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RESEARCH ARTICLE

Spatiotemporal variation in water footprint of grain production in China

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Abstract Water shortage has become a significant constraint to grain production in China. A more holistic approach is needed to understand the links between grain production and water consumption. Water footprint provides a framework to assess water utilization in agriculture production. This paper analyzes the spatiotemporal variation in water footprint of grain production (WFGP) in China from 1951 to 2010. The results show that, jointly motivated by the improvement of agricultural production and water use efficiency, WFGP in all areas showed a decreasing trend. National average WFGP has decreased from 3.38 to 1.31 $m^3 \cdot kg^{-1}$. Due to regional differences in agricultural production and water use efficiency, spatial distribution of WFGP varies significantly and its pattern has changed through time. Moreover, WFGP may show significant differences within areas of similar climatic conditions and agricultural practices, indicating that there is a strong need to improve the management of water use technology. Statistical analysis revealed that regional differences in grain yield are the main cause for variations in spatiotemporal WFGP. However, the scope for further increases in grain yield is limited, and thus, the future goal of reducing WFGP is to decrease the water use per unit area.

Keywords water footprint, grain production, grain security, water scarcity, water-saving

1 Introduction

The incompatibly between increasing demand for grain and limited availability of water for agriculture is a major challenge for agriculture in China. Water and food security are hot issues around the world, and this is especially true for China. China has the largest national population (1.3 billion) in the world, accounting for almost 20% of the world's total population. However, the arable land and water resources account for only 9% and 6% of the world's totals, respectively[1,2]. There is little scope to increase the supply of water to agriculture due to limited availability and the increasing demand for water by industrial and domestic sectors[3,4]. As China's population is expected to reach its maximum in the 2030s[5], the question of whether or not there will be sufficient water and land resources to support life in modern China with its growing water use for food and other activities has received huge attention worldwide[6–9].

The concepts of water footprint (WF) and virtual water (VW) provide new methods to deal with this growing challenge. The term VW was coined by Allan[10], and means water contained in products or services. Based on the concept of VW, a group of researchers introduced WF in early 2000 as a measure of water used to produce commodities or services consumed by people (country or region) for a time period[11]. The water footprint is an indicator of freshwater resource appropriation and brings valuable insight about the impact of consuming a given product[12,13] assessed the green, blue and gray water footprint of rice, at high spatial resolution and using local data on actual irrigation. Feng et al.[14] compared the advantages and limitations of the water footprint of nations based on two input–output top-down approaches. Results showed that total water footprints of nations based on different approaches vary by up to 48%. Stoeglehner et al.[15] introduced the water supply footprint (WSF) and indicated that this can serve as a strategic planning tool for local or regional water supplies by linking water demand

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with water supply in a water supply footprint matrix. For agriculture, WFGP is defined as volumetric water consumed for producing grain crop per unit weight ($m^3\cdot kg^{-1}$), and it can be also used for the evaluation of agricultural water use efficiency. The WF consists of three parts: evapotranspiration of blue water (irrigation with water abstracted from ground or surface water systems), evapotranspiration of green water (soil water originating from precipitation), and gray water (polluted freshwater)[16]. WF is used as an important assessment tool in water resource management, which considers both direct and indirect water[17–22]. The gray water footprint of a crop refers to the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards. It is a theoretical value that is not truly consumed by the crop. Therefore, this paper only takes into account the total water consumption (green plus blue footprint) for crop production[22].

Water shortage is one of the important factors restricting grain production. Therefore, analyzing water consumption during grain production can help clarify the water use characteristics and existing problems of grain production to improve the management of agricultural water use. Quantification of the WFGP and analysis of regional differences are important for evaluating water consumption type, water use efficiency and regional differences in the grain production process. This study analyzes spatiotemporal variation in the WFGPWF of grain production over 31 geographical areas of China for the period 1951 to 2010 and explores the factors driving regional differences in the WFGP.

2 Materials and methods

2.1 Study areas

This study covered 31 administrative areas including provinces, autonomous regions, and municipalities in Mainland China.

2.2 Data

Meteorological data included daily precipitation from 340 weather stations[23]. Data related to grain production, including grain yield, sown area and population, were obtained from China statistical data for 55 years[24] and China statistical yearbook (2005–2011)[25]. Grain crops in this study include cereal, beans and tubers (according to the conversion factor provided by National Bureau of Statistics of China, 5 kg of fresh tubers is equivalent to 1 kg of grain crops)[25]. Data on agricultural water use and irrigation were taken from China water resources bulletin[2] and Yearbook of China water resources[26].

2.3 Methods

2.3.1 Calculation of regional grain water footprint

Regional WF of grain is calculated as follows:

$$WFG = GWF + BWF \tag{1}$$

where WFG is regional grain WF (Gm^3); GWF and BWF are the regional green and blue WF (Gm^3).

GWF is calculated as follows:

$$GWF = \sum_{i=1}^{n} 10P_e^i \cdot S^i \tag{2}$$

where P_e^i is effective precipitation during the growth period of crop type i (mm); S^i is the sown area of crop type i (hm^2).

P_e is calculated according to the method developed by the USDA, where effective rainfall can be calculated according to Eq. 5[27]:

$$P_e = \begin{cases} P(4.17-0.02P)/4.17 & P<83 \\ 41.7 + 0.1P & P\geqslant 83 \end{cases} \tag{3}$$

where P is precipitation for a period of ten days (mm).

BWF is calculated as follows:

$$BWF = \sum_{i=1}^{n} IR^i \times S^i \tag{4}$$

where IR^i is irrigation water use per unit sown area of crop i ($m^3\cdot hm^{-2}$); S^i is irrigation area of crop i (hm^2).

2.3.2 Calculation of water footprint of grain production

WFGP is calculated as follows:

$$WFGP = WFP/G \tag{5}$$

where $WFGP$ is WF of grain production ($m^3\cdot kg^{-1}$); G is regional total grain production (kg), and it is calculated as follows:

$$G = \sum_{i=1}^{n} P^i \tag{6}$$

where P_i is the production of crop type i (kg).

3 Results

3.1 Temporal variation in water footprint of grain production

The results of the analysis of temporal variation in China's WFGP of grain production show that the national average

WFGP is decreasing, with a reduction from 3.38 $m^3 \cdot kg^{-1}$ per year in the 1950s to 1.31 $m^3 \cdot kg^{-1}$ per year in the 2000s, a reduction of 61% (Fig. 1). This indicates that water use efficiency has increased substantially over that period, which has helped relieve the pressure on water resources while maintaining food security. Over the same time period the proportion of blue and green water in the WFGP has changed, and the proportion of blue water used in six decades from 1951 to 2010 was 21.5%, 30.0%, 40.7%, 42.7%, 43.6% and 44.7%, respectively. This suggests that the blue water resources in China are increasingly important for grain production.

Over the study period (Fig. 2), temporal variation in each area's WFGP showed obvious differences. The most significant decrease was in Henan which reduced from 3.58% to 0.86 $m^3 \cdot kg^{-1}$ over the six decades, a 76% reduction. Shanghai's decrease, on the other hand, was the least, from 1.84 to 1.38 $m^3 \cdot kg^{-1}$, a reduction of only 25%. In general, the magnitude of the reductions in WFGP in northern areas was greater than those in southern areas. In northern areas, WFGP declined from 3.49 to 1.17 $m^3 \cdot kg^{-1}$, a 67% reduction. In southern areas, it declined from 3.30 to 1.45 $m^3 \cdot kg^{-1}$, a 56% reduction. From 1951 to 1970, the WFGP in southern China was less than that in northern China, a feature that was reversed in the subsequent 40 years, and by the 2000s southern China was 0.28 $m^3 \cdot kg^{-1}$

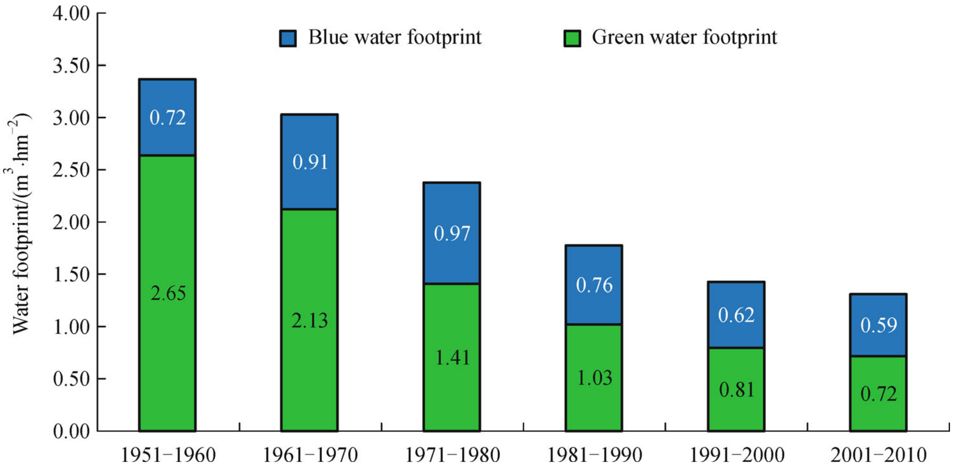

Fig. 1 National average blue (irrigation) and green (precipitation) water footprint of grain production in China for each decade from 1951 to 2010

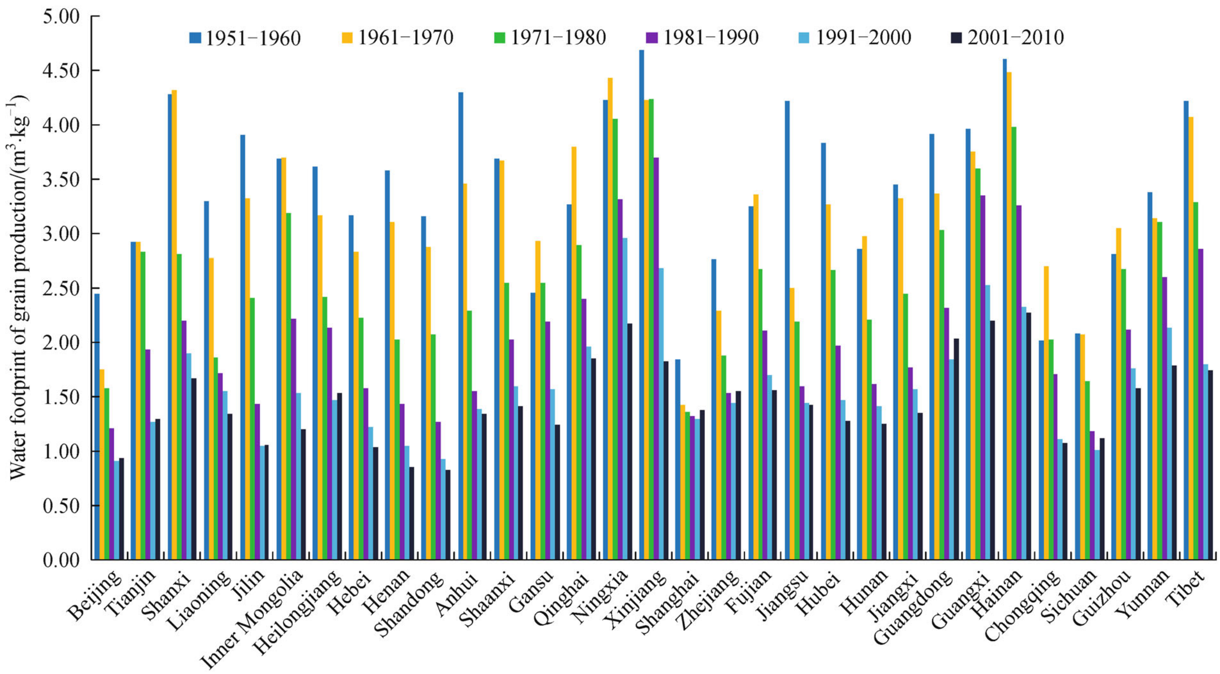

Fig. 2 Water footprint of grain production for the 31 administrative areas of China for each decade from 1951 to 2010

higher than northern China. A substantial reduction in WFGP occurred in the 1980s and the 1990s, which is consistent with the significant agricultural development in China during that period. During the last decade, WFGP in northern China decreased by only $0.16\,m^3\cdot kg^{-1}$, which implies that further improvement in agricultural water use efficiency through developing local water-saving technology has become more difficult.

3.2 Spatial variation in water use efficiency for grain production

The spatial analysis of WFGP in China showed significant interregional differences (Fig. 3). In the 1950s the WFGP ranged from 1.84 to $4.69\,m^3\cdot kg^{-1}$, with a coefficient of variation of 0.22. Higher WFGP was seen in parts of north-western and south-western China as well as Anhui and

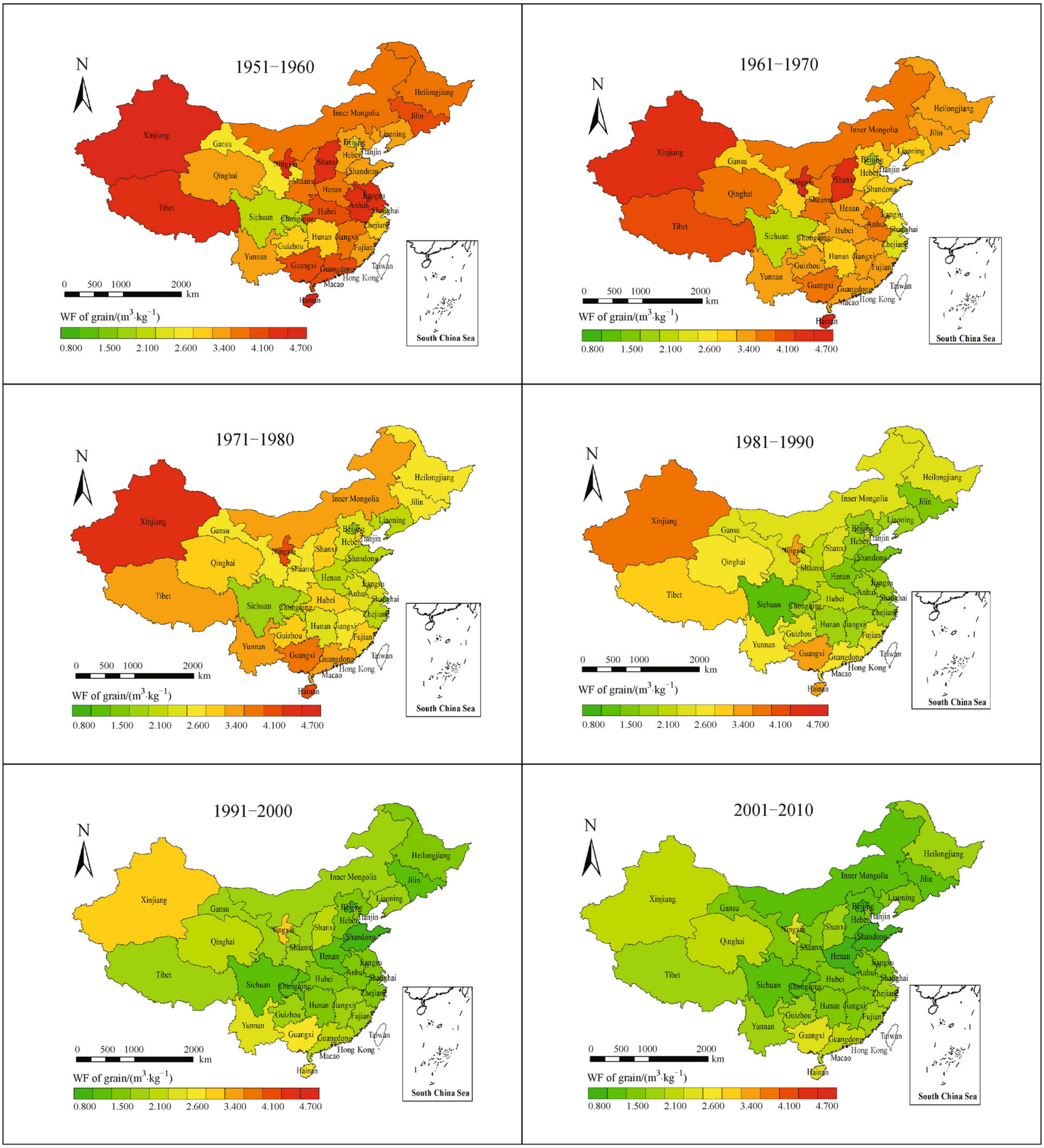

Fig. 3 Spatial variation in water footprint of grain production (WFGP) in China for each decade from 1951 to 2010

Jiangsu in the lower reaches of the Yangtze River, while WFGP in Huang-Huai-Hai, northern China and Sichuan in south-western China were relatively low. With the increase in grain productivity and water use efficiency, each area's WFGP declined in the 1960s and the differences between areas become more obvious, and the variation coefficient reached 0.23. Hainan had the highest WFGP at 4.49 $m^3 \cdot kg^{-1}$, and the lowest was Shanghai at 1.42 $m^3 \cdot kg^{-1}$. The spatial distribution of WFGP in the 1960s was almost the same as that in the 1950s. Each area's WFGP continued to decline in the 1970s. Over the same period the geographical pattern also changed, and high value areas of WF were concentrated in parts of north-west, south-west and south China, while low value areas were mainly located in the Huang-Huai-Hai region, middle and lower reaches of Yangtze River and Sichuan, Chongqing and other places in south-western China. This geographical pattern remained until the 1980s. From the 1990s onward, each area's WFGP declined, differences between areas increased, and the variation coefficient reached 0.31. The highest value of WFGP was Ningxia at 2.96 $m^3 \cdot kg^{-1}$, while the lowest was Beijing at 0.91 $m^3 \cdot kg^{-1}$. In addition, north-western and southern China's WFGP was relatively high, while in Huang-Huai-Hai and middle and lower reaches of the Yangtze River it was relatively low.

In summary, WFGP in north-eastern China, Huang-Huai-Hai, and other major grain producing areas declined significantly over the study period, while WFGP of grain production in southern and south-eastern China declined slightly. Moreover, areas with similar climatic conditions and agricultural practices had large difference in WFGP. For example, in the 1990s, the difference in WFGP between Jilin and Heilongjiang was 47%, although these two provinces are located nearby in north-eastern China with similar agricultural practices. This indicates that enhancing the management of water use in grain production is essential to save water used in agriculture and improve water use efficiency.

3.3 Attribution analysis of spatiotemporal variation in water footprint of grain production

According to the basic theory of WP, WFGP is codetermined by the degree of utilization of general water resources in the growth process and the yield per unit area. To perform an in-depth analysis of the driving factors of spatial distribution and temporal variation in WFGP, this study analyzed spatial variation in grain yield and water use per unit area.

The results show remarkable differences in grain yield per unit area related to spatial distribution (Fig. 4). The highest grain yield per unit area reached 2.74 $t \cdot hm^{-2}$, while the lowest was only 0.83 $t \cdot hm^{-2}$, and the coefficient of variation reached 0.33 during the 1950s. Since the 1950s the grain yield per unit area for each area has improved significantly, and the national grain yield per unit area has increased by 255%. At the same time, the difference in the grain yield per unit area between different regions has gradually declined, and the coefficient of variation decreased to 0.20 in the 2000s. Analyzing the variation in the grain yield per unit area over time showed that the increase in grain yield per unit area during the 1970s and 1980s was relatively large (more than 40%), but the growth rate dropped to 10% by the 2000s, indicating that there is limited potential for increasing the yield to lower the water footprint of grain in the future.

The analysis of water consumption per unit area of grain production also revealed remarkable differences. Taking the data for the 1950s as an example, the lowest water

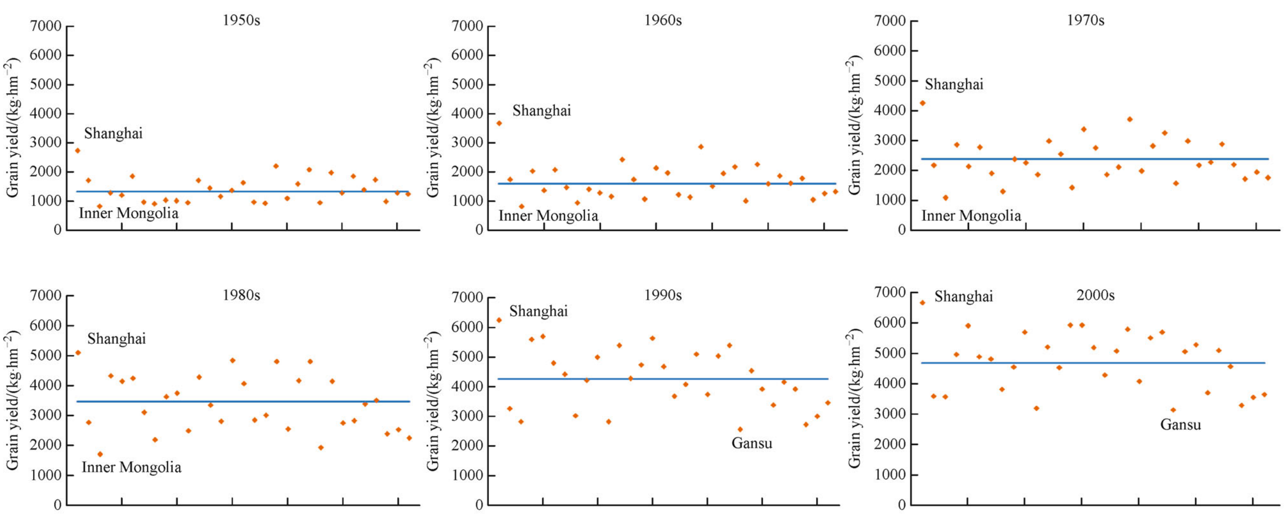

Fig. 4 Variation in grain yield per unit area across 31 study areas in China (areas with the highest and lowest values are indicated) for each decade from 1951 to 2010

consumption per unit area was 2333 $m^3 \cdot hm^{-2}$, while the highest was 6616 $m^3 \cdot hm^{-2}$, and the variation of coefficient reached 0.26. Considering the characteristics of temporal variation during the 1960s to 1980s, the water consumption per unit area increased by 9%, 17% and 9% for each subsequent decade (Fig. 5). After the 1990s, water consumption per unit area decreased as the water-use efficiency and grain yield increased, showing that improvement in water-use efficiency has helped reduce the WFGP.

Multiple linear regression was used to quantify the effect of grain yield and water consumption per unit area on WFGP, and the results show that the grain yield area contributed 64% to the spatial and temporal differences in the WFGP, whereas water consumption contributed only 36%. This analysis showed that the spatiotemporal variation in WFGP in China is determined mainly by grain yield per unit area. However, with a limited potential for increasing grain yield per unit area, decreasing water consumption per unit area of grain production will be the main method to reduce WFGP in China in the future.

4 Discussion

The significant reduction in WFGP fully aligns with the fact that there was a major investment in water saving technology research and its application in the field, which undoubtedly enhanced grain production in China. Although WFGP has been quite variable within and between different areas in China, there was no real difference in the available agricultural water-saving technology in those areas. This shows that the spatial differences were mainly caused by differences in the application and management of agricultural water-saving technology. The less developed and water-stressed northern China had a small WFGP and relatively high agricultural water use efficiency due mainly to effective water management. However, the highly developed and water sufficient southern areas had a large WFGP, indicating that effective measures have not been taken in those areas.

In the last six decades, the water-saving technology in China has improved remarkably. Nonetheless, it is difficult to improve agricultural water use efficiency by only relying on water-saving technology. In the 2000s, the average WFGP in China was 1.31 $m^3 \cdot kg^{-1}$, a decrease of 2.07 $m^3 \cdot kg^{-1}$ since the 1950s, giving an average decrease per decade of 0.15 $m^3 \cdot kg^{-1}$. In northern China, the decrease in WFPG was more rapid, declining by 2.32 $m^3 \cdot kg^{-1}$ from the 1950s to 2000s giving an average decrease per decade of 0.46 $m^3 \cdot kg^{-1}$. Since the degree of application of water-saving technology in northern China is high, further improvement in water-saving is likely to be limited and expensive. In addition, due to a low profit in grain production, it is difficult to apply further costly water-saving technology widely in China[28,29]. Therefore, the future water-resources strategy must focus on changes in agricultural water-saving technology for increasing the efficiency of use of precipitation and irrigation water in order to ensure sustainable development of agriculture and national food security[4,30–32]. Meanwhile, some studies have also indicated that to mitigate water scarcity, water productivity increases are an essential ingredient, although insufficient on its own. According to a recent study, blue water efficiency, in all sectors combined and as a global average, could be improved by 25 per cent[33]. According to the same study, the efficiency gains in water use will not be sufficient to offset the effects of population growth[34,35]. Dalin et al.[35] indicated that reducing irrigated land in regions highly dependent on scarce river flow and nonrenewable groundwater resources, such as

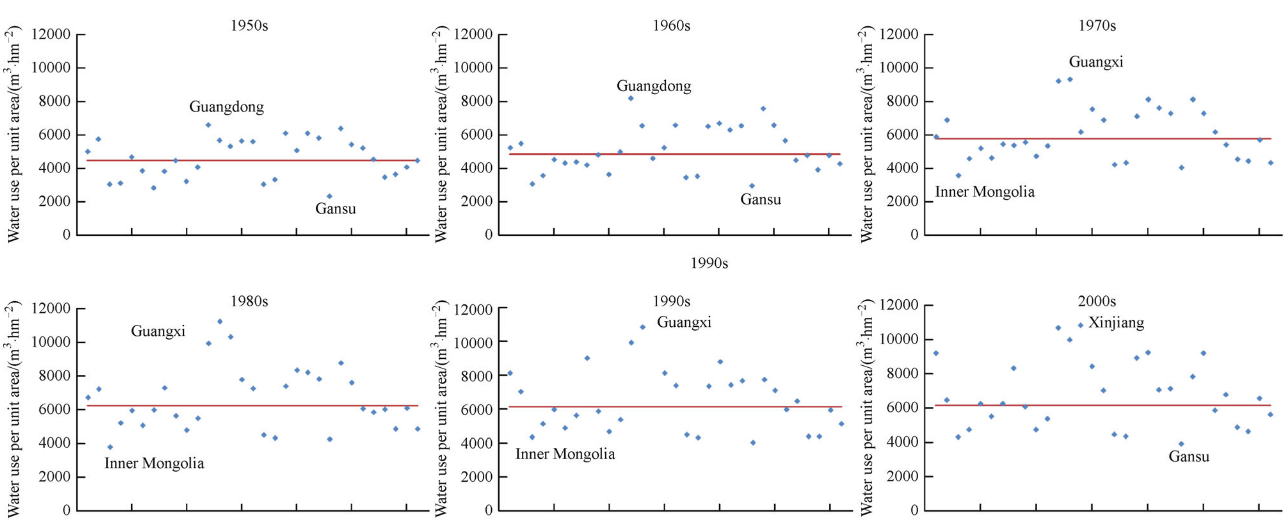

Fig. 5 Variation in water use per unit area during grain production across 31 study areas in China (areas with the highest and lowest values are indicated) for each decade from 1951 to 2010

Inner Mongolia and the greater Beijing area, can improve the efficiency of agriculture and trade regarding water resources. It can also avoid significant consumption of irrigation water across China while incurring relatively small decreases in national food self-sufficiency.

Water is not only a fundamental natural resource but also a strategic economic resource, which is vital for the well-being of nations and their people. However, in China the administrative agencies responsible for irrigation mainly gain profits from selling water, and thus they are not motivated to save water. The area of arable land per capita in China is less than 0.1 hm^2. The price of agricultural water is also low, usually less than 0.02 $USD \cdot m^{-3}$, but this cannot increase significantly due to the low economic capacity of famers. Thus the water pricing policy does not provide an incentive for farmers to save water. The application of water-saving technology in China is mainly promoted by government agencies, and because of the lack of a proper stimulus policy, irrigation administrators and farmers do not make much effort to improve water-saving methods. Also, further improvement in the efficiency of agricultural water use is difficult. Therefore, a comprehensive water management strategy is also needed. The incentive to develop water-saving agriculture could be enhanced by informed management.

5 Conclusions

The temporal variation in WFGP in China has been significant, and has shown a declining trend. The decline in the northern areas has been greater than in the southern areas. In the major grain producing areas including north-eastern China, the Huang-Huai-Hai region, the WFGP decreased significantly, whereas in regions such as south-ern and south-eastern China the decrease was less pronounced. The most significant decrease in WFGP occurred in the 1980s and 1990s, corresponding to the rapid development of Chinese agricultural productivity.

The spatial variation in WFGP in China is remarkable. In the 1950s and 1960s, some areas in north-western and south-western China and areas in the middle–lower reaches of the Yangtze River, such as Anhui and Jiangsu, had a higher WFGP, while the Huang-Huai-Hai Region, northern China and Sichuan in south-western China had a lower WFGP. In the 1990s and 2000s, north-western and southern China had a higher WFGP, while in north-eastern China, the Huang-Huai-Hai region and middle–lower reaches of the Yangtze River it was lower. The changes in spatial variation in WFGP between different periods was a result of geographic differences in development of agricultural and water productivity. In addition, a notable difference still exists in the WFGP between areas with similar climatic conditions and agricultural practices, indicating that the management of water saving technology must affect WFGP.

The analysis shows that spatiotemporal variation in WFGP in China is mostly due to the changes in the grain yield per unit area. However, with a limited potential in increasing the grain yield per unit area, decreasing water consumption per unit area will be the main method to reduce the national WFGP.

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Compliance with ethics guidelines Pute Wu, Yubao Wang, Xining Zhao, Shikun Sun, and Jiming Jin declare that they have no conflict of interest or financial conflicts to disclose.

This article does not contain any studies with human or animal subjects performed by any of the authors.

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