Science of the Total Environment 626 (2018) 11–21

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

# Land-Water-Food Nexus and indications of crop adjustment for water shortage solution

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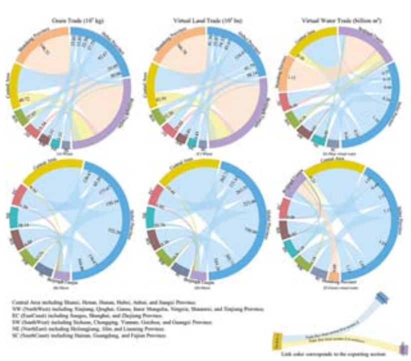
## HIGHLIGHTS

- Provided a method to show the Nexus among virtual water flow, food trade and crop adjustment.
- MRIO model used to clarify inflow and outflow of grain and water in a region.
- Used residential food consumption as baseline for crop adjustment for sustainable groundwater use.

## GRAPHICAL ABSTRACT



## ARTICLE INFO

*Article history:*
Received 20 June 2017
Received in revised form 8 January 2018
Accepted 8 January 2018
Available online xxxx

Editor: D. Barcelo

*Keywords:*
MRIO model
Virtual water trade
Water shortage solution
North China
Wheat and maize

## ABSTRACT

While agriculture places the greatest demand on water resources, increasing agricultural production is worsening a global water shortage. Reducing the cultivation of water-consuming crops may be the most effective way to reduce agricultural water use. However, when also taking food demand into consideration, sustaining the balance between regional water and food securities is a growing challenge. This paper addresses this task for regions where water is unsustainable for food production (Beijing-Tianjin-Hebei Region for example) by: (i) assessing the different effects of wheat and maize on water use; (ii) analyzing virtual water and virtual land flows associated with food imports and exports between Beijing-Tianjin-Hebei and elsewhere in China; (iii) identifying sub-regions where grain is produced using scarce water resources but exported to other regions; and (iv) analyzing the potentiality for mitigating water shortage via Land-Water-Food Nexus. In the Beijing-Tianjin-Hebei Region, the study reveals that 29.76 bn $m^3$ of virtual water (10.81 bn $m^3$ of blue virtual water) are used by wheat and maize production and 8.77 bn $m^3$ of virtual water used in nearly 2 million ha of cropland to overproduce 12 million ton of maize for external food consumption. As an importing-based sub-region with high population density, Beijing & Tianjin imported mostly grain (wheat and maize) from Shandong Province. Then, Hebei Province, as an exporting-based sub-region with severe water shortage, overproduced too much grain for other regions, which aggravated the water crisis. To achieve an integrated and sustainable development of the Beijing-Tianjin-Hebei Region, Hebei Province should stop undertaking the breadbasket role for Beijing & Tianjin and pay more attention to groundwater depletion. The analysis of the Land-Water-Food Nexus indicates how shifts in cultivated crops

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https://doi.org/10.1016/j.scitotenv.2018.01.071

can potentially solve the overuse of water resources without adverse effects on food supply. It also provides meaningful information to support policy decisions about regional cropping strategies.



## 1. Introduction

The burgeoning demand for food by a growing global population has necessitated increasing agricultural production, which has in turn increased global water shortages. When water is scarce, agricultural production can be limited. Generally, however, the balance between sustainability of water use and food security is complex (Hanjra and Qureshi, 2010).

Much hydrological research has focused on seeking sustainable solutions to water resource management, and increased water use efficiency seems to be promising in this regard (Sun and Ren, 2014; Cao et al., 2014). It has however been noted that traditional agriculture water saving, by improving irrigation efficiency in farmland have often failed to restore either a groundwater balance or regional water sustainability (Yan et al., 2015). Generally, water saved through improved farm practices is reused on additional cultivated land to increase both yields and total production to meet the population's demand for more food (Han et al., 2015). Thus directly or indirectly reducing irrigated areas or cultivated areas of water-consuming crops has been suggested as more effective ways of resolving global water shortages (Zheng et al., 2010).

Wheat, for example, is an irrigation-intensive crop that has been identified as causing groundwater depletion in the North China Plain (NCP). In order to reduce over-pumping, the current national policy — the “Water Red Line” (Liu et al., 2011) — was developed to encourage sustainable groundwater use in the long-term by reducing cultivated land area of wheat in annual wheat-maize rotation system in the NCP. To offset the negative economic impact on farmers, a subsidy of 500 RMB/Mu has been provided by the central government for not planting wheat, although applications of herbicides and land management to control wild grass are now an increasing necessity for lands no more covered by wheat. Field experiments (Sun et al., 2011) at two stations in the NCP, during the period from October 2004 to September 2006, suggested that if only a single crop (e.g., spring maize) is grown, groundwater use in the region can become sustainable in the long-term. But as wheat is a traditional staple food in the NCP, too much reduction in winter wheat production could damage food security in the region. Sustaining the regional water balance without an adverse effect on food security in the NCP has therefore been a challenging task.

‘Virtual water’, defined as the volume of water used in the production of commodities (Allan, 1998), offers a new perspective on water scarcity. As a measure of the effects of grain transfer on water resources, virtual water trade has been widely studied locally and internationally. For example, Chapagain et al. (2006) noted that 352 $Gm^3$/yr of global water resources could be saved by rationalizing virtual water trade in agricultural products (that is, by producing water-intensive crops in water-rich regions). Using empirical data, Dang et al. (2015) assessed virtual water trade in intra-national food transfer in the United States, concluding that water-intensive meat commodities accounted for a high fraction of water flows. Further studies identified problems within virtual water trade. Through the combined use of CHINAGRO (Fischer et al., 2007) and H08 models (Hanasaki et al., 2008a, 2008b), Dalin et al. (2014) noted that China's domestic food trade was inefficient in terms of irrigation, as food flow was from irrigation-intensive provinces to water-rich ones. With this, Dalin et al. (2017) explored the connection between groundwater depletion and global food consumption by integrating crop water use, groundwater depletion and international food trade. The study revealed that a vast majority of the world's population sourcing most of their staple crop imports from partners with severe groundwater depletion, highlighting the risks for global food and water security. So far, virtual water studies have focused on the effects of grain trade on water and land, while the crucial factors for both water and food not yet explored. Our research, for the first time, integrates croplands, agricultural water consumption and grain trade together to illustrate the Land-Water-Food Nexus, making the effects of crop adjustment on both water sustainability and food security clear and trying to provide useful information for the crop adjustment policies by the government.

## 2. Study area

The Beijing-Tianjin-Hebei Region (Fig. 1), which is treated as a single contiguous region by the central government, includes three administrative regions - Beijing City, Tianjin City and Hebei Province. The region is located in the Haihe River Basin (E113.5°–119.9°, N36.0°–42.6°), with an area of 217,716 $km^2$ and a population of 106 million (China Statistical Yearbook 2012 which is accessible at http://tongji.cnki.net/kns55/Navi/YearBook.aspx?id=N2012100019&floor=1). Annual mean water resource in this region has decreased from 28–29 bn $m^3$ in the 1950s to 14–15 bn $m^3$ in the 2000s. Meanwhile, average water resource per capita also reduced from 300–400 $m^3$ in the 1990s to <200 $m^3$ in the 2000s (Feng and Liu, 2006). Cultivated in 60% of the croplands in the region, wheat and maize are the main crops in the case study area, respectively contributing 39% and 53% to gross grain production in the region (China Statistical Yearbook 2012). Additionally, as one of the main grain production areas, this region respectively produces 12% and 9% of wheat and maize in China (China Statistical Yearbook 2012). Most city regions, including Shijiazhuang, Handan, Xingtai, Hengshui, Cangzhou, Baoding, Langfang, Beijing and Tianjin, practice a double cropping system that consist of winter wheat and summer maize. In the relatively cold areas such as Chengde, Zhangjiakou, Qinhuangdao and Tangshan, only one crop is cultivated per annum (wheat or spring maize). Traditionally, wheat flour is the preferred food in most rural areas and cities in the region, which is very different from that in South China where rice is preferred as the main daily food.

## 3. Methods

Crop water use, including green virtual water (effective precipitation) and blue virtual water (irrigation water), are simulated by DSSAT (Decision Support for Agro-technology Transfer) model. Grain (wheat and maize) inflow and outflow is estimated through food balance method, which is the difference between local grain production and household food consumption. Then, MRIO model (Multi-regional input–output model) is used to estimate grain trade between the study area and outside regions in China. Virtual water and virtual land come out by the combination of VWC (Virtual Water Content) and grain trade flow.

### 3.1. Crop virtual water content

Precisely, the term virtual water is definable from two distinct approaches — production-based approach and consumption-based approach (Hoekstra, 2003). The former quantifies virtual water as the actual water used to produce a unit mass of the commodity at the place of production and the latter define it in terms of virtual water content (VWC) as the amount of water that could have been required to produce a unit mass of the commodity at the place of consumption. Therefore, VWC is the real water (green and/or blue) required to