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Virtual land, water, and carbon flow in the inter-province trade of staple crops in China

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ABSTRACT

In the context of a growing world population and limited resources, trade plays an indispensable role in maintaining a constant food supply, and when commodities exchange occurs, it connects entire ecosystems and societies. In this study we used Chinese inter-province trade in staple crops to investigate the interaction of resource consumption and carbon emission systems. The trade in staple crops was simulated using an optimization model, we found that in the trade pattern the virtual land resources flowed from land-rich to land-poor provinces, but the situation was reversed for the redistribution of water resources. The trade pattern showed that total land resource use increased but water resource use decreased throughout compared with local production of traded commodities, based on the production efficiency of export and import provinces. The total carbon dioxide emissions from staple crops production in the inter-provincial trade was 254×10^8 kg carbon dioxide equivalents (CEs), and the average unit CE emissions was higher for export provinces than importing provinces. We combined the net staple crops trade, resource abundance, and unit CE emissions within provinces to define eight classes describing resource and environment management in specific areas, and to guide improvements in crop production and trade.

1. Introduction

China is facing water and land resources crisis with the water resource shortage and arable land degradation, and the crisis is getting worse due to the uneven resources distribution and unmatched water and land resources in areas. Besides the engineering resources allocation, resource can also be redistributed with virtual resources flows through trade (Feng et al., 2014a; Feng et al., 2014b; Zhao et al., 2015). Pace and Gephart (2016) concluded that trade has become a routine part of ecosystem services through monetization of its value. In addition, trading of commodities adjusts the balance of supply and demand among areas, and as trading process link society and the ecosystem there has been evaluation of the effects of trade on environment and resource management, and on economic and societal interests (Wichelns, 2001; Würtenberger et al., 2006). With the research findings, the inter-provincial study shows great significance as it is more practicable for further policy making and pattern adjusting without political factors existing within worldwide study.

The study of trade in ecosystem service science has recently become a major area of research emphasis, particularly in relation to the effects of trade on the ecosystem. It is typically discussed in terms of the interactions and trade-offs associated with production of traded commodities in export and import areas, trading mechanisms, and government policies (Han et al., 2017; Xie et al., 2010). For example, Martinezmelendez and Bennett (2016) studied the agricultural trade between the United States and Mexico, and identified that trade can reduce the environmental impact (including land, fertilizer, and water use) of food production by shifting crop production with subsequent trading to the most efficient country.

In evaluation of the effects of trade on the ecosystem, the concepts of virtual resource and carbon footprint have been widely used (Cheng et al., 2015; Galli et al., 2012; Sun et al., 2014; Dalin et al., 2015; Xie and Liu, 2015). The virtual resource concept directly reflects the major land and water resources used in association with crop trading (Chapagain and Hoekstra, 2003a,b; Chen and Han, 2015; Vanham, 2013; Wackernagel et al., 1997; Wackernagel and Hansson, 1999; Wackernagel et al., 1999; Wackernagel et al., 2004), while the carbon footprint is a measure of the direct and indirect CO2 emissions associated with certain activities (Cheng et al., 2015; Dong et al., 2013; Pathak et al., 2010; Weidman and Minx, 2008). In addition to the direct

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gaseous emissions from a crop field, the entire agricultural production process, including chemical fertilizer and pesticide use, and seed and other agricultural inputs, indirectly result in emissions of large quantities of greenhouse gases (Cao et al., 2014). Recent studies of carbon emissions from crop production have mostly concerned the crop production system, although transportation is also very important (Cristea et al., 2013; Howitt et al., 2011; Ponsioen and Blonk, 2012; Weber and Matthews, 2008; Zanni and Bristow, 2010). In recent decades, measurement of the carbon footprint has been extensively used to quantitatively evaluate carbon emissions related to crop agriculture. Most virtual resource mapping studies have been limited to international or regional levels. In China there have been few studies of the crop trade between provinces, because of the difficulty in obtaining relevant data (Hanasaki et al., 2010; Sun et al., 2016). In this regard, methods including general equilibrium models have been widely used (Chen et al., 2010). For example, Guo and Shen (2014) used a multi-regional input and output model to calculate China's farmland and water use, and Dalin et al. (2014) applied a linear optimization model to study the inter-province and international food trade in China. In relation to carbon emissions associated with crop trading, most studies have considered the entire agricultural production process, while few have evaluated the carbon footprint associated with specific crops.

In this study we used the inter-province crop trade in China to investigate the impact of trade on the ecosystem, focusing on land and water resource use and carbon emissions. Three main problems were considered: (1) how do water and land resources flow during inter-province trade? (2) what is the effect of the trade on carbon emissions? (3) how can each participant in inter-province trade of staple crops be evaluated? Our study included 31 provinces, autonomous regions, and municipalities. We simulated the patterns of the inter-province crop trade using a linear optimization model; and calculated the virtual resources and carbon footprints for the five main crops (wheat, maize, rice, potatoes, and soybean).

2. Materials and methods

Relevant data were collected for the 31 Chinese mainland province-level administrative regions (not including Taiwan, Hong Kong, and Macao) involved in the study. The traded commodities were studied as staple crops (rice, maize, wheat, soybean, and potato) accounting for 92% of all grain crops planting area, the statistical data on these crops were obtained from the China Statistics Yearbook (NBSC, 2010, 2011, 2012). The study was based on national daily food demand with self-sufficient state in China; international trade was not considered. To gain the trading data, we build the simulation model with total production and consumption data without classification due to the difficulty in getting specific consumption data. For accurate virtual resource and carbon calculation, the trading data was then separated into the five specific staple crops according to the production ratio in export provinces.

Considering the access of recent census data, and in order to reduce the deviation caused by the volatility of crop trade, the average trade data from 2010 to 2012 were used. A complete life cycle from sowing to harvest of the five crops is taken as the research boundaries, and only indirect emissions are considered, namely agricultural production inputs (such as chemical fertilizers, pesticides, irrigation, electricity, etc.).

2.1. Simulation of inter-province crop trade

Linear optimization was used to simulate the inter-province crop trade, with minimum cost as the goal and supply and demand as the constraints in Formula (1), below. Based on a closed state assumption, inter-province food trade is an unbalanced transportation issue, as production is greater than inter-provincial crop transported volume (trading volume). Costs included the transaction and transportation costs in the CHINAGRO model (China agricultural sustainable development decision support system); this is a general equilibrium model at the inter-regional level that has been used to simulate food transactions among different regions of China (Keyzer and van Veen, 2005). The transaction costs were studied from the food price, which was affected by the per capita crop possession in different provinces according to the resource scarcity economy theory. About the inter-provincial trade transportation ways, railway transportation was judged as the main way according to the relative society surveys (Zuo et al., 2006; Zhong and Kang, 2016) and data from China Traffic and Transportation Statistics Yearbook (MTC, 2010, 2011, 2012). The railway transportation costs analysis was based on data set from the Chinese national railway road network, and point vector data from 31 provincial administrative capital cities (except Taiwan, Hong Kong, and Macao) were used to calculate railway distances. We also used optimal path analysis to predict the lowest transport cost in relation to food transport regulations (China's Ministry of Railways) and food prices, to create a cost matrix (Gao et al., 2014). The average of the data from 2010 to 2012 was used to compute the optimal path analysis at the lowest cost, and the traffic origin–destination cost matrix (OD cost matrix) between provinces was derived in ArcGIS using the national railway network data set (Nie, 2009; Wang, 2007). In Formula (1): the crop trade volume t_{ij} *(kg)* is the crop volume traded from province *i* to province *j* and was an independent variable in the linear optimization; the OD cost matrix is the coefficient; S_i *(kg)* and D_i *(kg)*, respectively, show the crop supply and demand in a province; the province crop production was derived from the China Statistical Yearbook (NBSC, 2010, 2011, 2012); the province crop consumption data was summed up from each area's working report in China Grain Yearbook (SAG, 2010, 2011, 2012); and c_{ij} is the per unit crop transaction cost from province *i* to province *j*.

$$\min\left(f=\sum_{i=1,j=1}^{i=31,j=31} cij*tij\right)$$
$$\sum_{j=1}^{31} tij \le Si,\ i=1,2,\ldots,31$$
$$\sum_{i=1}^{31} tij = Di,\ j=1,2,\ldots,31$$
$$tij \ge 0 \tag{1}$$

2.2. Virtual land and water resources mapping, and estimation of carbon emissions

According to the Penman-Monteith theorem, virtual water was calculated from crop evapotranspiration and crop production, using "blue water" and "green water" (Renault, 2002). Meteorological data including rainfall, sunshine time, relative humidity, average wind speed, daily high and low temperatures, etc., were obtained from the CLIMWAT database of the FAO and the China Statistical Yearbook (NBSC, 2010, 2011, 2012). crop data such as the first and the last date of planting, the first and the last date of harvest, reference evapotranspiration rate, etc., were taken from the CROPWAT software website affiliated resources. Data on soil characteristics, maximum precipitation penetration, maximum root depth, etc., were used from CROPWAT software's default database. Virtual land and water resources from the perspective of producer and consumer were calculated with crop trade volumes and virtual resource usage of per unit crop production (Yan et al., 2008, Lamastra et al., 2017). Each inter-provincial crop trade is distributed in rice, maize, wheat, soybean and potatoes according to the crop yield ratios in the supply provinces from China Statistical Yearbook (NBSC, 2010, 2011, 2012). Unit virtual land usage equals to unit crop production land use from China Statistical Yearbook (NBSC, 2010, 2011, 2012), virtual water availability was calculated using provincial climate and crop attribute data. In Formula