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Inequality across China's Staple Crops in Energy Consumption and Related GHG Emissions

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ABSTRACT

It is significant to investigate the inequalities between energy consumption and related greenhouse gas emissions for sustainable crop production in China. We adopt a hybrid economic input-output and life cycle assessment model, in order to examine the crop-specific embodied energy intensity (EEI) and energy consumption related greenhouse gas intensity (ECR-GHGI) of 29 staple crops from 1990 to 2010. A sensitivity analysis is employed to investigate the relationship between ECR-GHGI and the different components of EEI. We further determine, via a structural path analysis, product-specific energy management priorities for each agricultural production input (API). Our findings indicate the following: (1) The EEI and ECR-GHGI of cash crops are greater than those of grain crops. (2) The EEI and ECR-GHGI of most grain crops increased during the sample period, while the EEI and ECR-GHGI of most cash crops decreased. (3) Energy consumption of synthetic fertilizers is the primary driver of ECR-GHGI across the full range of crops. Agricultural machinery and pesticides are also important factors. (4) Potential energy-savings practices in the API production processes should be taken seriously. (5) Different actions should be implemented to reduce energy consumption levels and ECR-GHG emissions in terms of the production processes of different APIs.

1. Introduction

Since 2009, China has been the largest energy consumer and greenhouse gas (GHG) emitter in the world (Xu et al., 2014). China's rapidly rising GHG emissions have received ever-increasing attention worldwide in recent years. Under the present circumstances, China is facing increasing pressure to reduce energy-consumption related GHG (ECR-GHG) emissions. In order to realize the sustainable development, it is essential to disaggregate the energy-saving obligations of different sectors, as well as each sector's distinct sensibilities to ECR-GHG emission mitigation (Cheng et al., 2015; Lin and Xie, 2016).

The role of agriculture cannot be underestimated in the context of energy-saving (Chen et al., 2006, 2009; Taghavifar and Mardani, 2015) and ECR-GHG emission abatement (Smith et al., 2008; Robaina-Alves and Moutinho, 2014; Bennetzen et al., 2016a). The crop production system (CPS) is the most important production sector in China's agriculture industry. Unlike other industries, crop production directly consumes both a large amount of fossil-based energy (e.g., diesel oil and electricity), as well as a great deal of energy-intensive agricultural production inputs (APIs) produced by other industries (e.g., synthetic fertilizers, pesticides, agricultural machinery and plastic film). Energy-intensive APIs are considered to be important sources of indirect primary fossil-based energy consumption and ECR-GHG emissions in the CPS (Popp et al., 2010; Soltani et al., 2013). Therefore, China's energy intensive CPS has both directly and indirectly emitted enormous amounts of GHG.

In China, relying on fossil-based energy consumption to enhance crop production is becoming an important feature of the country's CPS (Cao et al., 2010; Zhang et al., 2015). Some studies (e.g., Dong et al., 2013; Wang et al., 2015) show that China must increase its annual crop production capacity by an additional 545 Mt. over the next decade, just to meet the demands of the country's increasing population and ensure its food security. This growth has seen increases in the APIs of synthetic fertilizers, diesel oil, pesticides and plastic film of 114.71%, 115.61%, 139.84% and 350.83%, respectively, from 1990 to 2010 (NBSC, 1995-2013a). Understanding the features of energy consumption and ECR-GHG emissions from China's CPS is important in terms of assessing energy-saving and GHG mitigation potential and options (Smith et al.,

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2008; Schneider and Smith, 2009).

The crop-specific level plays a dominant role in GHG emission abatement in China's CPS. Thus, analyzing the inequality at the crop-specific level is significant in terms of managing the energy consumption and ECR-GHG emissions in China's CPS (Cheng et al., 2015). This topic has received considerable attention from the related academic communities (e.g., Khoshnevisan et al., 2013a, 2013b, 2013c, 2014; Nabavi-Pelesaraei et al., 2014; Yousefi et al., 2014a, 2014b; Taghavifar and Mardani, 2015). The metric *per unit area* is usually employed to assess energy consumption and ECR-GHG emissions in these studies. From the perspective of inequality in energy consumption, embodied energy intensity (EEI) (i.e., energy consumption *per unit product*) and energy consumption-related GHG intensity (ECR-GHGI) (i.e., GHG emissions *per unit product*) are more appropriate factors to be used in the analysis of the inequality from environmental impacts across different crops. These factors also provide more information than *per unit area* metrics (Grassini and Cassman, 2012; van Groenigen et al., 2012; Bennetzen et al., 2016a). Thus far, in China, most related studies have investigated energy consumption and ECR-GHG emissions at the whole CPS level (e.g. Cao et al., 2010; Zhang et al., 2015; Zhen et al., 2017b). Relatively few studies (e.g. Cheng et al., 2015; Lin et al., 2015; Xu and Lan, 2016) have quantified and compared the numerous crop-specific embodied GHG emission intensities (energy and land-based GHG). These earlier studies provide aggregate information regarding the distribution of embodied GHG intensities across several grain crops or hybrid crop groups. These studies also show that energy consumption (especially for synthetic fertilizers) was the primary contributor to embodied GHG emissions. Different crop types should bear different responsibilities for contributing to energy-saving and ECR-GHG emission reduction. Thus, making an in-depth study of the distributions of EEIs and ECR-GHGIs and the correlation between these two indicators in China's CPS (especially the staple crop system) is worthwhile. To the best of our knowledge, few studies have been conducted on the inequality of EEI and ECR-GHGI, as opposed to quantified crop-specific embodied GHG emission intensities (energy and land-based GHG) at the crop-specific level in China (Cheng et al., 2015; Lin et al., 2015; Xu and Lan, 2016).

This paper aims to uncover the inequalities of EEI and ECR-GHGI across China's staple crops. The motivations for this study are described as follows: (1) Agricultural products occupy a major segment of consumption activities in individual households (Liu and Wu, 2013; Xu et al., 2016). Increasing consumer living standards are facilitating energy consumption and ECR-GHG emissions in China's CPS (Khoshnevisan et al., 2013a; Wang et al., 2015; Zhen et al., 2017b). The need for the CPS to reduce its levels of energy consumption and ECR-GHG emissions has been emphasized in many mitigation policies. (2) In recent years, China's central government issued the planting structure adjustment as a means to improve farmers' incomes (Ministry of Agriculture of the People's Republic of China (MAC), 2011; Central People's Government of the People's Republic of China (CPGC), 2016). One of the main development goals in optimizing China's crop production system is to shift to the implementation of an ecologically friendly and economically beneficial planting structure. Uncovering the EEIs and ECR-GHGIs of staple crops is fundamental to the more efficient utilization of energy and to reducing production costs in the process of planting structure adjustment. (3) Energy consumption (such as the application of synthetic fertilizers) produces the largest emissions of GHG in China's CPS. Most previous studies have focused on measuring embodied GHG intensities, but few studies quantify the EEIs of different staple crops. Mitigation policies should consider the relationships between energy consumption and ECR-GHG emissions for different staple crops, as well as the different aspects of energy consumption related to crop-specific energy consumption and ECR-GHG emissions. (4) Most energy consumed by China's CPS stems from the API production processes (Zhen et al., 2017b). Therefore, analyzing energy consumption flows and identifying energy consumption hot spots and management priorities during the API production processes will help determine the effectiveness of crop production mitigation policies.

This paper quantitatively uncovers the variation trends and structures in the EEI and ECR-GHGI of 29 staple crops in China's CPS. To do this, we use a hybrid economic input-output and life cycle assessment (EIO-LCA) model. This paper also analyzes which crop types and which API types have higher ECR-GHG emission potential in the crop production processes. Using a structural path analysis (SPA), we investigated the energy consumption hot spots and energy-saving priorities in the production processes of different APIs, in order to reduce ECR-GHG emissions. Understanding these issues will help policymakers devise more effective mitigation polices and measures in the future.

The remainder of this paper is structured as follows: Section 2 introduces the methodology. Section 3 presents the data sources. Section 4 provides the empirical results and discussion. Finally, Section 5 presents our conclusions and identifies some policy implications.

2. Methodology

2.1. Hybrid EIO-LCA Model

In this study, a hybrid EIO-LCA model was used to measure the EEIs and ECR-GHGIs of staple crops in China. This hybrid model integrates an environmentally extended input-output (EIO) model and a life cycle assessment (LCA) model. Such an approach allows the detailed and accurate assigning of environmental impacts by using a bottom-up approach in lower-order stages, while the higher-order environmental impacts of consumption are systematically and holistically covered by the economic input-output model (Dong et al., 2013; Lin et al., 2015). Both the embodied energy consumption and ECR-GHG emissions from crop production have direct and indirect components (Zhen et al., 2017b).

Direct energy consumption and ECR-GHG emissions include the diesel oil used on farms and the electricity used for irrigation. These are obtained according to the following equation:

$$H_D = \sum H_{D,i} = \sum T_i \times EF_i \tag{1}$$

where H_D, $H_{D,\ i}$, T_i and EF_i, respectively, denote the crop-specific direct energy consumption and ECR-GHG emissions, direct energy consumption and ECR-GHG emissions from source *i*, the amount of source *i*, and the energy conversion coefficient or ECR-GHG emission coefficient of source *i*.

As national statistical data do not produce the crop-specific amount of electricity used for irrigation, we used Eq. (2) to calculate the amount of electricity used to irrigate different crops, as follows:

$$T_E = W \times P \times HW \times EIR \tag{2}$$

where T_E denotes the quantity of crop-specific electricity used for irrigation per unit area; *P* denotes the crop yield per unit area; *HW* denotes the hoisting height of water, which was set to 20 m (Xu and Lan, 2016); *EIR* denotes the average electromechanical irrigation rate, and *W* denotes the crop-specific average water consumption per unit yield. The average water consumption per unit crop yield for each staple crop was calculated as Xu and Lan (2016).

Indirect energy consumption and ECR-GHG emissions include the energy consumption and ECR-GHG emissions caused by the production processes of seeds, farm machinery, synthetic fertilizers, pesticides and plastic film. We estimated the indirect energy consumption and ECR-GHG emissions of each crop as in an EIO analysis, which is a top-down method of assigning environmental impacts to consumption (Reynolds et al., 2015). The EIO analysis captures the energy consumption and ECR-GHG emissions of each economic sector from a supply chain perspective (Liu et al., 2012). The total output of an economy is expressed as follows:

$$\mathbf{X} = \mathbf{Z} + \mathbf{y} = \mathbf{AX} + \mathbf{y} \tag{3}$$