Science of the Total Environment 497–498 (2014) 1–9

Contents lists available at ScienceDirect

Science of the Total Environment

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

Application of water footprint combined with a unified virtual crop pattern to evaluate crop water productivity in grain production in China

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HIGHLIGHTS

- A comprehensive index to evaluate crop water productivity needs to be developed.
- Crop patterns are different in each region and had important impact on WF.
- WF of each crop among areas or among crops in the same area differed greatly.
- WF of both the actual and virtual crop patterns differed greatly across regions.
- WF can evaluate CWP and help decision making on agricultural water savings.

ARTICLE INFO

Article history:
Received 11 April 2014
Received in revised form 22 July 2014
Accepted 22 July 2014
Available online xxxx

Editor: D. Barcelo

Keywords:
Water footprint
Crop pattern
Crop water productivity
Water use efficiency
Irrigation efficiency
China

ABSTRACT

Water shortages are detrimental to China's grain production while food production consumes a great deal of water causing water crises and ecological impacts. Increasing crop water productivity (CWP) is critical, so China is devoting significant resources to develop water-saving agricultural systems based on crop planning and agricultural water conservation planning. A comprehensive CWP index is necessary for such planning. Existing indices such as water use efficiency (WUE) and irrigation efficiency (IE) have limitations and are not suitable for the comprehensive evaluation of CWP. The water footprint (WF) index, calculated using effective precipitation and local water use, has advantages for CWP evaluation. Due to regional differences in crop patterns making the CWP difficult to compare directly across different regions, a unified virtual crop pattern is needed to calculate the WF.

This project calculated and compared the WF of each grain crop and the integrated WFs of grain products with actual and virtual crop patterns in different regions of China for 2010. The results showed that there were significant differences for the WF among different crops in the same area or among different areas for the same crop. Rice had the highest WF at 1.39 m^3/kg, while corn had the lowest at 0.91 m^3/kg among the main grain crops. The WF of grain products was 1.25 m^3/kg in China. Crop patterns had an important impact on WF of grain products because significant differences in WF were found between actual and virtual crop patterns in each region. The CWP level can be determined based on the WF of a virtual crop pattern, thereby helping optimize spatial distribution of crops and develop agricultural water savings to increase CWP.

1. Introduction

Sustainable water supply is fundamental to grain security, economic growth and ecological balance in China (Huang and Li, 2010a; Martellaro, 1991; Ni et al., 2012). Water shortages have threatened China's grain production, while in high water-consumption food production can cause water crises, social instability and ecological degradation (Brown and Halweil, 1998; Sun et al., 2013b). The annual per capita renewable freshwater availability in China is only 2300 m^3, which is 1/4 of the global average level at 9200 m^3 (Cheng et al., 2009; Jiang, 2009; Khan et al., 2009), and even worse is the unbalanced spatial distribution of water resources (Ge et al., 2011). Only 17% of the total water resources with 60% of the total cultivated land are located in northern China (MWRC, 2011; Varis and Vakkilainen, 2001; Wang et al., 2012; Yang, 1998). Northern China is particularly vulnerable to water-related problems which are expected to be exacerbated in the future by more serious droughts, land degradation, and loss of biodiversity due to

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http://dx.doi.org/10.1016/j.scitotenv.2014.07.089
0048-9697/© 2014 Published by Elsevier B.V.

100 billion kg of grain output being necessary for China to satisfy its peak population of 1.6 billion in the 2030s (Ito and Ni, 2013; Jin and Young, 2001). One hundred billion kilograms of grain means approximately 100 Gm^3 of water consumption (Huang and Li, 2010a). A prerequisite for tackling these challenges in China is increasing crop water productivity (CWP, expressing the amount of marketable product in relation to the amount of input water, kg/m^3) to relieve pressures on water resources and conflicts in water use (Qadir and Oster, 2004; Wu et al., 2012).

To increase CWP in grain production, accurate assessment of comprehensive CWP is important (Blum, 2009; Hsiao et al., 2007). This may be especially significant in China because China's central government mainly decides and invests in the regions where water-saving agriculture should be developed first based on the level of integrated CWP of grain products. Usually, the index of water use efficiency (WUE: ratio of the final harvest yield and the seasonal values of actual evapotranspiration) or irrigation efficiency (IE: the amount of irrigated water transported to field for crop use divided by the amount of irrigated water diverted from water sources) is used to evaluate CWP (Katerjia et al., 2013; Molden and Oweis, 2007; Zwart and Bastiaanssen, 2004). However, there are some disadvantages in use of WUE or IE to evaluate CWP. For WUE, it is only CWP in fields, which does not take IE into account. That is, the WUE doesn't contain loss of irrigation water during the conveyance process from the water sources to field, which has significant influences on irrigation water efficiency. Secondly, the components of water consumption, precipitation or irrigation, are difficult to distinguish from WUE due to its calculation methods based on evapotranspiration (ET) which combines precipitation and irrigation water. Finally, the WUE is usually used to evaluate water productivity of an individual crop, while it is difficult to appraise water productivity of all the grain crops as a whole because there are big differences among different crops. For example, corn has a high water use efficiency which is 1.5 times that of wheat at a global level (Mekonnen and Hoekstra, 2010, 2011). Thus, the WUE of grain products can't be compared among different regions since their crop patterns are diverse. The disadvantages of IE are more obvious, which only consider the irrigated system conditions and management, as the precipitation and crop yield aren't considered.

The water footprint (WF) tool combined with a virtual crop pattern (ratio of output of different crops) can help address these questions. The 'WF' concept was introduced by Hoekstra (2003). The water footprint (WF) of a product is the volume of freshwater used to produce the product over the full supply chain. It shows, specified in space and time, water consumption volumes by source (green and blue WFs) and polluted volumes (gray WF) by type of pollution (Hoekstra et al., 2009, 2011). WFs are gaining increasing attention with a large number of studies on WF since the advent of the concept (Aldaya et al., 2010; Boulay et al., 2013; Chapagain and Hoekstra, 2007; Fang et al., 2014; Liu and Savenije, 2008; Steen-Olsen et al., 2012; Zhang et al., 2013).[1]

This paper focuses only on green and blue components of WF because gray water is not water consumed for crop use, which is the freshwater required to assimilate the load of pollutants (Fader et al., 2011; Liu and Yang, 2010; Zhuo et al., 2014). Thus, WF includes blue water footprint (BWF, actual volume of blue water appropriated from surface and groundwater resources) and green water footprint (GWF, actual volume of green water which is the precipitation stored in the soil and eventually evaporated, transpired or incorporated into plants) (Hoekstra et al., 2011).

WF has been primarily used to study wise water management based on water consumption and pollution for human production or consumption along the supply chain of a product (Bulsink et al., 2010; Chapagain and Hoekstra, 2011; Chapagain and ORR, 2009; Ercin et al., 2013; Hoekstra, 2014). The WFs are usually calculated based on Evapo-Transpiration (ET) calculated with an empirical formula as suggested by FAO with average meteorology data for 5–10 years (Hoekstra et al., 2011). The calculation of WF of crop products is crop ET per unit area divided by the average yield per unit area in the same period. The use of average meteorology and crop yield data makes it hard to reflect the temporal change of WF of grain products, a point noted by Hoekstra et al. (2012). Wu et al. (2012) argued that WF should be calculated based on the annual effective precipitation, the actual water use (water withdrawal: water diverted or withdrawn from a surface water or groundwater source) and crop yield when WFs were chosen to evaluate CWP. Thus, the BWF calculated with water use data could reflect water use efficiency in fields and irrigation efficiency simultaneously. Moreover, it will be able to distinguish how much is GWF and BWF with spatial and temporal dimensions, respectively.

However, regional differences in crop patterns make the CWP of grain products difficult to compare directly across different regions (Wang et al., 2010). In this paper, a virtual crop pattern was used to evaluate integrated CWP in grain production and make it comparable among different regions. The crop pattern for the whole country was used as the virtual crop pattern, making the average value of comprehensive CWP in the whole country unchanged.

There are several studies which analyzed the spatial differences in CWP in China. Mekonnen and Hoekstra (2010, 2011) quantified the green, blue and gray WFs of 126 crops at a 5 by 5 arc minute grid for the period 1996–2005 based on a field ET method. Sun et al. (2013a) calculated the green and blue WFs of rice, wheat and corn at a provincial scale based on a field ET method for 2009. Huang and Li (2010a,b) studied the WUE of staple grain crops (i.e. rice, wheat, corn, and soybean) for seven selected basins between 1997 and 2004 based on a field ET method.

There are a number of limitations in the previous studies of CWP in China. One of these studies is calculated ET to obtain the water footprint (WF) of agricultural products. Therefore, the calculated CWP came from empirical formulas or simulation models instead of calculation using the actual annual effective precipitation, water use and crop yield. Secondly, these studies did not consider the water loss in the irrigation network, while IE has important impacts on CWP. Finally, the previous studies usually only compared the CWP of a single crop and didn't study the comprehensive CWP of crop products as a whole. However, decision making is difficult based on CWP comparison for a single crop because CWPs of some crops may be higher while CWPs of the other crops may be lower in a region than those in another area.

This paper calculated the integrated WFs of actual and virtual crop patterns based on the actual effective precipitation, water use and crop yield to evaluate CWPs of 31 provinces, autonomous regions and municipal cities, and 8 regions of grain production, and compared WFs between southern and northern China for 2010. The aims of the paper were to develop a comprehensive evaluation index of CWP and assess CWP spatial differences in China.

2. Methods and data

2.1. Methods

2.1.1. Study area

The research area of this study is China Mainland excluding Taiwan Province, Hong Kong and Macao. It consists of 31 provinces, autonomous regions and municipal cities (PAMs) (Fig. 1). These provinces (autonomous regions and municipal cities) were classified into eight regions: North-central (NC), Northeast (NE), Huang-huai-hai (HHH), Northwest (NW), Southeast (SE), Yangtze (YT), South-central (SC) and Southwest (SW) according to their geographic location and conditions of weather, water resources and food production. Then, the former 4 regions were classified as the north except the Anhui province in the HHH region was placed into the south, and the latter 4 regions were classified as the south. Usually, the annual precipitation decreases from Southeast (over 2000 mm) to Northwest (less than 100 mm) in China (Prieler, 1999).

[1] Most of these studies are accessible from the Water Footprint Network website (http://www.waterfootprint.org/?page=files/Publications).