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Discussions

# Decreased virtual water outflows from the Yellow River Basin are increasingly critical to China

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**Abstract.** Water scarcity is an emerging threat to food security and socioeconomic prosperity, and it is crucial to assess the response of crop production to water scarcity in large river basins. The water footprint, which takes into account water use in supply chains, provides a powerful tool for assessing the contributions of water resources within a certain region, by tracking the volume and structure of virtual water flows. In this study of the structure of the water footprint network from a complexity perspective, we reassessed the significance of water resources for crop services in a large river basin with a severe water shortage -the Yellow River Basin (YRB) of China. The temporal increase of the complexity index indicated that the Virtual Water out-Flows (VWF) from the YRB were becoming increasingly critical to China; i.e., the ability of YRB to produce crops boosted difficulty of its water being replaced by water exporting from other basins. Decomposition of complexity suggested that during the 1980s to 2000s, the temporally increased complexity was due mainly to the paucity of competitors and the increasing uniqueness of crops supporting VWF. This complexity deeply embedded the YRB into the footprints of a water network that facilitated further development with constrained water resources, but it also reinforced reliance from other regions on YRB's scarce water. Based on this analysis, we therefore suggest that resource regulation should be carried out at an appropriate time to ensure both the ecological sustainability and high-quality development of river basins.

## 1 Introduction

Water scarcity is an emerging threat to food security and socioeconomic prosperity (Zhou et al., 2020; Liu et al., 2017; Dolan et al., 2021; Mekonnen and Hoekstra, 2016). Water resources play an essential role in the production of crops within a river basin, and the export of those crops to other river basins can greatly exacerbate the negative consequences of water shortages. Although the per capita water resources in China are only 25% of the global average, China is trying to decrease its dependence on imported crop, with the goal of becoming basically self-sufficient in terms of food production and to ensure that its food supply is secure. A reasonable assessment of the contribution of the water resources in a river basin to domestic crops supplies will be the first step in balancing the water-food nexus (Wang et al., 2020). The Yellow River Basin (YRB) is the most important area of agricultural production in China. Although the YRB uses only 2% of the water resources in China, it accounts for over

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13% of the national grain production, with 41% of the grain produced in the YRB is consumed outside the basin (Zhuo et al., 2016b, 2020). Because consumption of water for agricultural purposes once accounted for 80% of the natural runoff of water in the YRB and caused the Yellow River to run dry, the supply of water in the YRB is now strictly controlled (Wang et al., 2019). Although agricultural production in the YRB is constrained by the availability of water resources, the national crop yield per unit of water resources has been increasing rapidly (Zhou et al., 2020). An assessment of the changing status of agricultural production in the YRB may therefore provide a useful example to guide the development of water resources in other resource-deficient basins.

The water footprint, a geographically explicit indicator that involves water use in supply chains, has provided a powerful tool for assessing the contribution of water resources to a basin and tracking the transfer of water resources across regions (Jaramillo and Destouni, 2015). Water footprint can be associated with certain products that are transferred through complex trade relationships between geographic units. Induced, water footprint networks consist of Virtual Water out-Flows (VWF) that are embedded in production and consumption trajectories of crops (Zhai et al., 2019; Chini et al., 2018; Bae and Dall'erba, 2018). For example, the VWF from China's water-rich south to its water-scarce north has been quantified, and the network represented by crop trade between provinces has been mapped (Zhai et al., 2019; Zhuo et al., 2016a). However, because these volume-based studies have ignored the complexity of crop supply and demands (linked with trade) and the uniqueness of each basin (determined by regional characteristics), they have failed to consider the structure of water footprint networks. The structure of a water footprint network reflects the inherent heterogeneity of the distribution of the resources as well as the pattern of production and consumption. This heterogeneity is consistent with the fact that a water resource cannot be simply replaced by the same volume of water in another basin (Yu and Ding, 2021; Zhuo et al., 2016a; Li et al., 2020). This replacement problem reflects the fact that water is not the only resource needed for widely circulated agricultural products. Because of path dependence, others resources such as the unique hydrothermal conditions and the status of infrastructure within a basin, all determine the position of basin (or a region) in a water footprint network (Best, 2019). Complexity, a rapidly developing concept in fields of study such as complexity science, network science, and development economics, represents the "capacity" that is embedded in a certain region, based on measurement of its position in structural terms (Hidalgo, 2021; Arthur, 2021; Meng et al., 2020; Hidalgo et al., 2007). For water resources that are unevenly distributed geographically, complexity can therefore simply characterize the overall capacity of a basin to provide water services that are required for national crop production. Because complexity-based metrics have been extensively studied in the empirical assessment of economic vitality through a bipartite-networks approach, the concept of complexity should be taken into consideration in the context of water footprint networks to upgrade the toolbox used for integrated water resources management (Hidalgo, 2021; Hidalgo and Hausmann, 2009; Liu et al., 2017). With such a toolbox, the regional significance of the water supply services provided by the basin through agricultural production can be comprehensively reassessed in a way that takes into account structural factors (Figure 1).

Recently, a growing idea is that the heart of China's crop production should cease to be the water-poor basin (e.g., the YRB) and that other water-rich basins (southern areas of China) should contribute more (Liu Yong et al., 2021; Zhuo et al., 2016a). Another call is to ease the water shortage in the YRB by transferring water across the basins as soon as possible (Liu Yong et al., 2021). These strategies rely on a comprehensive assessment of the significance of water resources, thus it would be an oversight to ignore the water footprint network in a structural context because each basin differs in terms of its capacity to use water resources to provide services for crop production (Li et al., 2020; Mekonnen and Hoekstra, 2020, 2011). In this study, we took a complexity perspective with respect to water footprint networks and assessed the significance of the YRB to China's crop supply. Our results showed that although the YRB had reduced its virtual water outflow because of resource constraints, its importance to crop production in China had been increasing when water footprint networks were considered. The complexity of the water footprint network enabled our approach to provide a new perspective for understanding the changes in the status of a basin with a severe water shortage with respect to national crop production.

## 2 Methods

We looked at provincial crop product associations by using virtual water flow data (waterfootprint.org). The dataset included the water footprint consumption and production of 22 different crops in each province of China ($n = 31$, no data in Taiwan, Hong Kong and Macau) between 1978 and 2008. The more important role in the nation's crop supply palyed by regions with more connections and more unique export baskets echoed the concept of "VWF complexity". We constructed such bipartite networks of province-crop associations and used a reflecting method to decompose and quantify the properties. Sensitivity tests were carried out with random networks (as null models).

### 2.1 Construction of network

We mathematically represented a province-crop bipartite network with an adjacency matrix $M_{pc}$, where $M_{pc} = 1$ if province $p$ is a significant net surplus region of crop $c$, and $M_{pc} = 0$ otherwise. In a practical sense, this bipartite network, which consisted of all provinces (or regions) and 22 crops, reflected which crops a region exported heavily that diverted water out of the region virtually. The Relative Comparative Advantage (RCA) procedure was used to construct the incidence binary matrix $RCA_{cp}$ with the goal of capturing the network topology (Balassa, 1965; Dolan et al., 2021; Sciarra et al., 2020). The relative comparative advantage of production referred to a region's export of a particular product in terms of its proportion of the total trade of that product. An analogy can be made to the VWF as a proportion of the national total volume of water flows, embedded in a specific crop. The RCA therefore weights how much virtual water of crop $c$ counts within the basket of province $p$. This fraction is weighted by the ratio of the total virtual water flux of all provinces. The relevant equation is

$$RCA_{cp} = \frac{\frac{D_{cp}}{\sum_p D_{cp}}}{\frac{\sum_c D_{cp}}{\sum_{cp} D_{cp}}} \tag{1}$$

where $D_{cp}$ is the virtual water volume of province $p$ transferred through crop $c$. The adjacency matrix $M$ is given by $M_{cp} = 1$ if $RCA_{cp} >= 1$ and 0 otherwise.

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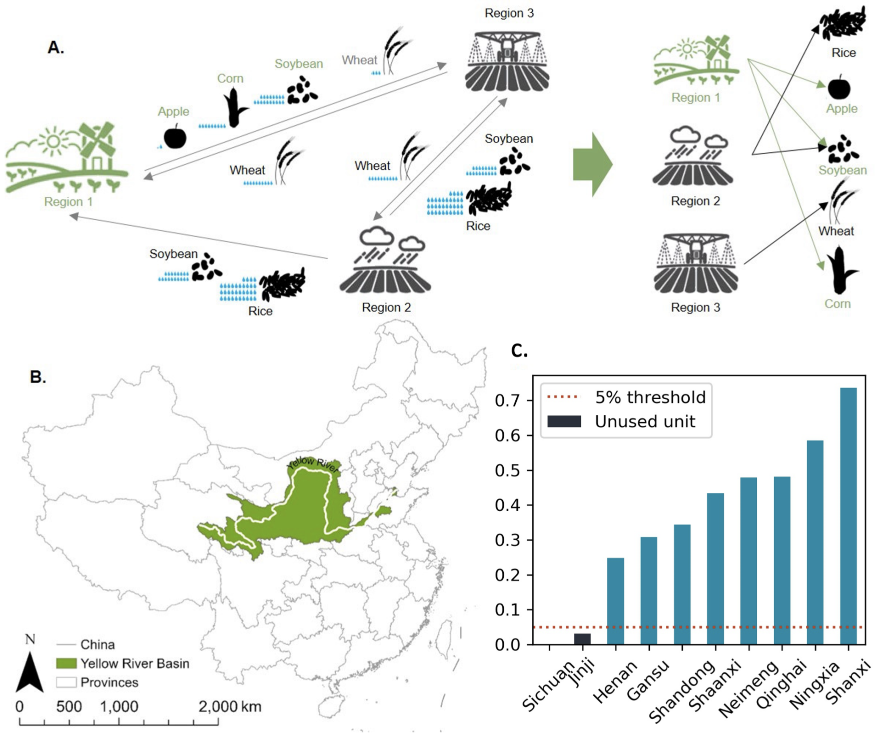

**Figure 1.** Diagram used to construct water footprint networks by Virtual Water out-Flows (VWF). **A.** Virtual water is transferred between regions through multiple dominant crops. When the proportion of the VWF from a region through a certain crop is large enough compared to the total amount of VWF from this crop in the whole country, a connection is established between the region and this crop. For example, region 1 does not export rice but exports a small amount of wheat and apples to region 3. A comparison of the VWF associated with exporting these crops to the total volume of VWF globally revealed that region 1 consumed a negligible volume of VWF by exporting wheat, but the VWF associated with exporting apples was significantly larger than for other regions. Region 1 was therefore not linked to rice and wheat, but it was linked to apples. **B.** The Yellow River flows through 10 provinces in arid and semi-arid region of China. **C.** Among them, 8 provinces rely heavily on the Yellow River for water resources (Qinghai, Gansu, Ningxia, Neimeng, Shananxi, Shanxi, Henan and Shandong province). In other words, sichuan and Jinji (Tianjin and Hebei), which use water from the Yellow River but take less than 5% of their total water use, have been excluded.

## 2.2 Quantitative metrics of complexity

The complexity of the virtual water footprint contained two dimensions: the volume of the virtual water footprint transferred to other regions and its irreplaceability. We therefore used a general index to refine the two dimensions of information in reference to economic complexity:

$$Index_p = \left(\sum_{i=1}^{2} \lambda_i X_{p,i}^2\right)^2 + 2\sum_{i=1}^{2} \lambda_i^2 X_{p,i}^2 \qquad (2)$$

where $X_{p,1}$ and $X_{p,2}$ are the eigenvectors corresponding to the first two largest eigenvalues $\lambda_1$ and $\lambda_2$ of the proximity matrix.

$$\begin{cases} N_{cc^*} = \sum_p M_{cp} M_{c^*p} = \sum_p \frac{M_{cp} M_{c^*p}}{k_c k_{c^*} \left(k'_p\right)^2}, & \text{if } c \neq c^* \\ N_{cc^*} = 0, & \text{if } c = c^* \end{cases} \tag{3}$$

where the redundant information of the self-proximity (i.e., when $c = c^*$) is deleted by setting related values to zero. In addition, the symmetric square matrix $N$ is interpreted as the mathematical description of the weighted topology of the network, whose similarities between exported crops are the links. Then, eigenvector centrality of the nodes (refered by the eigenvectors of matrix $N$) can be a useful tool to interprete complexity of the network. For more details we refer the reader to Sciarra et al. (2020).

In this way, based on the idea of dimensionality reduction, we could use the average index of the YRB to simply assess its importance to the outflow of a virtual water footprint of China.

$$\frac{1}{n} * \sum_{p \in YRB}^{n} (index_p) \tag{4}$$

In addition to integrating the composite indicators of the two dimensions, we could also use the network method to decompose and compute the two dimensions:

$$k_{\mathrm{p,N}} = \frac{1}{k_{\mathrm{p,0}}} \sum_c M_{\mathrm{cp}} k_{\mathrm{c,N-1}} \tag{5}$$

where $k_{p,0}$ represents the observed levels of diversification of a province (the number of products exported by that province). We therefore characterized each province through the vector $\boldsymbol{k_c}(\boldsymbol{k_{c,1}}, \boldsymbol{k_{c,2}}, \boldsymbol{k_{c,3}})$ in its different dimensions.

### 2.3 Decomposition of complexity

The main factors affecting the outflow capacity of regional water resources needed to be decomposed to explain the reasons for the changes of the complexity index. The Reflection Method can describe a structure of bipartite network (Hidalgo and Hausmann, 2009; Hidalgo, 2021) where the connotation of different levels was indicated based on the different mapping times $N$:

$$k_{\mathrm{p,N}} = \frac{1}{k_{\mathrm{p,0}}} \sum_c M_{\mathrm{cp}} k_{\mathrm{c,N-1}} \tag{6}$$

where $c$ represents a certain crop and $p$ a certain province, $M_{\mathrm{cp}}$ defines the network, and $k_{\mathrm{p},0}$ represents the observed levels of diversification of a province (the number of products exported by that province). For $N \geq 1$, with initial conditions given by the degree (i.e., the number of links of provinces and crops):

$$k_{\mathrm{p},0} = \textstyle\sum_c M_{\mathrm{cp}} \tag{7}$$

**Table 1.** Interpretations of the first three pairs of variables describing the province-crop network through the method of reflections.

| | Definition | Working name | Description |
|---|---|---|---|
| N=1 | $k_{p,1}$ | Diversification | How many products are exported by province p? |
| N=2 | $k_{p,2}$ | Uniqueness | How common are the crops exported by province p? |
| N=3 | $k_{p,3}$ | Competitiveness | How diversified are provinces exporting crops similar to those of province p? |

With reference to existing complexity studies, the first three major dimensions can therefore be intuitively explained when $N = 1$, $N = 2$ and $N = 3$ as summarized in Table 1. When the reflection method is used in this way, it reflects the crop diversification, crop uniqueness and regional competitiveness of the water footprint outflow of the YRB. Although we could have used the reflection approach to continue iterating for more complex explanations, the decomposition of complexity into three steps helped explain the changes in complexity more clearly and intuitively.

### 2.4 Null models and sensitivity tests

As a sensitivity test, we randomly created provincial-crop bipartite networks, and we calculated the same metrics as a comparable reference values to decide wheather the structure of networks was trivial. We imagined three scenarios that randomly generated (executed by Python 3.9 and numpy 1.2) comparable dichotomies based on progressively stricter assumptions. They were consistent with the network based on empirical data ($M_cp$) of the number of edges and the sequence of edges on a side (province or crop) respectively (Table 2):

**Table 2.** How different null models were generated.

| | Null model 1 | Null model 2 | Null model 3 |
|---|---|---|---|
| Number of links | =Mcp | =Mcp | =Mcp |
| $k_{p,0}$ sequence | ≠Mcp | ≠Mcp | =Mcp |
| $k_{c,0}$ sequence | ≠Mcp | =Mcp | ≠Mcp |

## 3 Results

### 3.1 Increasing complexity with decreasing VWF volume

The total volume of virtual water outflows from the provinces in the YRB decreased continuously during the study period (Figure 2 A), and its proportion of the national total decreased by an even greater percentage (Figure 2 B). In 1979, there were five provinces in the YRB whose virtual water outflows (VWF) exceeded the national average, but there were only three of them in 2008, and their overall ranking had decreased significantly. Though the total volume, share, and ranking of VWF across provinces of the YRB were all decreasing, the average complexity index of the YRB was holistically higher than that of China (Figure 3 A). The gap between the two increased rapidly after 1985 and reached its widest point in 1993, when the average complexity index of the YRB was about 1.4 times the national average (Figure 3 B). After then, the difference between the two decreased with some fluctuations but the complexity of the YRB remained about 1.2 times the national average (Figure 3 B).

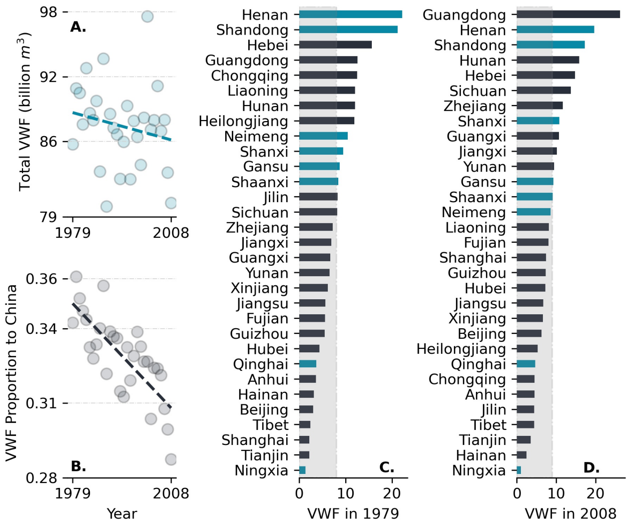

**Figure 2.** Virtual Water out-Flows (VWF) in the Yellow River Basin (YRB) from 1978 to 2008. **A.** Total VWF in the YRB and China. **B.** Proportion of total VWF in the YRB to the national volume. **C.** Ranking of VWF in Chinese provinces in 1978. Blue bars are provinces in the YRB. **D.** Ranking of VWF in Chinese provinces in 2008. Blue bars are provinces in the YRB.

### 3.2 Decomposition of changing complexity

An indication of crop diversification ($N = 1$, Figure 4A) was that, almost every region was transferring virtual water through 7-8 dominant crops on average, and there was no significant difference between the YRB, China, and the random network (null models). When $N = 2$ (Figure 4B), however, both the YRB and the national average had a significantly ($p < 0.1$) lower number of competitors that transferred virtual water though their similar dominant crops than the random network. The implication is that the crops supporting VWF were not all the same, -and qre usually more unique than that from other regions. The opposite

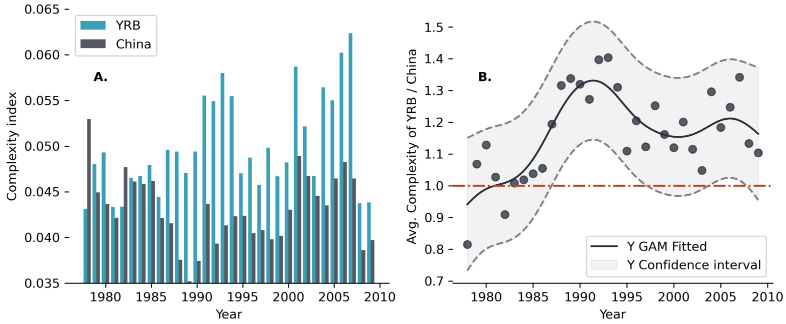

**Figure 3. A.** Average complexity index of YRB and of China from 1978 to 2008. **B.** Ratios of average complexity index of YRB to that of China from 1978 to 2008. Solid line was fitted with Generalized Additive Models (GAMs). Gray shaded area indicates 90% confidence interval. The red dashed line indicates the baseline where the average complexity index of the YRB is equal to that of China.

nature of the trends of the YRB before the 2000s indicated that its uniqueness was rising and significantly higher (i.e., reflecting index was lower, $p < 0.1$) than the national average. For $N = 3$ (Figure 4C), whereas the national average of competitivenss was relatively similar to that of the random networks, the total number of types of crops that were competitors with the YRB were significantly lower between 1987 and 2000. The implication is that the competitiveness of the YRB exceeded the average level. In general, since the 1980s, the uniqueness and competitiveness of the YRB has been very different from that of the whole country. That difference gradually disappeared in the 2000s.

## 4 Discussion

The use of regional VWF, especially within a water footprint network, has been a common approach to assess the importance of water resources, but complex structures have not been comprehensively evaluated in these assessments (Mekonnen and Hoekstra, 2020, 2011; Fang et al., 2014). The Yellow River, an agriculture-oriented basin with strong heterogeneity in the upper, middle, and lower reaches, has scarce water resources that are the cornerstone of its crop productio (Wang et al., 2019). With "The Reform and Opening" of China since 1978, domestic crop trades have gradually increased, and that increase may have caused the total VWF volume to keep increasing. At the same time, however, the YRB was the first basin to apply a water allocation scheme because extreme water shortages caused the river to frequently dry after the 1970s (Wang et al., 2019). Therefore, during the time that the national VWF was transferred mainly from the north (where the YRB located) to the south (Zhuo et al., 2016b), the contribution of the YRB, which is deficient in water resources, decreased in volume (Figure 2). However, consideration of the structure of the crop-water footprint bipartite network, that did not indicate the YRB had been decreasing in importance to China. On the contrary, our complexity-based analysis revealed that the differences of complexity between the YRB and the China have existed since 1978, and the YRB's water footprints have been difficult for other basins to replace for crop production. Our decomposition results suggested that this difficulty was due mainly to a low number of

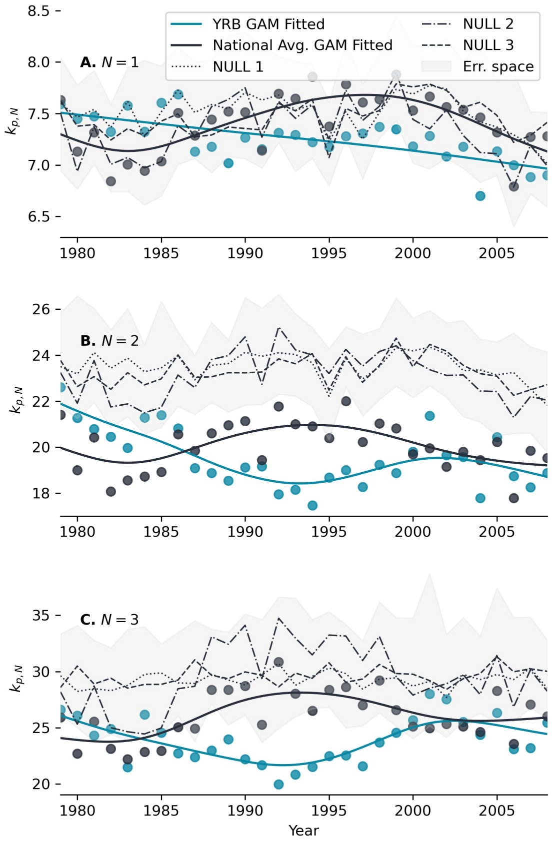

**Figure 4.** Trends of different dimensions based on the reflecting method decomposed from complexity (see the Methods *Sect. 2.3 and Table 1*). Blue and grey colours show the average levels of the YRB and China, respectively. **A.** $N = 1$, number of major crops that support virtual water outflow (VWF), an indication of diversification of a certain region. **B.** $N = 2$, total number of provinces where similar dominant crops supporting VWF are included, a smaller number indicating the greater uniqueness of the particular region. **C.** $N = 3$, total number of dominant crop types supporting VWF from all competitors (who have similar dominant crops). A smaller number of competitors means higher competitiveness of the YRB.

competitors and the increasing uniqueness of crops which were supporting VWF from the YRB. The Yellow River is a large river that crosses an arid, semi-arid, and monsoon climate zone. The small number of competitors and the relatively high uniqueness of the YRB depend partially on the unique geographical conditions in the YRB (Fu et al., 2017). For example, high-quality apples produced in the fertile but arid loess Plateau in the middle reaches of the YRB and the wet areas in the

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lower reaches together account for more than 90% of the total apple production in China, and few other regions can compete with the YRB. The increasing uniqueness of the YRB means that its ability to improve the quality of its agricultural products and push competitors out of the crop supply network is growing. Those regions that can compete with a certain crop from the YRB (such as Xinjiang, which also exports many high-quality apples) are limited by extreme shortage of water resources and are unable to increase diversification, and hence lack overall competitiveness.

Assessing the value of natural resources has been a constant problem because of the trade-off between economic efficiency, social equity and resource availability (Dalin et al., 2015; Grafton et al., 2018; Yoon et al., 2021). The "Porter hypothesis" of the environment has proposed that environmental regulation can stimulate technological innovation, and similarly, the stimulus of resource scarcity can improve optimization of a market allocation for efficient use of resource (Wagner, 2004; Luptáčik, 2010). The complexity of the YRB has risen above the national average since about 1987, when the river basin was regulated because of water scarcity, and provinces were required to adhere to strict resource quotas (Wang et al., 2018). During this period of time, although the total VWF of the YRB and its proportion decreased, the increasing complexity indicated that the resource-constrained YRB was gaining a market advantages. In different ways, this advantage has manifested itself as an increase of the position of the YRB in the virtual water network and by an increase of both the competitiveness and uniqueness (Figure 4) (Fang and Chen, 2015; Fang et al., 2014; Yang et al., 2012). After the 1990s, the complexity index of China evidenced a similar trend of improvement, which was concomitant with the period when the strict control of water resources and a transformation to water-conservation were implemented throughout the whole country (Zhou et al., 2020; Liu and Yang, 2012). According to the literature (Zhou et al., 2020), the slowdown of the growth of China's water consumption can be divided into two stages by the 1990s. While growth during the earlier period occurred mainly in arid and semi-arid areas (e.g., the YRB), growth during the latter period affected the whole country. The increase of the national average level of complexity therefore lagged behind that of the YRB. This lag was probably the result of the rest of China pursuing structural advantages later than the YRB. Traditional development economic theory points out that the use of resources with a comparative advantage is a prerequisite for producing an economically efficient division of labor and a marketing network (Hidalgo and Hausmann, 2009). In this case, however, before water resources are severely restricted, it may not be more cost-effective to intensify development of a comparative advantage than to expand resource investment. This conlusion is consistent with the theories related to the "peak water use" and the "efficiency paradox" (Gleick and Palaniappan, 2010; Grafton et al., 2018). Taken together, here, the complexity index may depict the process by which the YRB and then China pursued this structural advantage within the water footprint network as constrained by resources.

In the process of gradually being deeply embedded in the water footprint network, the quality of crops in the YRB has constantly been improved. That improvement has become the structural driving force behind basin development. However, it must be pointed out that the YRB is a basin with a serious water shortage, and the proposed water resource regulations were also promulgated during a crisis period when the river was dring up (Wang et al., 2019, 2018). The increased complexity, like a double-edged sword, was facilitating the continued development of the YRB with constrained water resources but also embedding it more deeply into the water footprints networks where scarce water could not be easily replaced. Complexity, from this structural perspective, provided a reminder to help guide China as quickly as possible from resource-dependent development to high-quality development that would enhance regional competitiveness. When there is a crisis in the availability of resources, regulations must be implemented, and those regulations may deepen structural issues and make it more difficult to completely solve the ecological crisis that has been exposed.

## 5 Conclusions

This paper took into account the structure of the water footprint network from a complexity perspective and assessed the significance of water resources for crop services in a large river basin with a severe water shortage -the Yellow River Basin (YRB). From 1978 to 2008, the amount of Virtual Water out-Flows (VWF) from the YRB and its percentage of the total amount of VWF from the national total decreased significantly. The fact that the YRB has lagged behind the national VWF trend has probably related to policies that have restricted water use. However, our results showed that the complexity of the YRB increased and was significantly higher than the national average during the period from the 1980s to the 2000s. Decomposition of complexity suggested that this pattern was due mainly to few competitors and the increasing uniqueness of supporting VWF crops for the YRB. Based on an assessment of water conservation policies in China, we suggested that the initial promulgation of resource regulations was the key to a competitiveness-oriented transformation for crops production in the YRB. Subsequently, the increased complexity enabled the YRB to continue development with limited water resources, but it also more deeply embedded the YRB into water footprints networks where scarce water cannot be easily replaced. From the analysis of complexity, we therefore point out that resource regulation should be carried out at an appropriate stage to ensure both ecological sustainability and high-quality development of river basins.

*Code availability.* All code is open in my Github repository: SongshGeo/complexity-yrb

*Data availability.* Using published data, available from waterfootprint.org

*Author contributions.* Shuai Wang and Bojie Fu designed this research, Shuang Song performed the research and analysed data, Shuang Song and Yongyuan Huang wrote the paper, Xutong Wu and Yongyuan Huang revised, polished the manuscript and gave some major advices.

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