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Impacts of water and land resources exploitation on agricultural carbon emissions: The water-land-energy-carbon nexus

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A R T I C L E I N F O

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A B S T R A C T

Exploring the effect of water & land resource exploitation on agricultural carbon emissions helps explain agricultural "water-land-energy-carbon" (WLEC) nexus and improve the efficiency of agricultural water and land use. Based on the estimation of agricultural carbon emissions and provincial Matching Degree of Water and Land Resources (MDWL), this paper discussed the relationship between water & land resource exploitation and agricultural carbon emissions by Logarithmic Mean Divisia Index (LMDI) model, and put forward policy suggestions for the future low-carbon development of agriculture in China. The main conclusions are as follows: (1) The agricultural carbon emissions increased from 53.42×10^6tC in 2005–65.12×10^6tC in 2013, with an increasing rate of 21.89%. The carbon emission and its intensity have great spatial differences. (2) The MDWL of China fluctuated from 2005 to 2013, during which the MDWL in 2010 was the highest ($1.56 \times 10^6 m^3/km^2$). It has huge spatial difference across China. Generally, the MDWL of southern and eastern provinces was higher than that of northern and western provinces. (3) The order of contributing effect of each factor on agricultural carbon emissions is: economic output of water resources > the ratio of water and land resources > population factor > land use area per capita > agricultural carbon emission intensity. In those factors, agricultural carbon emission intensity is the main inhibitory factor, while the economic output of water resources is the main contributing factor. (4) The ratio of water and land resources has different effect on agricultural carbon emissions in different provinces. Generally, the inhibitory effect was much higher in the provinces with high MDWL than that of provinces with relatively lower MDWL. (5) To improve agricultural energy efficiency and promote carbon emission reduction, the agricultural technology should be improved, and land consolidation, large-scale operation, water-saving irrigation and the fallow rotation system of crops should be adopted.

1. Introduction

Greenhouse gas (GHG) emission from agricultural activities is one of the important parts of global GHG emissions (Robertson et al., 2000; McCarl and Schneider, 2001). According to IPCC's special report on emission scenarios, about one fifth of the worldwide annual anthropogenic GHG emissions came from agricultural sectors (excluding forest conversion). Therefore, agricultural GHG emission has become a hot topic in recent decades (Gan et al., 2014). Agriculture is a kind of human activities that depends directly on resources exploitation. In agricultural production system, water, land and energy, three of the most important resources needed for crops growth and agricultural activities, are inextricably interlinked. Through their interaction, carbon is emitted from energy consumption during water and land related agricultural activities. Therefore, the interaction processes and the efficiency of agricultural water-land-energy system are main factors that influence agricultural carbon emissions. As growing populations demand more energy, water resources and food supplies, understanding agricultural water-land-energy nexus and its relationship with carbon emissions has become increasingly important (Khan et al., 2009a, 2009b; Skaggs et al., 2012).

There were researches on the relationship between carbon emissions and land & water resources in recent years. One the one hand, some researchers found that energy consumption brings carbon

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emissions from agricultural water use, such as irrigation and pumping (Wang et al., 2012) and the exploitation of groundwater and diverted water (Li et al., 2013). For example, Li et al. (2013) found that the GHG emissions from groundwater accounted for 65–88% of the total emissions from agricultural water sector. Also, there were researches on the water-energy nexus of certain crops and its relationship with carbon flux (Kothavala et al., 2005; Zhang et al., 2013), and found that carbon emissions in agricultural processes were influenced by water and energy flux. Those researches provided important ideas for understanding the relationship among water, energy and carbon efficiency on micro scales. On the other hand, the relationship between land use and carbon emissions also became a hot topic in recent years. Some researchers studied the impacts of land use on carbon emission or carbon balance from national (Houghton et al., 1999; Houghton and Hackler, 2003; Lai and Huang, 2011; Lai et al., 2016), provincial/regional (Koerner and Klopatek, 2002; Araújo et al., 2009; Zhang et al., 2012; Zhang et al., 2015) or urban level (Ali and Nitivattananon, 2012; Zhao et al., 2015), and found that land use would greatly influence carbon processes through human energy consumption and land management practices. Agricultural land use activities, such as agricultural management and operations (Lal, 2004; Nadeu et al., 2015; Pugh et al., 2015; Ogle et al., 2014), land sparing (Lamb et al., 2016), Land management (Smith et al., 2008), tillage system (West and Marland, 2002) and land consolidation (Tan et al., 2011), will influence agricultural carbon emissions and eventually change carbon budget through different intensities of human input and land use. Those studies were mainly focused on carbon equivalents (including CO_2, CH_4 and N_2O) emissions from natural processes of crops. However, energy use in agricultural activities such as cultivation, land leveling, irrigation, farmland consolidation and fertilizing & herbicides production are also important sources of direct carbon emissions (mainly CO_2) in agricultural sector (Cheng et al., 2011; Xiong et al., 2016a; Xu et al., 2013). Actually, carbon emissions from agriculture were mainly caused by energy consumption during agricultural production (Khoshnevisan et al., 2013; Mohammadi et al., 2014; Camargo et al., 2013), especially in water use and land related activities (Barbosa et al., 2015; Smidt et al., 2016). Therefore, some researchers have studied water-land-energy nexus and its relationship with climate change (Skaggs et al., 2012; Howells et al., 2013), food production (Ringler et al., 2013) and ecosystem service (Watanabe and Ortega, 2014), which showed that exploring the mechanism of water-land-energy system is meaningful to understand the connection between human and nature, and provide new thoughts for evaluating the impacts of human activities on environment. Generally, those past studies mainly focused on agricultural carbon emissions of different land use activities and water exploitation separately, especially on natural carbon fluxes from agricultural system. Although the water-land-energy nexus was studied on some aspects, the combination study on the relationship between water & land resources exploitation and carbon emissions should be further strengthened, which will not only help understand the water-land-energy-carbon interaction mechanism, but also has great significance for understanding the efficiency and capacity of agricultural water and land resources exploitation, and further promoting the comprehensive study on carbon effect of regional multi-resources exploitation.

The most commonly used methods in the researches of water, energy, carbon flows and nexus includes material flow analysis (MFA) or substance flow analysis (SFA) (Warren-Rhodes and Koenig, 2001; Pataki et al., 2006; Zhou et al., 2013), input-output analysis (IOA) (Wang et al., 2017; White et al., 2017), life cycle assessment (LCA) (Venkatesh et al., 2014; Chang et al., 2015), ecological network analysis (ENA) (Chen and Chen, 2012), carbon flow network (CFN) (Chen and Chen, 2016), etc. The integration of the above methods was also used in some studies (Wang and Chen, 2016; Chen and Chen, 2015). Generally, MFA/SFA and LCA are bottom-up methods, which is a useful tool to quantify the materials/substances flows on micro-regional scale or manufacturing processes (Duan and Chen, 2016). As a top-down method, IOA is much feasible for considering data availability at multiple scales (Okadera et al., 2014), and can estimate both direct and indirect flows (Shao and Chen, 2016; Chen et al., 2013; Chen and Chen, 2015). ENA was usually used to explain system interactions (Chen and Chen, 2012). Furthermore, the coupling of regional energy-carbon nexus also has been analyzed based on other approaches such as statistical regression (Dhakal, 2009), non-linear decomposition modeling (Zhou et al., 2016) and land cover modeling (Parshall et al., 2010). However, it is a challenge to comprehensively simulate the water-land-energy- carbon (WLEC) nexus on the regional scale.

With rapid population growth, economic development and urban expansion, China faces serious shortage of water and land resources (Piao et al., 2010; Jiang, 2009). For example, China's population and GDP increased 8.46% and 272.52% (in constant price) during 2000–2014 respectively (National Bureau of Statistics of China, 2015), while water resources per capita decreased from 2193.9 m^3 in 2000–2039.2 m^3 in 2014, and arable land area per capita declined from 0.094 hm^2 to 0.077 hm^2 during the same period (World Bank, 2017). Presently, there still exists low-efficiency and extensive use of water & land resources in many provinces of China (Deng et al., 2006). Agricultural production in some arid and ecologically fragile zones has exceeded the carrying capacity of local water and land resources (Varis and Vakkilainen, 2001), which caused the decrease of land productivity, salinization and desertification (Wang and Cheng, 2000; Zhang et al., 2007). Meanwhile, extensive input of resources and energy in agricultural activities also caused more carbon emissions (Liu et al., 2017). Agriculture sector in China is responsible for roughly 17–20% of annual GHG emissions (Wang et al., 2010) of which an unknown proportion originates from energy use in land and water exploitation. Indeed, the broader "energy for water and for land" dimensions of the water–land-energy nexus are under-recognized and poorly quantified (Rothausen and Conway, 2011; Wang et al., 2012). Energy uses in agricultural land and water resources exploitation are main reasons for carbon emissions (Zhao et al., 2015; Wang et al., 2012). Therefore, in China's "Thirteenth Five-Year Plan" in 2016, the government proposed the aim of "promoting resource saving and the transformation of resource exploitation mode, and significantly reducing consumption intensity of energy, water and land within the next five years." Therefore, researches on the impacts of water and land resources exploitation on agricultural carbon emissions has great significance for the development of low-carbon agriculture in China.

There exists obvious difference of land and water resources on the provincial level of China, which determines the crop patterns, water and land use modes and intensities. Therefore, this paper tries to answer the following two questions: (1) How much carbon emitted from energy consumption of land and water exploitation processes during agricultural activities? (2) To what extent the matching patterns of water and land resources will influence agricultural carbon emissions on the provincial level? Actually, water and land matching degree is one of the key elements that influence carbon emissions from agricultural processes. Logarithmic Mean Divisia Index (LMDI) model is a method that can flexibly decompose the main factors of carbon emissions on multiple scales. It is also suitable to explore influencing mechanism of water/land matching relations on carbon emissions from provincial level. Therefore, this paper attempts to estimate agricultural carbon emissions of land and water exploitation and the provincial Matching Degree of Water and Land Resources (MDWL) of China, and analyze the influencing factors of agricultural carbon emissions by introducing water and land factors into LMDI model from the view of agricultural WLEC nexus.

The aim of the paper is to explain the relationship between water & land resource exploitation and agricultural carbon emissions, and analyze its spatial-temporal distribution on China's provincial level. Through establishing the framework of agricultural WLEC system, this paper provides a new perspective to explore the impact of water & land resource exploitation on agricultural carbon emissions. This study