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Changes in water footprint of crop production in Beijing from 1978 to 2012: a logarithmic mean Divisia index decomposition analysis

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ABSTRACT

Beijing has been facing increasingly severe water scarcity. Water consumed by crop production is a notable proportion. To estimate total water consumption of crop production in Beijing, we refer to the water footprint concept, taking both direct and indirect water into account. The water footprint (WF) of crop production consists of blue, green and grey components. We use the logarithmic mean Divisia index (LMDI) decomposition method to quantitatively analyze the driving factors for changes in WF. From 1978 to 2012, WF of crop production in Beijing experienced a decrease of 35.1%. This offset primarily resulted from rapid urbanization. The structure and technological factors acted as additional decrease factors. On the contrary, surged population and production scale effect hindered the water conservation process. To further promote water conservation in crop production, we have to continue improving water saving technology and adjusting plantation structure. Crop production in Beijing shows a greater blue WF than the green and grey ones, so rain-fed crops should be further promoted. This work elucidates how diverse determinants affect WF of crop production, which can provide detailed insights into the summary and outlooks of local crop water sustainability.

1. Introduction

Beijing, the capital of China, is faced with increasing water demand due to the rapid economic development and surging population. Beijing is located on the edge of the North China Plain, covers 16,410.54 km^2 area. It is one of the most populous cities in the world, holding 20.69 million residents in 2012 (BWA, 2013). With the implementation of the water diversion project, although the total share of water resource has increased, Beijing is still serious water scarce area when allocated to each person (BBS, 1980–2013). In 2012, there is 3.95 billion m^3 water resource totally in Beijing and 191 m^3 per capita, far from the average of the whole world (BWA, 2013). The rational utilization of water resources in Beijing has become a widely concerned topic. Agricultural irrigation is an important part of water usage. By 2020, the agricultural water consumption in Beijing will decrease by 14% compared to 1997, but it will still take half of the total (Hubacek et al., 2009).

The water footprint concept is closely linked with virtual water, which contains both direct water use and indirect water use of a consumer or producer (Hoekstra and Hung, 2002). Total water footprint consists of three parts: consumption of surface and ground water, consumption of rainwater stored in the soil as soil moisture, and the volume of freshwater that is required to assimilate the load of pollutants. They are defined as blue water footprint, green water footprint and grey water footprint respectively (Hoekstra et al., 2009). The global volume of water used for crop production, including both effective rainfall and irrigation water, is 6390 Gm^3/yr (Hoekstra and Chapagain, 2007b).

There are two approaches to calculate water footprint, the bottom-up and the top-down approaches (Oel et al., 2008). We have already evaluated the gross water footprint of different sectors in Beijing with a modified input–output model (Wang et al., 2013), which is considered as a typical top-down approach. In this paper, we evaluate water footprint of crop production with a bottom-up approach. Generally, the water footprint of a crop is calculated as the ratio of total water used at farm level (m^3) to production of that crop (ton) (Chapagain and Hoekstra, 2004), which reflects the water consumption intensity of different crops. Here we primarily focus on water footprint of local crop products in Beijing by the total water consumption of crop production (m^3).

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For a certain crop, the volume of irrigation water consumption represents blue water footprint. Green water footprint is only directly relevant to the agricultural sector, which is consistent with effective rainfall for plants. Grey water footprint refers to the volume of water required to dilute pollutants to agreed maximum acceptable levels (Hoekstra and Chapagain, 2007b). It was ignored in some studies due to the lack of information and the complex nature of pollutants, but grey water footprint is an indispensable potential part of total water footprint (Adeoti, 2010; Zhang et al., 2011). The water footprint of different crops like cotton, mango, rice, maize and so on has been studied by a number of investigators (Chapagain and Hoekstra, 2011; Chapagain et al., 2006; Hoekstra and Chapagain, 2007b; Ridoutt et al., 2010; Sun et al., 2013b). Huang et al. (2012) reported the water footprint associated with the consumption of crop products produced locally in Beijing during 2009, which did not include temporal analysis of dynamic changes.

Index decomposition analysis (IDA) was firstly introduced in the late 1970s to study the impact of structural change on energy use in industry. IDA defines a governing function relating the aggregate that later will be decomposed to a number of pre-defined factors of interest (Ang, 2004). Recently, it has been extended and used in several other application areas for policymaking. The simplicity and flexibility of the methodology make it easy to be adopted as compared to some other decomposition methodologies, such as the input–output structural decomposition analysis where input–output tables are needed. Various IDA methods can be formulated to quantify the impacts of factors on the aggregate. Logarithmic mean Divisia index (LMDI) is one of them. It is a weighted sum of relative changes represented by growth rate, which uses the Divisia index concept. To be more scientific, it uses log changes. The weights in LMDI are given by the log-mean weight function (Ang and Liu, 2001). Ang (2004) compared various IDA methods and concluded that LMDI method is the preferred method. So far, most of the empirical studies utilized LMDI method to identify quantitatively the relative impact of different factors on the changes in energy consumption and CO_2 emissions (Zhang and Guo, 2013), few works have been carried out on decomposition analysis of water footprint with LMDI method.

In this paper, we analyzed the dynamic changes in water footprint of crop production in Beijing from 1978 to 2012. The water footprint was distinguished and calculated as blue, green and grey water. Driving factors of water footprint was decomposed and quantified by LMDI method. The results of this study provide detailed insights into the summary and outlooks of crop water sustainability in Beijing.

2. Methodology

2.1. Data and software

CropWat 8.0 (FAO, 2009) was used to calculate the reference crop evapotranspiration and effective rainfall. Below is the input data for CropWat model. Monthly meteorological data (1978–2012) from the weather station in Beijing, including average maximum temperature, average minimum temperature, wind velocity, relative humidity, sunshine duration, precipitation were obtained from China Meteorological Data Sharing Service System (CMA, 2013). Crop and soil parameters were provided by FAO (2006).

Beijing Statistical Yearbooks (BBS, 1980–2013) supplied data related to population, crop yield, crop acreage and fertilization. The irrigation quota was based on Municipal Water Quota of Main Sectors in Beijing (BMWC, 2001). The fertilizer for each kind of crop was amended by recommended quota provided by Ministry of Agriculture of the People's Republic of China (MAC, 2013).

2.2. Water footprint evaluation

The water footprint (WF) of crop production is the sum of blue, green and grey water components (Chapagain et al., 2006), calculated separately for the 6 main kind of crops planted in Beijing (BBS, 1980–2013):

$$\mathrm{WF} = \sum_i \mathrm{WF}_i \tag{1}$$

$$\mathrm{WF} = \mathrm{WF}_{\mathrm{blue}} + \mathrm{WF}_{\mathrm{green}} + \mathrm{WF}_{\mathrm{grey}} \tag{2}$$

where WF is the total water footprint of local crop production in Beijing ($\mathrm{m}^3\ \mathrm{yr}^{-1}$), WF_i is water footprint of each type of crop in Beijing, $\mathrm{WF}_{\mathrm{blue}}$ refers to blue water footprint ($\mathrm{m}^3\ \mathrm{yr}^{-1}$) appropriated from surface and groundwater resources, $\mathrm{WF}_{\mathrm{green}}$ is green water footprint ($\mathrm{m}^3\ \mathrm{yr}^{-1}$) which is represented by rainfall consumed through crop evapotranspiration, and $\mathrm{WF}_{\mathrm{grey}}$ is grey water footprint ($\mathrm{m}^3\ \mathrm{yr}^{-1}$) defined as the volume of freshwater needed to assimilate emissions to freshwater.

We also evaluate water footprint intensity (WFI) of crop production by dividing WF with crop yield:

$$\mathrm{WFI}_i = \mathrm{WF}_i / Y_i \tag{3}$$

where WFI_i refers to water footprint intensity of a certain crop production in Beijing ($\mathrm{m}^3\ \mathrm{ton}^{-1}$) and Y_i is the yield of that kind of crop (ton).

(1) Blue water footprint of crop production, mostly represented by irrigation water (*IR*), was calculated as actual acreage (hm^2) times irrigation quota ($\mathrm{m}^3\ \mathrm{hm}^{-2}$) each year. Irrigation quota here differs according to type of crop and rainfall during the year, which is totally based on the real situation of crop farming in Beijing.

(2) Green water footprint here was represented by effective rainfall or crop evaporation, which can be estimated with the CropWat model (FAO, 2003):

$$\mathrm{WF}_{\mathrm{green}} = 10 \times \mathrm{ET}_{\mathrm{green}} \times A \tag{4}$$

$$\mathrm{ET}_{\mathrm{green}} = \min\{P_e, ET_c\} \tag{5}$$

where $\mathrm{ET}_{\mathrm{green}}$ is green water evapotranspiration (mm); Crop evapotranspiration during the growth period (mm). P_e is the effective precipitation (mm); A is acreage of calculated crops (hm^2); the factor 10 converts water depth (mm) into water volume per acreage ($\mathrm{m}^3\ \mathrm{hm}^{-2}$).

Here we use a Soil Conservation Service Method developed by U.S. Department of Agriculture (USDA) to calculate the effective rainfall:

$$P_e = \begin{cases} P \times (125 - 0.6 \times P)/125 & P \le 250/3 \\ 125/3 + 0.1 \times P & P > 250/3 \end{cases} \tag{6}$$

where P is the precipitation (mm). In the water balance calculations included in the irrigation scheduling part of CropWat, a possibility exists to evaluate actual efficiency values for different crops and soil conditions (Clarke et al., 2001).

ET_c was calculated by reference evaporation along with crop factors. The FAO Penman-Monteith model (Allen et al., 1998) was used for reference evapotranspiration:

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