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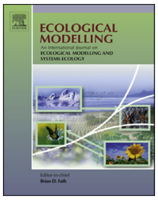

Index decomposition analysis of urban crop water footprint

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ABSTRACT

Rapid urbanization has resulted in often unplanned increases in population, and food demand in cities. Historically, hinterlands to these cities have acted as breadbaskets producing food to the urban residents. Accordingly, a large amount of available freshwater has been needed to support these croplands. However, the rapid expansion of cities in developing countries has significantly changed both the croplands around cities and the water demand. It is thus important to quantitatively investigate the water-food nexus of cities related to the changing hinterland agriculture. Water footprint is an indicator reflecting the human impact on water. In this study, we quantified both the blue and green water footprint of major crop products in Suzhou city, China using a bottom-up accounting method. A novel decomposition analysis was carried out with a Logarithmic Mean Divisia Index (LMDI) method to study the driving forces that changed the water footprint during the period 2001–2010. The drivers were designed to reflect the factors related to farmland, such as yield and crop area. This is different from previous decomposition analyses, which focused on economic factors such as GDP. The results show that the crop water footprint of Suzhou city has seen a general decreasing trend between 2001 and 2010. The decomposition analysis showed that the decline of crop area was the main driver that decreased the crop water footprint, followed by the virtual water content (water consumption per unit of production). In contrast the changes of crop combination and yield contributed to an increase in the crop water footprint. Although the shrink of urban croplands decreased the water footprint of crop products. Cities' increasing demand for food will increase the crop water footprint of consumption. This will increase the dependence of cities on external water footprint of crop products (water embodied in imported crops), which may impact upon food security in cities in the long term.

1. Introduction

Cities constitute primary agglomerations of people. In 2014 54% of the world's population lived in cities, and this is forecast to rise to 66% by 2050 (United Nations, 2014). One of the key challenges faced by cities around the world is to meet food demand for residents (Barthel and Isendahl, 2013; Lynch et al., 2013). Traditionally, farmlands around cities, also known as hinterlands, have supported this food demand (Zezza and Tasciotti, 2010). Such urban agriculture has historically been critical to achieving food security in cities (Lynch et al., 2013). However, the huge water demand associated with agricultural production conflicts with the increasing water demand due to urban population growth. Current trends of rapid expansion of cities, especially in developing countries, has significantly changed both the croplands around cities and the associated water demand. To the best of our knowledge, few studies have focused on the interactions between hinterland agriculture and the water demand associated with urbanization.

The water-food nexus of cities related to changing hinterland agriculture can be evaluated using the water footprint (WF) concept. The WF is defined as the volume of freshwater used during the production process (Hoekstra et al., 2011). It has been widely used in quantifying and assessing freshwater consumption in crop production (e.g. Chapagain and Hoekstra, 2011; Mekonnen and Hoekstra, 2011; Vanham et al., 2013). Freshwater refers to both green water and blue water. Green water is the precipitation on land which does not run-off or recharge groundwater but is stored in the soil or remains on the surface of the soil or vegetation.

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The accounting of green water footprint is closely related to crop growth. The blue water for crop growth can be substituted by green water, so a complete picture can be obtained only by accounting for both (Hoekstra et al., 2011). A bottom-up method is widely applied to accounting for the crop WF, which starts from the smallest unit feasible in assessing the WF and aggregates each unit to the desired scale and period (Yang et al., 2013).

The changes in the WF of crops can be related to crop production and changes in hinterland usage, with drivers such as water productivity, yield, agricultural area etc., to understand the interactions between hinterland agriculture changes and freshwater consumption. In recent years, decomposition analyses has been applied to study the driving forces or determinants that underlie changes to the WF (Feng et al., 2015). For example, Zhang et al. (2012) decomposed the effects of contributing factors to Beijing's WF changes during 1997–2007. The contributing factors were technological, economic system efficiency, scale, and structural effects. Zhao et al. (2014) investigated the impact of population, affluence, urbanization level, and diet factors on the WF of agricultural products in China based on an extended STIRPAT model. The above decomposition analyses, however, were not designed to reflect the factors related to changing farmland, such as crop yield or area, and thus were unable to identify the interrelationships between hinterland agricultural changes and associated water consumption. In addtion, green water was excluded from most decomposition analyses of WF changes.

In the context of increasing urbanization in developing countries, this study has quantitatively investigated the water-food nexus in Suzhou city, China by performing a novel decomposition analysis with a Logarithmic Mean Divisia Index (LMDI) model. The aim was to study the contributing factors to urban crop WF changes, including virtual water content (reciprocal of water productivity), yield, crop structure, and crop area. To best of our knowledge the driving forces related to crop production that changes both green and blue WF has been rarely reported. The driving forces and the implications to water-food security at urban scale are also discussed.

2. Water endowment and water stress in suzhou city

Suzhou city is located in the Taihu Lake Basin, which is a subtropical humid area of plentiful rainfall. The annual available water resource in Suzhou is 2.98 billion m^3 (in 2010). The total administrative area of Suzhou is 8488 km^2, with 3609 km^2 covered by water (Suzhou Water Resources Bureau, 2010). Lake Taihu, a large shallow freshwater lake in the lower Yangtze Delta, is close to Suzhou (Fig. 1), and is the main water resource for Suzhou. Significant nutrient pollution from wastewater discharges, along with agricultural run-off from the northwestern shores flows into Lake Taihu. Nutrient concentrations decrease with the current towards the eastern and southern reaches of the lake which, as a result, have better water quality i.e. the reaches close to Suzhou city, despite extensive blue-green algae problems in the northwestern part of the lake (Hu et al., 2010).

Suzhou is an ideal case for illustrating how hinterland agriculture can be changed through urbanization and industrialization. Although in contemporary China, Suzhou is known as an industrialized city with many high-tech industries, it was until the 1980′s on of China's grain production center. The Taihu Lake Basin has long been known as "the land of rice and fish" in China. Agriculture in the Taihu Lake Basin sustained high productivity for more than nine centuries (Ellis and Wang, 1997). As such, Suzhou has historically had a large amount of hinterland agriculture dedicated to producing rice and other grain products for both local consumption and export to other regions in China. After the foundation of the People's Republic of China in 1949, Suzhou was established as a grain production base (Wang et al., 2015). In 1984, the sown area was about 5000 km^2 with grain production peaking at 3.1 million tons (Suzhou Statistics Bureau, 2011). Since then Suzhou has accelerated its industrialization transformation process by creating a series of industrial park and development zones to stimulate industrial development and attract Foreign Direct Investment (Wang et al., 2015). Today, Suzhou has become one of the wealthiest industrial cities in China. In 2010, GDP in Suzhou ranked 5th among China's 337 cities, following the mega-cities of Beijing, Shanghai, Guangzhou, and Shenzhen. Per capita GDP was about 87,607 CNY (about 12,800 US dollars) (Suzhou Statistics Bureau, 2011). Urbanization in Suzhou, as with other Chinese cities, has experienced land grab and population growth, which have substantial impacts on hinterland agriculture.

Despite its location in a subtropical and humid area, Suzhou as a developed city in China faces water stress. We evaluated water stress in Suzhou during 2007–2010 with two well-known water scarcity indices. The Falkenmark Index evaluates water stress through the total annual renewable water resource per capita (Falkenmark et al., 1989), and the "Criticality ratio" evaluates water stress using the ratio of total annual withdrawals to renewable water resources (Alcamo et al., 2000). The classification of both indices was adjusted according to Zeng et al. (2013) and Zhao et al. (2016) following China's water endowment. As a result, four classifications were generated with C as the "Criticality ratio" and F as the Falkenmark Index: Absolute Scarcity ($C > 1$ or $F < 500$ m^3/capita); Scarcity ($1 > C > 0.4$ or 1000 m^3/capita $> F > 500$ m^3/capita); Stress ($0.4 > C > 0.2$ or 1700 m^3/capita $> F > 1000$ m^3/capita); and No Stress ($C < 0.2$ or $F > 1700$ m^3/capita). The results for the Criticality ratio show the highest level of water stress in Suzhou (Table 1), while the results for the Falkenmark Index show the second highest level of water stress during 2007–2009, and the highest level in 2010. These results suggest that intensive water use and high population density are the main causes of Suzhou's water stress.

3. Method and data

3.1. Quantification of blue and green water footprint of crop products

The WF of crop products in this study refers to the WF of crop growth. The indirect water requirement for crop production, i.e. the water required in production of upstream products only takes a small share of the total crop WF (Zhao et al., 2009), thus is ignored in this study. A bottom-up method to quantify the WF of crop products can be expressed as follows:

$$WF_{tot} = WF_g + WF_b = \sum_i [CWR_{g.i} \cdot A_i] + \sum_i [CWR_{b.i} \cdot A_i] \tag{1}$$

Where WF_{tot}, WF_g and WF_brefer to the total, green and blue water footprint of crops, i is the type of crops planted,A_i is the plant area of crop i, $CWR_{g.i}$and $CWR_{b.i}$are annual green and blue crop water requirements per hectare of crop i. Crop water requirement can be calculated using the CROPWAT model developed by the Food and Agriculture Organization (FAO) (available at http://www.fao.org/nr/water/infores databases cropwat.html). The CROPWAT model takes into account both rainfed and irrigated conditions. So in the CROPWAT model, the green crop water requirement is obtained through quantifying effective rainfall, while the blue crop water requirement is obtained through quantifying irrigation.