emission from the application of nitrogen fertilizer plays an important role in crop production. China is now the world's largest producer and consumer of nitrogen fertilizer. The application of nitrogen fertilizer has increased by three times since 1980 [67,95]. In order to mitigate the GHG emission from the use of nitrogen fertilizer, strict policies on improving the efficiency of nitrogen fertilizer were released [96]. In addition, although the CO_2 coefficient of the use of pesticide is nearly five times of that of nitrogen fertilizer, the amount of its application is much lower, leading to the low GHG emissions from this source. GHG emission from the use of diesel is also much less due to the lower consumption by the diesel-based engines. Finally, although the manure from local farms and breeding enterprises may contribute GHG emissions such as nitrous oxide and methane [55,97], the total GHG emission from the manure is limited due to the increased reuse of manure.

GHG emissions had the similar spatial characteristics as the energy inputs. Fig. 5 shows that those northern cities contributed more GHG emissions in 2014. Huainan had the highest GHG emissions with a share of 10.76%, followed by Bengbu, Tongling and Huaibei. Huainan has less cultivation area due to many coal mining areas. Several large coal-burning power plants are operating in Huainan and provide adequate electricity for crop production, but with lower efficiency and higher GHG emissions. For the case of Bengbu, the application of both chemical fertilizers and pesticides were higher than other cities, resulting in higher GHG emissions. Tongling had the 3rd highest GHGs from its crop production, mainly due to its lower energy efficiency and higher energy consumption. Conversely, Fuyang, had the 3rd lowest GHGs next to Chizhou. This is mainly because the four main agricultural resources including machinery, diesel fuel, electricity, and chemical fertilizers in Fuyang were consumed much less than the average level of Anhui. Moreover, the crop production in Chizhou emitted the 2nd lowest GHGs emissions with the low energy output, resulting in the low EUE. This is mainly caused by two reasons. The first reason is that Chizhou has many mountain areas and therefore cannot widely use agricultural machines and plant more crops. The second reason is that its low economic development restricted the local governments and farmers to invest more in crop production. Finally, Ma'anshan has the strict agricultural policies on energy consumption and with better economic situations, leading to less resource and energy consumption and correspondingly the least GHGs.

4. Discussions

4.1. Comparison with other studies

It is clear that energy inputs mainly determine both energy indicators and GHG emissions. However, different studies use different indicators, making it difficult to compare them. Under such a circumstance, this study selects several relevant studies that contain similar indicators, including those for China [7,51], Iran [98], and Thailand [39].

Wang's study [51] shows that the GHG emissions of crop production in China generally increased from 454.25 CO_2-eq ha^{-1} in 1991 to 761.22 CO_2-eq ha^{-1} in 2013, with only 3.07% annual increase. This is due to the fact that energy consumption from the use of agricultural machines was not considered. Another study

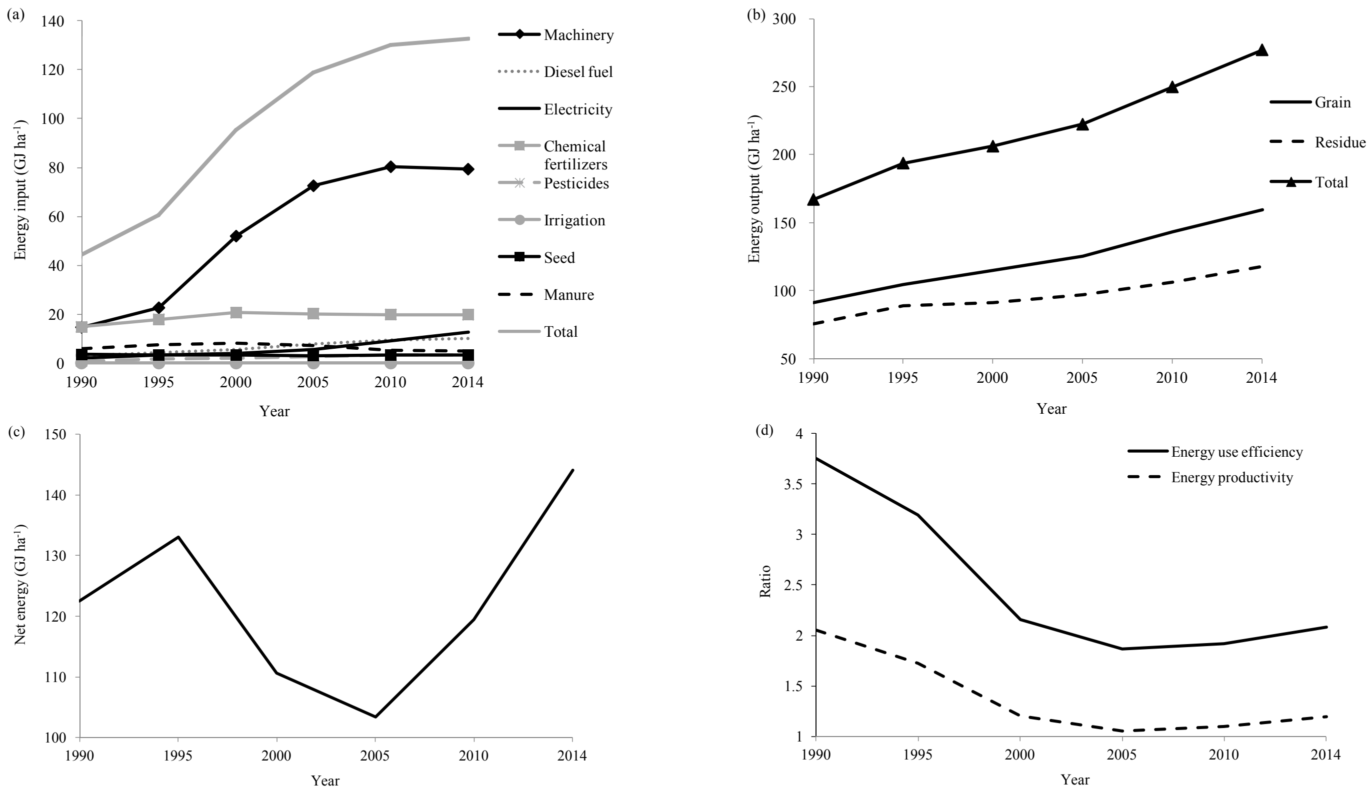

Fig. 2. Energy indicators for crop production in Anhui Province during 1990–2014.

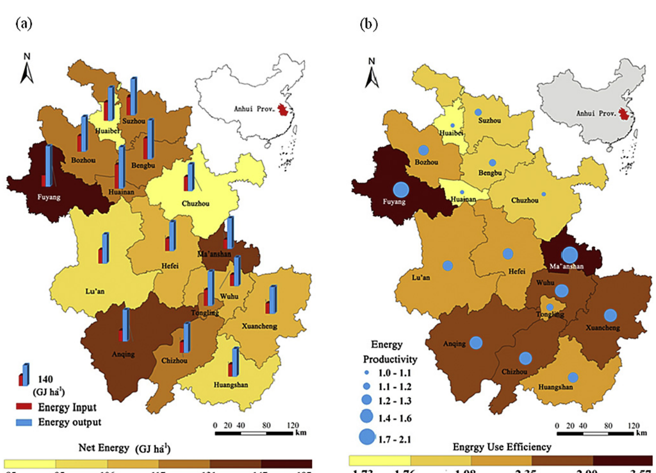

Fig. 3. The spatial distributions of energy indicators for crop production in Anhui Province in 2014.

conducted by Yu et al. [7] has similar research findings, with an annual 2.1% increase of GHG emissions. Comparing with these two studies, this study focuses on Anhui, a typical agricultural province with more intensive agriculture activities and decreasing agricultural land due to both industrial and urban development. Consequently, the use of fertilizer, pesticide and agricultural machines is more intensive than the national average. This is also consistent with governmental statistical data [71,99] (Fig. 6), in which it is clear that these energy inputs experienced a fluctuating increasing trend, except for the nitrogen fertilizer and phosphate fertilizer. The main reason is that China has promoted the wide use of chemical fertilizers since 2000, leading to serious environmental concerns, such as climate change, eutrophication, acidification, soil contamination, etc [100–103], But in Anhui province, with rapid development of livestock breeding and improved environmental awareness of local farmers, most manure were applied as the organic fertilizer to reduce the consumption of the chemical fertilizers. Hence, the application intensity of these chemical fertilizers in Anhui was lower than the national average level.

With regard to studies in other developing countries, Tabar and his colleagues [98] investigated energy consumption for crop production in Iran. Their study covers energy consumption related with agricultural machines, the use of diesel, chemical fertilizer, pesticides, irrigation, seed, but not electricity and manure [98]. They found that total energy input increased from 32.40 GJ ha^{-1} in 1990 to 37.20 GJ ha^{-1} in 2006, increased only by 0.30% annually and much lower than that in Anhui. Their results also show that irrigation (40.0%) and fertilizer (28.4%) had the highest shares because agricultural irrigation is widely performed and nitrogen fertilizers are extensively used in Iran. Another similar study was conducted by Soni and his colleagues [39] for the crop production in Northeast Thailand during 2008–2009. They found that energy intensities of the uses of seeds and the chemical fertilizers are the top two total energy inputs, with figures of 23.75 GJ ha^{-1} and 21.06 GJ ha^{-1} in 2009, respectively, while other two energy inputs (including energy consumption related with manure and pesticide) were only 4.84 GJ ha^{-1} and 0.89 GJ ha^{-1}. Energy intensities of chemical fertilizers and manure in Northeast Thailand were similar to those in Anhui, but the energy intensities of other two energy inputs were very different. Energy intensity of seed was much higher than that in Anhui, with a figure of 3.00 GJ ha^{-1}. This was probably caused by the different calculations of the energy intensities of the studied crops in these two regions. Energy intensity of the seeds in Thailand was calculated by the total energy of seeds being divided by the total area of crops, which was much smaller than the total

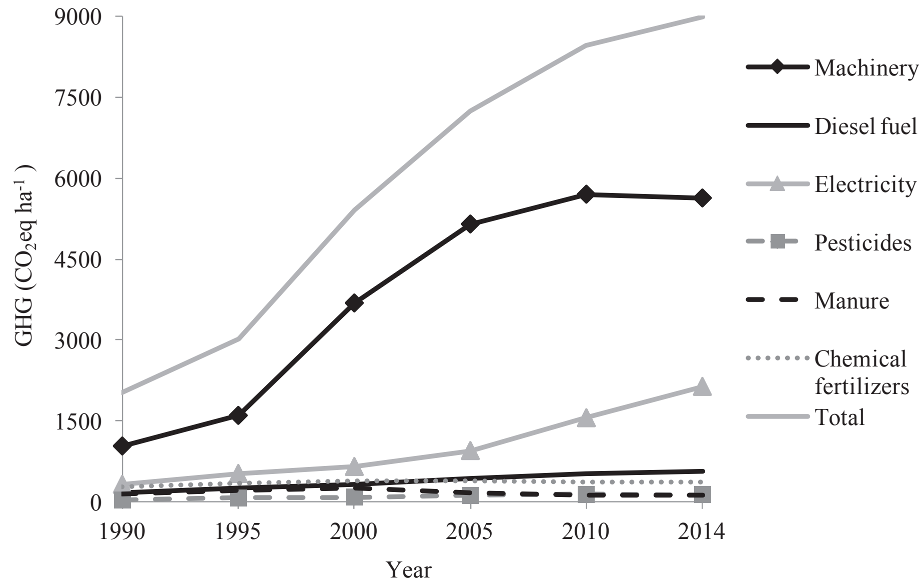

Fig. 4. The greenhouse gases emissions from crop production in Anhui Province during 1990–2014.

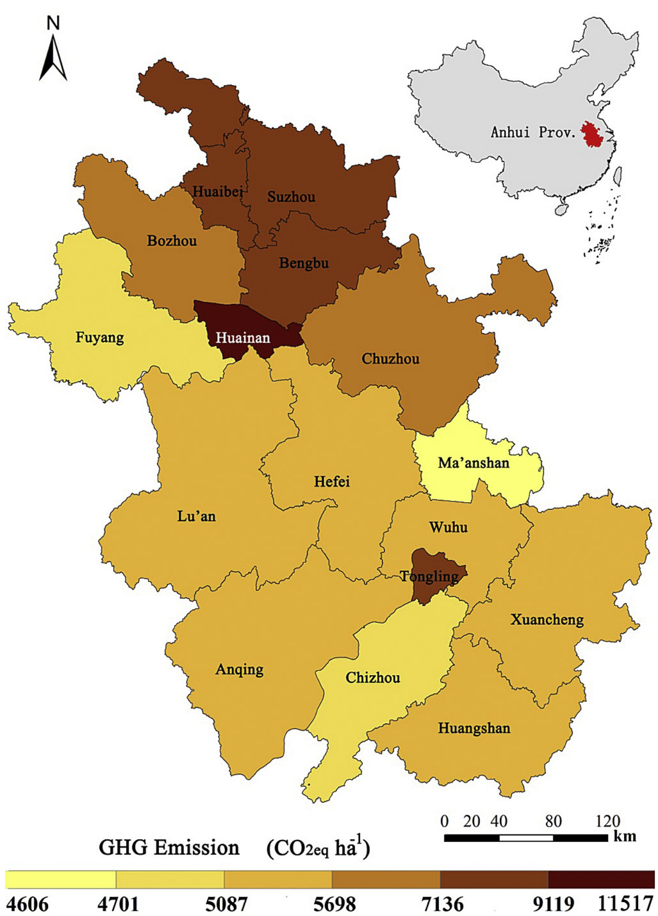

Fig. 5. The spatial distributions of greenhouse gases emissions from crop production in Anhui Province in 2014.

cultivated area in Anhui. In addition, energy intensity of the pesticides in Thailand was only 1/3 of that in Anhui. This may be explained by the fact that few pesticide enterprises exist in Thailand.

4.2. Optimization of energy structure

Since the EUEs, EPs, and GHG emissions are all determined by the energy inputs, the energy inputs should be optimized for increasing EUE and reducing GHG emissions. The results show that the energy consumption from the use of agricultural machines increased from 32.86% to 61.58% of the total energy input, while the corresponding GHG emissions increased from 51.45% to 71.10% of the total GHG emissions. Under such a circumstance, it would be rational to improve the energy efficiency of all the agricultural machines. Several measures can be taken. For example, some modern agricultural machines are now being operated by renewable energy, such as solar power based mowers. Also, the provincial government should encourage more renewable energy sources in its power grid, such as wind power, solar power, biomass, and hydrological power so that the embodied GHG emissions for the final use of agricultural machines can be reduced. In addition, more innovative efforts should be made so that the engine efficiency of those agricultural machines can be improved.

Also, chemical fertilizers contributed a lot to the energy inputs and corresponding GHG emissions, which is consistent to Liu et al.'s research [75]. However, the application of chemical fertilizers led to many concerns, including soil contamination, groundwater pollution, heavy metal accumulation in the crops and retarded crop growth, etc. Therefore, it will be reasonable to consider how to phase out the use of chemical fertilizers and increase the use of organic fertilizers (such as manure from local farms). Organic fertilizers can provide more nutrients to the crops, with up to five times phosphorus element to the soil under the appropriate use [83], such as rational transport and storing facilities on manure and pre-dewatering treatment [104]. Moreover, some researchers found that the return of straws to the agricultural field is one effective measure to reduce the impact resulted from the chemical fertilizer [105–107]. However, the open burning of straws is widely implemented. Many straws were incompletely combusted, leading to the emissions of a large amount of pollutants (including carbon monoxide (CO), volatile organic compound (VOC), and carcinogenic polycyclic aromatic hydrocarbons and fine/inhalable particles) [108]. Such actions would also bring serious health threats to the local residents. In general, these measures should be taken with

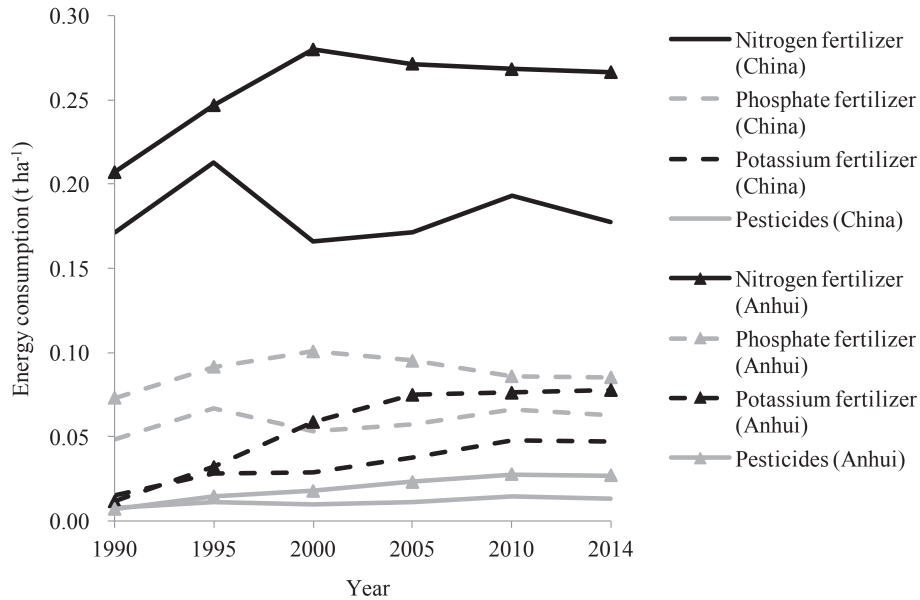

Fig. 6. Comparisons of energy consumptions from crop production between China and Anhui Province during 1990–2014.

more capacity-building efforts so that the practitioners can better understand the potential benefits of using organic fertilizers and learn the most appropriate management options so that they can improve the use efficiency. In addition, innovative technologies should be supported so that the used fertilizer can better fit the local soil with the optimal amount and under the right time [109]. This will require the local government to provide more technical support. For instance, the local government can send trained technicians to educate the local farmers so that the best practices can be delivered to them.

Also, after the use in the agricultural field, the surplus manure can be reprocessed to generate biogas as one renewable energy source [110]. Such a measure can reduce the overall volume of residual sludge and improve the storage, transport and field application of the sludge [111]. Finally, the capability of waste treatment in the local breeding enterprises must be improved. The local governments should increase their investment on constructing sewage and solid waste treatment facilities and strengthen the rural residents' environmental awareness through various capacity-building activities, such as TV and newspaper promotion, workshops, and pamphlets.

4.3. Methodological discussions

This study analyzes the energy indicators and GHG emissions at the province level and proposes some strategies for improving EUE and reducing GHG emissions. The method is straightforward and easy to use, especially with reference to regions in central China. However, several limitations remain in the study and should be improved in future studies.

4.3.1. Data uncertainties

Suh and Yee [112] showed the data were assessed individually according to several criteria: the existence of multiple data sources for cross-checking, the fitness of the data used in terms of the average base year, the fitness of the data used in terms of the geographical coverage, and the method of original data compilation. Thus, the data used in the study are inevitably subject to various degrees of uncertainty. Firstly, due to many categories of agricultural machines, crops, and livestock, this study only considered the main categories. Correspondingly, the results of energy inputs, energy outputs, and GHG emissions may be slightly smaller than the actual values. In addition, the consumption of electricity gained from the statistical yearbook refers to the total energy consumed in rural areas including the crop production and the rural consumption. However, this study utilized such data as the total energy consumed in crop production due to the data availability, which may enlarge the related energy input and the GHG emissions. Moreover, the use of energy equivalents and the GHG emission factors for the energies could also lead to uncertainty because of the diversities of their sources. Wang et al. [113] indicate that emissions from livestock and crops depend on many factors, such as animal types, their weights and ages, types of animal housing and manure storage and application, weather, and soil types. While these realistic data could be hardly obtained, the IPCC method can be used for estimating these GHGs emissions. However, as the inventory data developed by the IPCC method are also comprehensive and some are hardly collected, this study selected the direct method which needs less data to determine CO_2 emission coefficients. Moreover, different manure management practices may lead to different emission factors. However, due to the lack of further information on the related practices, such an aspect has not been fully considered in this study.

This study assumed the proportion of manure applied to field to be 57.50%, 52.50%, 47.50%, 42.50%, 37.50%, and 37.50% over 1990–2014, referred to the national studies [82,111], since the local characteristics of the discharge of the manure in Anhui were not available. Also, this study assumed that the remaining manure not be applied to fields was directly discharged to the environment, neglecting other uses such as fish feeding and biogas production.

In fact, as Wu et al. [114] indicated, all the data uncertainties could be minimized by comparing an extensive range of reference sources, including literature, questionnaires, and interviews. The accuracy of the data could also be improved through local monitoring and site surveys. In addition, data uncertainty could be quantified by using some software or methods such as Monte Carlo simulation, which is used to predict/simulate measurement results on the basis of probability density functions of the input quantities

[115].

4.3.2. Model limitations

4.3.2.1. Energy inputs selection. This study only analyzes the major energy inputs of crop production but neglects several marginal energy inputs because of data availability, including the environmental inputs (eg. Sunshine radiation, wind, and rain), human labor and gasoline. Since inputs related with natural environment is hard to track and estimate, many studies also did not consider such inputs. Although human labor was often analyzed in several studies [11,14], it contributed a very marginal part to the total energy input and would not significantly influence the model results. For example, such an input occupied only 0.07%, 0.87%, 2.0%, 0.02%, and 5.47% of the total energy inputs for broiler production [44], canola production [19], potato production [41], wheat production [73], and olive oil production [74] in Iran.

4.3.2.2. Temporal analysis. This study analyzes the energy indicators and GHG emissions of the crop production in Anhui for the period of 1990–2014. However, these indicators may change annually. Due to the data availability, only years of 1990, 1995, 2000, 2005, 2010, and 2014 were selected for detailed calculations. There are also some similar studies analyzing energy consumption and GHG emissions with a five-year period [98,116]. However, the results in these years cannot be used to accurately reflect the precise values of other years. Additional data collection and accurate calculations should be considered in the future studies so that a more complete picture can be presented. In addition, this study only analyzes the spatial characteristics of energy indicators and GHG emissions for the year of 2014, while the spatial characteristics for other years have not been studied. Thus, it would be rational to have more studies on different years so that more comprehensive perspectives can be reflected.

4.3.2.3. System definition. This study focuses on energy consumption and corresponding GHG emissions from crop production in Anhui. Other processes, such as agricultural resource production, transportation, livestock breeding, residential consumption, and waste disposal, are not considered. In fact, these processes are parts of the life cycle of the entire agricultural production [72,111]. Correspondingly, it would be more efficient to combine the proposed method with life cycle assessment (LCA) so that more holistic views can be achieved [117]. For example, Liu et al. [75] applied LCA to analyze the energy use and GHG emissions of the pear production system, including agricultural resource production, cultivation, processing, retailing, consumption, and waste management.

4.3.2.4. Method selection. LCA is a holistic accounting approach that captures environmental pressure related to the production, usage and disposal (life cycle) of a product or a service [118]. It has been applied in many agricultural studies. Especially, several studies used LCA to assess the environmental impacts associated with livestock commodities [119,120]. However, the use of LCA is data intensive. The agricultural activities such as livestock breeding are also complex and need more site-specific data. Furthermore, it has a weakness on mechanism processes of pathways, which limits its possibility to simulate the material flows within a complex system. Hence, the LCA method may be used by combining with other methods. For example, substance flow analysis (SFA) can be applied to each unit-process along the life cycle [121]. Bouman et al. [122] recommended another hybrid method that simultaneously employs the LCA, SFA, and partial equilibrium analysis (PEA) methods, thus harnessing the advantages and mitigating the shortcomings of each method.

4.4. Research contributions

This study analyzes energy consumption and GHG emissions for the whole agricultural sector in Anhui Province, which has many typical agricultural features in China. Thus, this study can help provide more valuable experiences on reducing energy consumption and GHGs from agricultural sector at the regional level. In addition, this study provides relevant data inventories for similar studies in the future. The coefficients of energy indicators and GHGs from this study can be used for future comparison studies so that more scientific information can be shared by those policy makers to make more appropriate mitigation policies on agricultural production.

5. Conclusions

This study analyzes dynamic and spatial characteristics of energy flows, EUEs, and GHG emissions from the crop production in Anhui Province. It shows that the EUE decreased from 3.75 in 1990 to 1.87 in 2005, and then increased to 2.08 in 2014. This is mainly due to the changes of energy inputs and energy outputs. On one hand, the total energy input increased from 44.54 GJ ha^{-1} in 1990 to 132.97 GJ ha^{-1} in 2014, especially during the period of 1990–2005, mainly because of the use of agricultural machines and chemical fertilizers. On the other hand, the total energy output also increased from 167.05 GJ ha^{-1} in 1990 to 277.05 GJ ha^{-1} in 2014, indicating the improved agricultural efficiency and the increased grain harvest.

The total GHG emissions from the crop production of Anhui during 1991–2014 had a similar trend as the total energy input due to the interlinkages between the two issues, increasing from 2919.51 CO_2-eq in 1990–8993.46 CO_2-eq in 2014. The rapid increase was mainly due to the fast increase of the use of agricultural machines and chemical fertilizers.

With regard to the spatial characteristics of EUE and GHG emissions from crop production in Anhui in 2014, cities in the central and northern Anhui, such as Fuyang, Bengbu, Suzhou, Huaibei, and Hefei, had the higher energy inputs and outputs than other cities, leading to both smaller EUE and EP values and higher GHG emissions in these cities. The main reason is that these cities had higher inputs of agricultural resources.

Several mitigation measures are proposed by considering the local realities in order to further reduce both energy consumption and the corresponding GHG emissions, such as the improvement of f fertilizer application efficiency, the construction of sewage and solid waste treatment facilities, the application of environmentally friendly fertilizers and pesticide, etc.

In general, this case study in Anhui province can provide valuable policy insights to other Chinese provinces, especially those provinces with more agricultural activities. However, due to different development stages and challenges that different provinces are facing, policy makers will have to prepare more appropriate strategies and adopt more feasible measures by considering their local realities.

Acknowledgments

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