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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