

Article

Are Water Use Efficiency and Effectiveness Relatively Lower in Arid Zones? Comparative Analyses of the Water Productivity of Typical Crops

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Abstract: Agriculture is the largest water user of all sectors. In arid regions in particular, achieving efficient water use in agriculture is an important way to solve water scarcity. However, the difference in water use efficiency between arid and humid regions has long been a focus of academic debate. Many studies consider water use efficiency to be higher in humid areas due to the abundance of water resources. This view is based on the fact that less irrigation in humid areas may lead to higher crop yields and better conditions for agricultural production; however, it ignores the efforts of researchers and agricultural workers in arid zones who have attempted to develop efficient water-saving technologies, as well as the effect of natural conditions on agricultural production. Correctly evaluating the efficiency of agricultural water use in arid zones is important for achieving efficient use of water resources, as well as for water management decisions. This study calculates the yield structure and water productivity of typical crops in both arid and humid regions in China based on the footprint theory and other methodologies. This approach allows for an accurate assessment of irrigation water benefits in various regions, providing a scientific basis for improving agricultural water use efficiency under different climatic conditions. The study results indicate that the average reliance on blue water for wheat and cotton gradually increases from 49.9% to 93.6% as regional aridity intensifies, ranging from the Central China Humid Region to the Northwest China Arid Region. Similarly, the average contribution of blue water to crop yield rises from 31.0% to 100%, while irrigation water productivity increases from 0.27 kg·m⁻³ to 0.53 kg·m⁻³. Finally, this study concludes that, in arid zones with lower precipitation and more hours of sunshine, a higher dependence on blue water for crop growth and development leads to a higher productivity of irrigation water. In addition, in arid zones, the focus should be on optimizing the use of irrigation water and improving irrigation technology and efficiency, while, in humid zones, there should be more use of natural precipitation to efficiently reduce dependence on irrigation water.

Keywords: dry zone; water footprint; water productivity; irrigation water use



Citation: Zhang, Y.; Long, A.; Zhang, P.; Deng, X.; Gu, X. Are Water Use Efficiency and Effectiveness Relatively Lower in Arid Zones? Comparative Analyses of the Water Productivity of Typical Crops. *Agronomy* **2024**, *14*, 2153. <https://doi.org/10.3390/agronomy14092153>

Academic Editor: Dimitrios Savvas

Received: 16 August 2024

Revised: 14 September 2024

Accepted: 18 September 2024

Published: 21 September 2024



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1. Introduction

China is both a populous and an agricultural country. According to the 2020 China Water Resources Bulletin, while the country's total water resources are abundant, at 3160.52 billion m³, due to its large population base, the per capita water resources are very low, at only 2238.7 m³—which is one-quarter of the world's average level—and the shortage of water resources has become an important factor, restricting China's economic and social development [1]. The total water consumption of the country in 2020 was 581.29 billion m³, of which 361.24 billion m³ was used for agriculture, accounting for 62.1% of the total

water consumption [2]. This situation has led to increasing competition for water between agriculture and other sectors, and improving agricultural water efficiency and optimizing the allocation and management of water resources have become important tasks in regard to alleviating water scarcity.

Xinjiang and other northwestern arid zones are important agricultural production bases in China, and their agricultural water consumption ranks first in the country. However, in terms of evaluating the effectiveness of agricultural water use, the conventional view is that it is less efficient in arid areas, while humid areas have a higher efficiency of water use due to their abundant water resources [3,4]. This view is based on the fact that wetter regions with less irrigation may lead to higher crop yields and better conditions for agricultural production [5]. This leads to policy makers being cautious about whether to invest large amounts of human and material resources in agricultural water use in arid regions. However, this prevailing view not only ignores the efficient water management and advanced irrigation technologies adopted in arid zones in the face of water scarcity [6], but also fails to take into account the beneficial effects of the natural conditions of the humid zone on agricultural production. Several studies in recent years have begun to question this traditional view by pointing out that agricultural water use benefits may be higher in arid than in wet zones [7]. These studies suggest that governments in arid zones have responded to water scarcity by adopting more sophisticated irrigation management and efficient water use techniques which have significantly increased water use efficiency [8]. Therefore, a systematic comparative analysis of agricultural water use efficiency in arid and humid zones is important for reconceptualizing water use efficiency [9].

The efficient use of water resources is crucial to sustainable agricultural development. Agricultural water use efficiency, which can be expressed as the ratio of agricultural output or production value to water input, has also been a hot topic of discussion in the academic community in terms of how to evaluate it, resulting in a number of methods. Comprehensive evaluation can be carried out for all factor indicators, and common methods include the entropy weight method [10] and data envelopment models such as the DEA model and SBM model [11–14]. In addition, single-factor efficiency indicators can be evaluated, such as crop water productivity [15], canal water use coefficients, and irrigation water effective use coefficients [16]. Among them, crop water productivity refers to the ratio of crop yield to the amount of water consumed, which is the single-factor indicator that most directly responds to the efficient of agricultural water use; thus, this study focuses on the differences in crop water productivity between arid and humid areas in China.

Although there have been a number of studies focusing on water productivity in both arid and humid regions, in general, there are still some shortcomings in academic research in this area. First, many of the existing studies tend to assume that water use efficiency is higher in humid areas and pay insufficient attention to efficient water management and advanced irrigation technologies in arid areas [17,18]. Second, many studies focus only on single crops or localized areas and lack systematic comparative analyses [19,20]. Finally, although some studies have begun to explore the application of efficient irrigation technologies in arid zones, the specific benefits and dissemination strategies are still insufficiently researched [21].

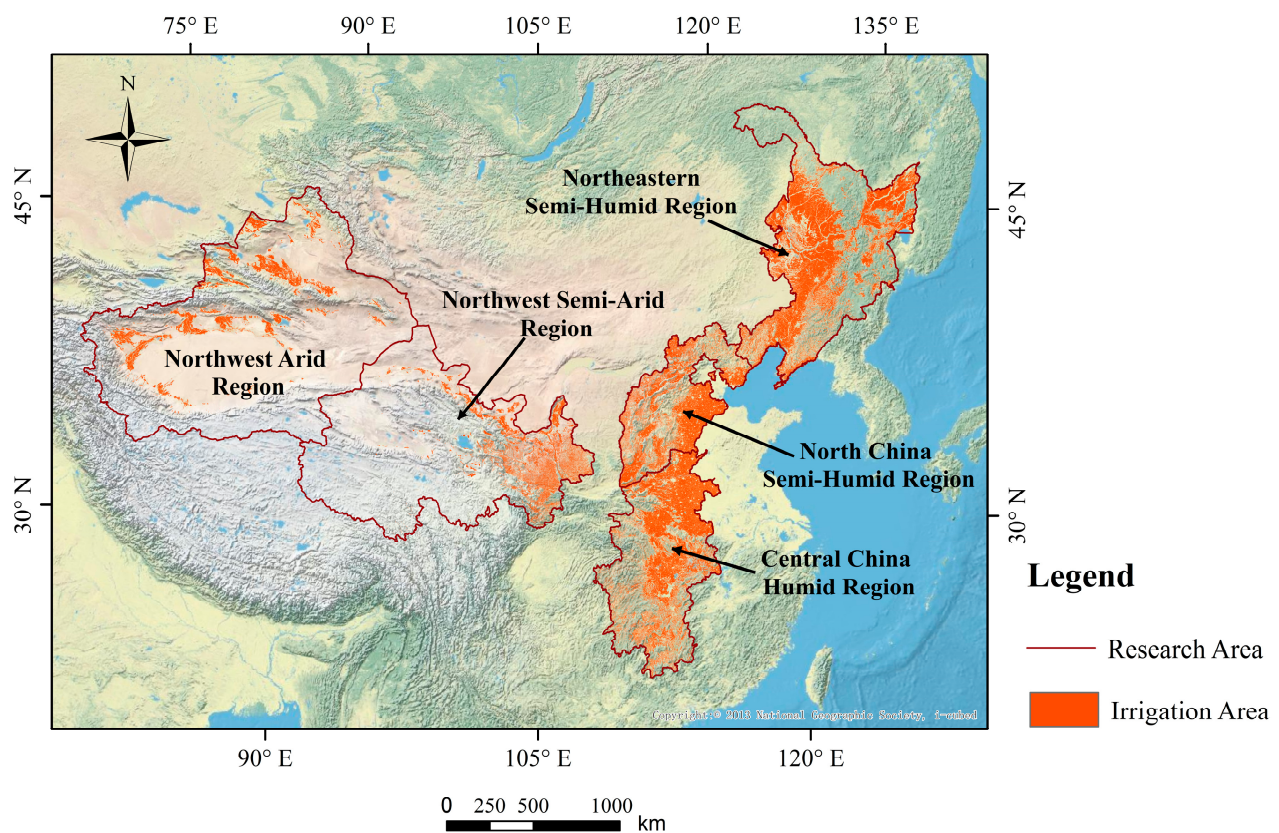
The main research objective of this study is to explore the differences in irrigation water use efficiency in arid and humid zones in China, choosing a typical grain crop (wheat) and a typical cash crop (cotton) for comparative analyses. Before the analysis of water use efficiency can be carried out, an accurate assessment of water use is first needed. It is worth noting that there may be a large gap between the agricultural water use statistics and the actual situation in the study area due to the imperfections in farmland metering facilities [22]. Therefore, we adopt the agricultural water footprint as the real water consumption data of crops [23,24], considering the blue water footprint of crops as the amount of anthropogenic irrigation water they consume and the green water footprint as the amount of natural precipitation they consume [25]. Based on the agricultural water footprint theory, this study utilizes the Doorenbos–Kassam model [26] to evaluate the yield

structure of typical crops; moreover, it calculates and systematically compares the water productivity of typical crops in China's arid and humid regions over the past 20 years. The main content of this study includes the following: (1) a more detailed categorization of crop water productivity, along with the development of a research framework for crop water productivity; (2) an analysis of the water footprint, yield structure, and water productivity of typical crops in the study areas; (3) an exploration of the reliability of the study and the relationship between crop irrigation water productivity and influencing factors. The results of this study will provide a scientific basis for water resource management decision makers to help formulate more rational and efficient water resource management policies, thereby promoting sustainable agricultural development.

2. Materials and Methods

2.1. Selection of Study Areas

This study focuses on the differences in water productivity of wheat (including spring and winter wheat), a typical grain crop, and cotton, a typical cash crop, in arid and humid regions in China. As shown in Figure 1, 12 provinces or autonomous regions were selected for this study and divided into five regions based on their geographical location and climatic conditions: the Northwest Arid Region (Xinjiang Uygur Autonomous Region), the Northwest Semi-Arid Region (Qinghai, Gansu, and Ningxia Hui Autonomous Regions), and the Northeastern Semi-Humid Region (Heilongjiang, Liaoning, and Jilin Provinces), where spring wheat and cotton are mainly grown, as well as the North China Semi-Humid Region (Hebei and Shanxi Provinces) and the Central China Humid Region (Henan, Hubei, and Hunan Provinces), where winter wheat and cotton are mainly grown.



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Figure 1. Map of the study areas.

The arid and semi-arid regions of Northwest China have a typical continental climate with low annual precipitation, high evaporation rates, and scarce water resources. Agricultural production in this region is heavily dependent on irrigation. It has a low population density and per capita GDP, with economies focused on agriculture, resource extraction, and energy. The Northeastern Semi-Humid Region experiences a temperate continental climate, with annual precipitation ranging between 500 and 800 mm, making it ideal for cultivating staple crops such as corn, soybeans, and rice. With a population of approximately 100 million and a GDP of around RMB 6 trillion, and its economy is largely dominated by agriculture and heavy industry. North China receives about 500 mm of annual rainfall and has a semi-humid climate. It has a population of around 110 million, a GDP of RMB 7 trillion, and its economy is driven by agriculture, mining, and manufacturing. However, water resources in this region are relatively scarce. Central China enjoys a humid climate, with an annual precipitation of between 800 and 1500 mm, ensuring ample rainfall. The region is rich in high-quality arable land and water resources. With a dense population of over 200 million and a GDP exceeding RMB 16 trillion, it is a developed economy dominated by agriculture and industry and serves as one of the country's major grain-producing regions.

2.2. Data Sources

The meteorological data in this study were obtained from the National Meteorological Information Centre (NMIC) China Surface Meteorological Data Daily Value Dataset, which included rainfall (mm), sunshine hours (h), average wind speed ($\text{m}\cdot\text{s}^{-1}$), relative humidity (%), minimum temperature ($^{\circ}\text{C}$), and maximum temperature ($^{\circ}\text{C}$) from 825 meteorological stations during the period of 2000–2020. Crop production data were obtained from the statistical yearbooks of each province and autonomous region, the China Statistical Yearbook, and the China Rural Statistical Yearbook, which included the area planted with crops (hm^2), the total crop production (t), the total mechanical power (10,000 kw), fertilizer application (10,000 t), and pesticide use (t). In checking the reliability of the study results, data on crop water consumption (mm) and yield ($\text{kg}\cdot\text{hm}^{-2}$) were obtained from the China National Knowledge Infrastructure (CNKI) database, which is the largest and most authoritative academic resource database in China. Individual missing data were obtained by supplementing them using methods such as fitting extensions and linear interpolation.

2.3. Research Methodology

2.3.1. Crop Water Demand and Water Production Footprint

We calculated crop water requirements using the standard evapotranspiration model for crops [27]:

$$ET_c = K_c \times ET_o \quad (1)$$

where ET_o is the reference crop evapotranspiration (mm), calculated using the Penman–Monteith formula; K_c is the crop coefficient, using the recommended values of the Food and Agriculture Organization of the United Nations (FAO); and ET_c is the actual evapotranspiration of the crop (mm).

The formula recommended by the Soil Conservation Service of the United States Department of Agriculture (USDA) was used to calculate the effective rainfall for crops; it can effectively calculate the rainfall distribution and farmland water demand characteristics of different regions of China and has been used extensively by Chinese scholars [28–30]:

$$P_{eff} = \begin{cases} P_{month}(125 - 0.2P_{month})/125 & P_{month} \leq 250 \text{ mm} \\ 125 + 0.1P_{month} & P_{month} > 250 \text{ mm} \end{cases} \quad (2)$$

where P_{eff} is the effective rainfall (mm) and P_{month} is the actual monthly cumulative rainfall (mm).

For crops, if the effective rainfall meets their water requirements during the reproductive period, no supplementary irrigation is required; otherwise, supplementary irrigation

is required, which is the difference between the total water requirement and the effective rainfall. The effective rainfall actually utilized by the crop (green water dissipation) and the supplementary irrigation (blue water dissipation) can therefore be calculated with the following formula:

$$ET_g = \sum_i^n \text{Min}(ET_c, P_{eff}) \quad (3)$$

$$ET_b = ET_c - ET_g \quad (4)$$

where ET_g is green water dissipation; ET_b is blue water dissipation; and n is the number of days of crop growth and development.

The water footprint of crop production has two parts: the green water footprint of production and the blue water footprint of production. It is an important indicator reflecting the water consumption structure of crops and the amount of water used for production, and it is numerically equal to the ratio of crop dissipation to production. In this study, it is assumed that crop yields in each region are obtained under fully irrigated conditions, from which the following formula can be obtained:

$$WF = ET_c / 1000Y_m \quad (5)$$

$$WF_g = ET_g / 1000Y_m \quad (6)$$

$$WF_b = ET_b / 1000Y_m \quad (7)$$

where WF is the water footprint of crop production ($\text{m}^3 \cdot \text{kg}^{-1}$); WF_g is the green water footprint of crop production ($\text{m}^3 \cdot \text{kg}^{-1}$); WF_b is the blue water footprint of crop production ($\text{m}^3 \cdot \text{kg}^{-1}$); Y_m is the maximum yield of the crop obtained under full irrigation ($\text{kg} \cdot \text{m}^{-2}$); and 1000 is the unit conversion factor.

2.3.2. Structure of Crop Yields

A crop yield consists of the following two components: the green water yield, which is the weight of the final agricultural product produced when the water used in the growth and development of the crop is supplied exclusively by green water under non-irrigated conditions, and the blue water yield, which is the net increase in the yield of the crop over the green water yield under irrigated conditions.

In this study, the Doorenbos–Kassam model [26] was used as a crop water production function for yield evaluation, which is commonly used by the FAO [31] and is based on the assumption that yield is linearly related to plant water consumption. In fact, plant photosynthesis and transpiration are coupled through stomatal regulation, and both are linearly proportional to stomatal conductance [8,32], so the assumption of a linear relationship between crop yield and transpiration is based on a reasonable ecohydrological basis [33]. The calculation formula is as follows:

$$(1 - Y_a/Y_m) = k_y(1 - ET_a/ET_m) \quad (8)$$

where Y_a is the actual crop yield ($\text{kg} \cdot \text{m}^{-2}$); Y_m is the maximum crop yield ($\text{kg} \cdot \text{m}^{-2}$); and k_y is the yield response factor (the value of k_y for spring wheat ranges from 0.8 to 1.3, for winter wheat from 0.7 to 1.2, and for cotton from 0.5 to 1.1). The value of k_y is mainly determined using the type of crop, the stage of growth of the crop, the climate of the region, and the soil conditions, and the detailed values can be found in the results of the study by Doorenbos and Kassam [26]. ET_a is the actual crop evapotranspiration (mm), and ET_m is the maximum crop evapotranspiration (mm). The formula is valid when moisture deficits up to 50% ($1 - ET_a/ET_m \geq 0.5$); therefore, it is widely used worldwide [34].

Assuming that the crops in the study area are adequately irrigated, the actual yield is the maximum yield of the crop Y_m , where the green water yield of the crop, Y_g , is a part of

the maximum yield, Y_m , and hence the green water yield of the crop, Y_g , can be obtained using appropriate deformation of Equation (8):

$$Y_g = Y_m [1 - k_y(1 - ET_g/ET_c)] \quad (9)$$

Having obtained the green water yield Y_g of the crop, it is possible to determine the net additional yield of the crop after adequate irrigation, i.e., the blue water yield Y_b :

$$Y_b = Y_m - Y_g \quad (10)$$

2.3.3. Crop Water Productivity

Water productivity of crops was subdivided in this study into green water productivity WP_g ($\text{kg}\cdot\text{m}^{-3}$), blue water productivity WP_b ($\text{kg}\cdot\text{m}^{-3}$), irrigation water productivity WP_i ($\text{kg}\cdot\text{m}^{-3}$), and water productivity WP ($\text{kg}\cdot\text{m}^{-3}$). They can be determined from the corresponding water dissipation of the crop as well as the yield:

$$WP = 1000Y_m/ET_c \quad (11)$$

$$WP_g = 1000Y_g/ET_g \quad (12)$$

$$WP_b = 1000Y_b/ET_b \quad (13)$$

$$WP_i = \alpha \times 1000Y_b/ET_b \quad (14)$$

where 1000 is the unit conversion coefficient and α is the irrigation efficiency, i.e., the ratio of the actual water consumption of crops to the amount of water withdrawn from the head of the irrigation canal. This study assumes that the level of irrigation engineering is the same in each region, the blue water productivity is the irrigation water productivity, and α is taken as 1.0.

2.4. System of Indicators of Impact Factors

Combined with relevant theories and research methods, this study uses Pearson regression analysis to correlate the efficiency factor, meteorological factor, and production factor of agricultural production. The system of indicators of impact factors is shown in Table 1.

Table 1. System of indicators of impact factors.

Factor	Indicator	Description of Indicator	Calculation Method
Efficiency factor	WP	Water productivity ($\text{kg}\cdot\text{m}^{-3}$)	Total crop production/total water dissipation
	WP_g	Green water productivity ($\text{kg}\cdot\text{m}^{-3}$)	Crop green water production/green water dissipation
	WP_b	Blue water productivity ($\text{kg}\cdot\text{m}^{-3}$)	Crop blue water production/ blue water dissipation
Meteorological factor	Sun	Sunshine hours (h)	Meteorological station data
	P	Annual precipitation (mm)	
	T	Average temperature ($^{\circ}\text{C}$)	
Production factor	Machinery	Mechanical power per unit area ($\text{kw}\cdot\text{hm}^{-2}$)	Total machinery power/crop sown area
	Fertilizer	Fertilizer application per unit area ($\text{kg}\cdot\text{hm}^{-2}$)	Fertilizer application/crop sown area
	Pesticide	Pesticide use per unit area ($\text{kg}\cdot\text{hm}^{-2}$)	Pesticide use/crop sown area

3. Results and Analyses

3.1. Comparative Analysis of the Water Footprint of Typical Crop Production

An analysis of the changes in the water footprint of typical crop production in each region from 2000 to 2020 is shown in Figure 2. From the perspective of the changes in the water footprint of wheat (including spring and winter wheat) production in each region over the past 20 years, the water footprint of wheat production in arid and humid regions has been gradually converging, while the water footprint of cotton production in each region has been slowly decreasing. The green water footprint of wheat and cotton production in each region fluctuates but basically remains at a relatively stable level. The blue water footprint of wheat and cotton production in all regions shows a gradually decreasing trend. Among them, it is not difficult to find that, in the arid regions, the green water footprint of production of winter wheat, spring wheat, and cotton are all lower than that of the humid regions, while the blue water footprint of production is higher than that of the humid regions. This phenomenon is mainly determined by regional climate. In wetter regions, where rainfall is higher, more green water resources can be accessed during crop growth and development, thus requiring fewer blue water resources.

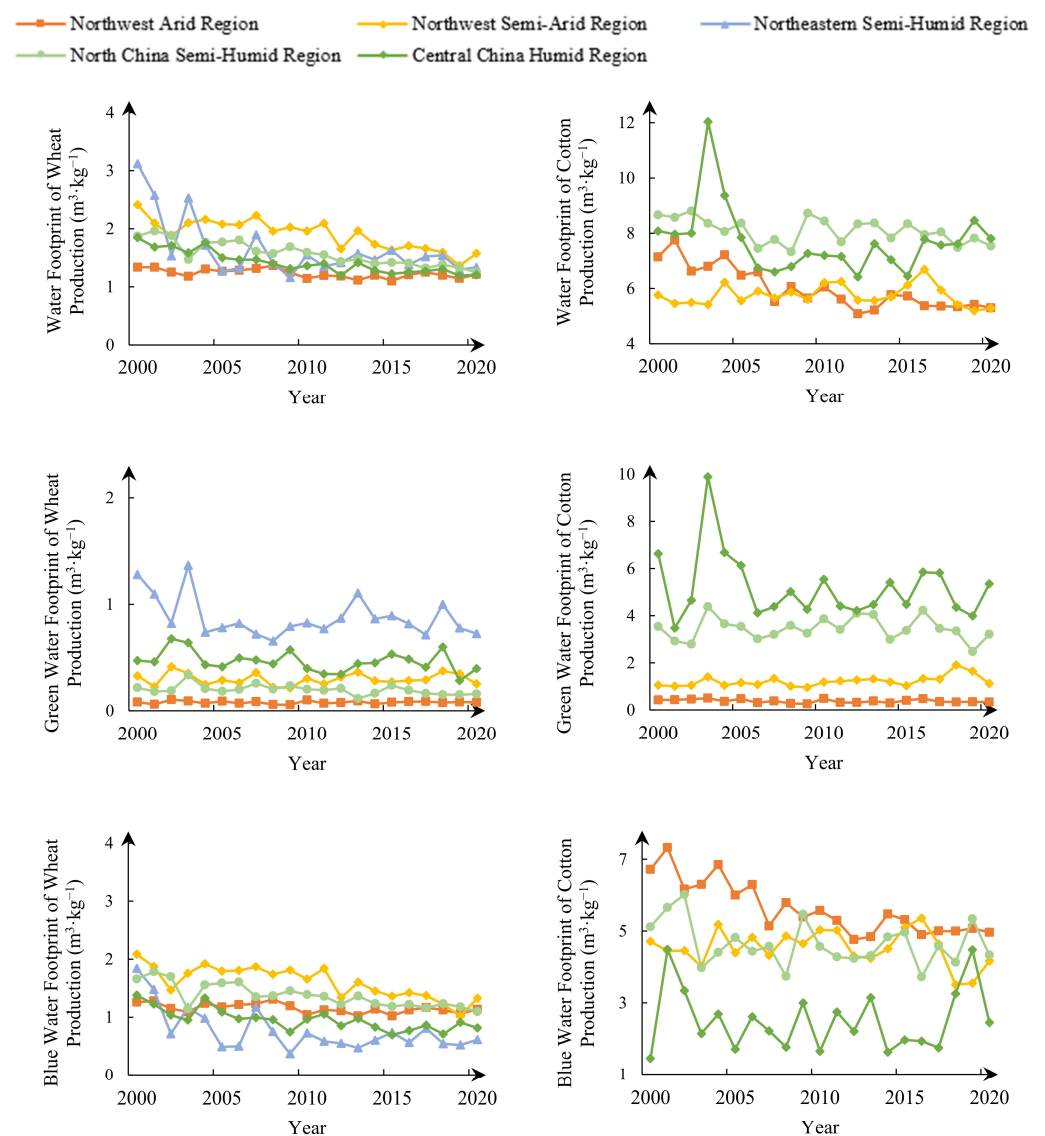


Figure 2. Analysis of changes in the water footprint of typical crop production in arid and humid regions from 2000 to 2020.

The distribution of the multi-year average production water footprint structure of typical crops in arid and humid regions from 2000 to 2020 is shown in Table 2. The Northwest Arid Region, Northwest Semi-Arid Region, and Northeastern Semi-Humid Region are the main planting areas of spring wheat, among which the blue water dissipation in the production process of spring wheat in the Northwest Semi-Arid Region is the highest, with a multi-year average production blue water footprint of $1.60 \text{ m}^3 \cdot \text{kg}^{-1}$, while, in the Northwest Arid Region, the dependence on blue water during spring wheat growth and development was the highest, reaching 93.5%. In the North China Semi-Humid Region and the Central China Humid Region, the average blue water footprint of winter wheat production was $1.37 \text{ m}^3 \cdot \text{kg}^{-1}$ and $0.96 \text{ m}^3 \cdot \text{kg}^{-1}$, respectively, accounting for 87.4% and 67.3% of the respective production water footprints. Cotton, a typical cash crop, is grown in all the study areas, except in the Northeastern Semi-Humid Region, where it is hardly grown. Water consumption per unit of cotton produced was the smallest in the Northwest Semi-Arid Region at $5.76 \text{ m}^3 \cdot \text{kg}^{-1}$ and the largest in the North China Semi-Humid Region at $8.09 \text{ m}^3 \cdot \text{kg}^{-1}$. Dependence on blue water during the growth and development of cotton was the highest in the Northwest Arid Region at 93.7%, while it was the lowest in the Central China Humid Region at 32.6%. For both wheat and cotton, the dependence on blue water for growth and development was higher in the more arid regions, while the opposite was true in the humid regions.

Table 2. Average multi-year production water footprint of typical crops in arid and humid regions, 2000–2020 ($\text{m}^3 \cdot \text{kg}^{-1}$).

Region	Wheat			Cotton		
	WF	WF _b	WF _g	WF	WF _b	WF _g
Northwest Arid Region	1.23	1.15	0.08	6.01	5.63	0.38
Northwest Semi-Arid Region	1.90	1.61	0.30	5.76	4.54	1.22
Northeastern Semi-Humid Region	1.65	0.77	0.88	—	—	—
North China Semi-Humid Region	1.57	1.37	0.20	8.09	4.64	3.45
Central China Humid Region	1.42	0.96	0.46	7.71	2.51	5.20

3.2. Comparative Analysis of the Yield Structure of Typical Crops

The multi-year average yields and structural distribution of typical crops in arid and humid regions from 2000 to 2020 are shown in Figure 3. Among the spring wheat growing areas, the wheat yield was highest in the Northwest Arid Region, reaching $0.54 \text{ kg} \cdot \text{m}^{-2}$, and there was not much difference between the Northwest Semi-Arid Region and the Northeastern Semi-Humid Region, with $0.32 \text{ kg} \cdot \text{m}^{-2}$ and $0.33 \text{ kg} \cdot \text{m}^{-2}$, respectively. The blue water yield and its percentage of yield were highest in the Northwest Arid Region at $0.54 \text{ kg} \cdot \text{m}^{-2}$ and 100.0%, respectively, and lowest in the Northeastern Semi-Humid Region at $0.14 \text{ kg} \cdot \text{m}^{-2}$ and 42.3%, respectively. In winter wheat growing areas, winter wheat yields were $0.49 \text{ kg} \cdot \text{m}^{-2}$ and $0.53 \text{ kg} \cdot \text{m}^{-2}$ in the North China Semi-Humid Region and the Central China Humid Region, respectively, while blue water yields were $0.44 \text{ kg} \cdot \text{m}^{-2}$ and $0.24 \text{ kg} \cdot \text{m}^{-2}$, with the proportion of blue water yields accounting for 88.2% and 45.2%, respectively.

The Northwest Arid Region has the highest amounts in regard to both cotton, a typical cash crop, and blue water yields, both at $0.18 \text{ kg} \cdot \text{m}^{-2}$, and its blue water yield share is also the highest at 100.0%. Cotton yields were also higher in the drier regions but lower in the North China Semi-Humid Region and the Central China Humid Region, both at $0.10 \text{ kg} \cdot \text{m}^{-2}$. Of these, the Central China Humid Region had the highest green water yield at $0.08 \text{ kg} \cdot \text{m}^{-2}$, while the blue water yield and its share were the lowest at $0.02 \text{ kg} \cdot \text{m}^{-2}$ and 16.7%, respectively.

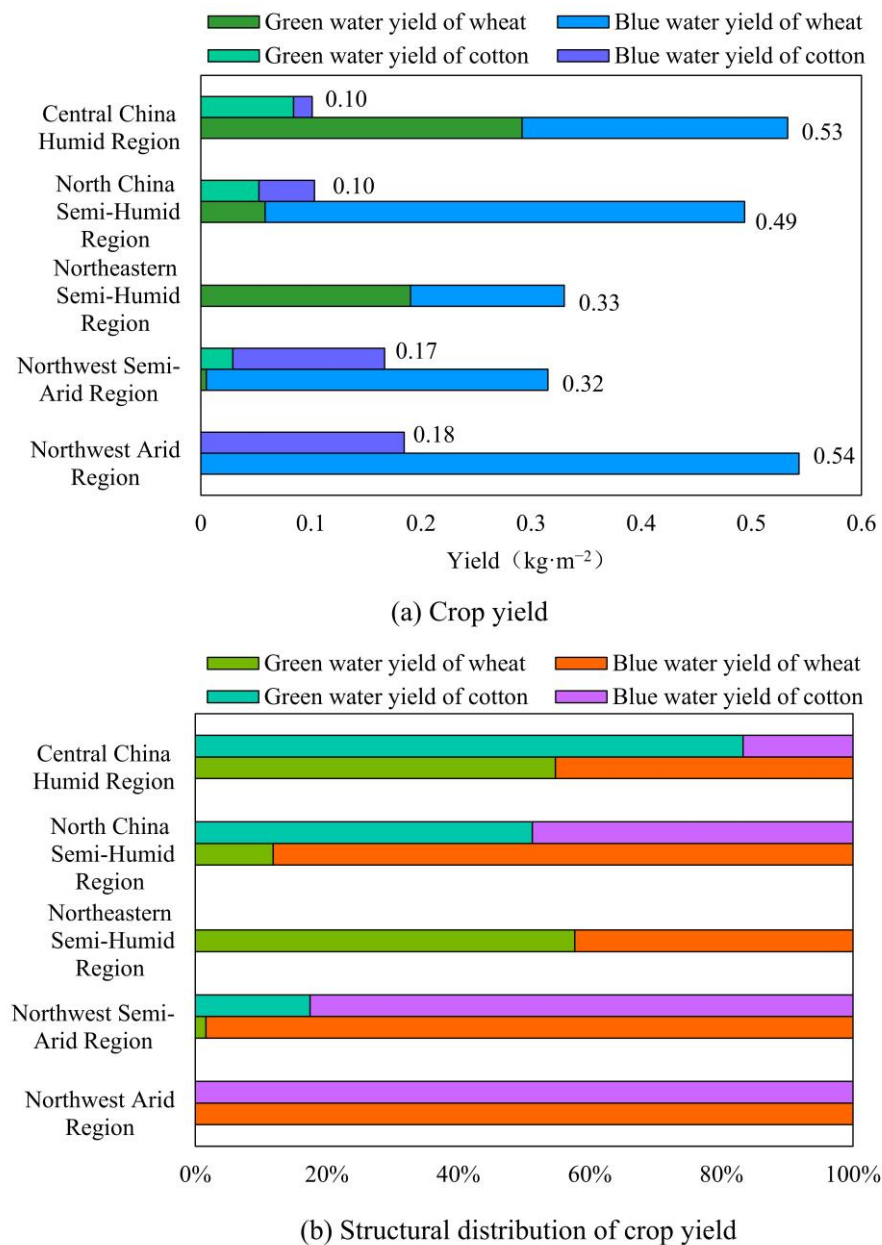


Figure 3. Multi-year average yield and structural distribution of typical crops in arid and humid areas from 2000 to 2020.

Crop yield per unit area and blue water yield are important indicators for evaluating the level of local agricultural production, while crop types, the level of agricultural production technology, and the efficiency of agricultural water use are the main factors affecting crop yield. From the above analysis, it can be found that wheat and cotton in the Northwest Arid Region are higher than those in other regions both in terms of yield and blue water yield. This is because of the high-scale industrialization of agriculture in the Northwest Arid Region represented by Xinjiang, which also directly makes its crop yield per unit area among the highest in the country. It is worth mentioning that the share of blue water production for wheat and cotton in the Northwest Arid Region reaches 100%, which means that their crop yields are completely dependent on blue water resources, i.e., without irrigation conditions, the crop yields in the Northwest Arid Region are zero. The spatial structural distribution of each crop yield also shows the same pattern as the spatial structural distribution of the production water footprint: the higher the degree of

aridity, the lower the share of green water yield and the higher the share of blue water yield. Therefore, the net increase in crop yields due to irrigation is more significant in arid regions.

3.3. Comparative Analysis of Water Productivity of Typical Crops

The average multi-year water productivity of typical crops in arid and humid regions from 2000 to 2020 is shown in Table 3. In spring wheat growing areas, spring wheat in the Northwest Arid Region has the highest water productivity and blue water productivity at $0.81 \text{ kg} \cdot \text{m}^{-3}$ and $0.87 \text{ kg} \cdot \text{m}^{-3}$, respectively, and green water productivity is highest in the Northeastern Semi-Humid Region at $0.67 \text{ kg} \cdot \text{m}^{-3}$. In winter wheat growing areas, winter wheat moisture productivity and green water productivity were highest in the Central China Humid Region at $0.72 \text{ kg} \cdot \text{m}^{-3}$ and $1.19 \text{ kg} \cdot \text{m}^{-3}$, respectively, and blue water productivity was highest in the North China Semi-Humid Region at $0.65 \text{ kg} \cdot \text{m}^{-3}$. For the cash crop cotton, cotton water productivity and blue water productivity were highest in the Northwest Arid Region at $0.17 \text{ kg} \cdot \text{m}^{-3}$ and $0.18 \text{ kg} \cdot \text{m}^{-3}$, respectively. The highest green water productivity was $0.17 \text{ kg} \cdot \text{m}^{-3}$ in the Central China Humid Region.

Table 3. Average multi-year water productivity in arid and humid areas, 2000–2020 ($\text{kg} \cdot \text{m}^{-3}$).

Region	Wheat			Cotton		
	WP	WP _g	WP _b	WP	WP _g	WP _b
Northwest Arid Region	0.81	0.00	0.87	0.17	0.00	0.18
Northwest Semi-Arid Region	0.54	0.04	0.63	0.17	0.14	0.18
Northeastern Semi-Humid Region	0.65	0.67	0.61	—	—	—
North China Semi-Humid Region	0.65	0.60	0.65	0.12	0.15	0.11
Central China Humid Region	0.72	1.19	0.48	0.13	0.17	0.07

It is worth mentioning that, since green water productivity is the ratio of the green water yield of a crop to the amount of green water consumed during its growth and development, at the same time, blue water productivity is the ratio of the net increase in yield (i.e., the blue water yield) obtained by the crop on the basis of the green water yield to the amount of blue water consumed during the crop's growth and development under irrigated conditions. Thus, numerically, the sum of blue water productivity and green water productivity of a crop is greater than its overall water productivity.

Changes in irrigation water productivity of wheat and cotton in arid and humid regions from 2000 to 2020 are analyzed in Figure 4. Crop water productivity is related to local climatic conditions, the level of irrigation project construction, and the level of irrigation district management. In terms of temporal changes, except for cotton in the Northwest Arid Region, the irrigation water productivity of typical crops in all regions generally shows a growth trend, which is attributed to the overall improvement in agricultural production levels across regions. Wheat in the Northwest Semi-Arid Region exhibits the highest average annual growth rate of 2.6%. However, the increasing frequency of regional extremes, such as droughts and high temperatures, driven by global climate change, is constraining the growth of environmentally sensitive crops such as cotton, thereby slowing the improvement in irrigation water productivity for these crops [35–37]. Furthermore, in the Northwest Arid Region, there is a growing tension between supply and demand due to water scarcity and the continuing increase in agricultural water demand [38], which has further led to a decline in irrigation water productivity for cotton in the region. In terms of spatial distribution, spring wheat, winter wheat, and cotton all exhibit the phenomenon of a gradual decline in blue water productivity and a gradual increase in green water productivity with the increase in regional wetness, which is in line with the authors of a related study's view that there is a negative relationship between resource endowment and resource use efficiency [39].

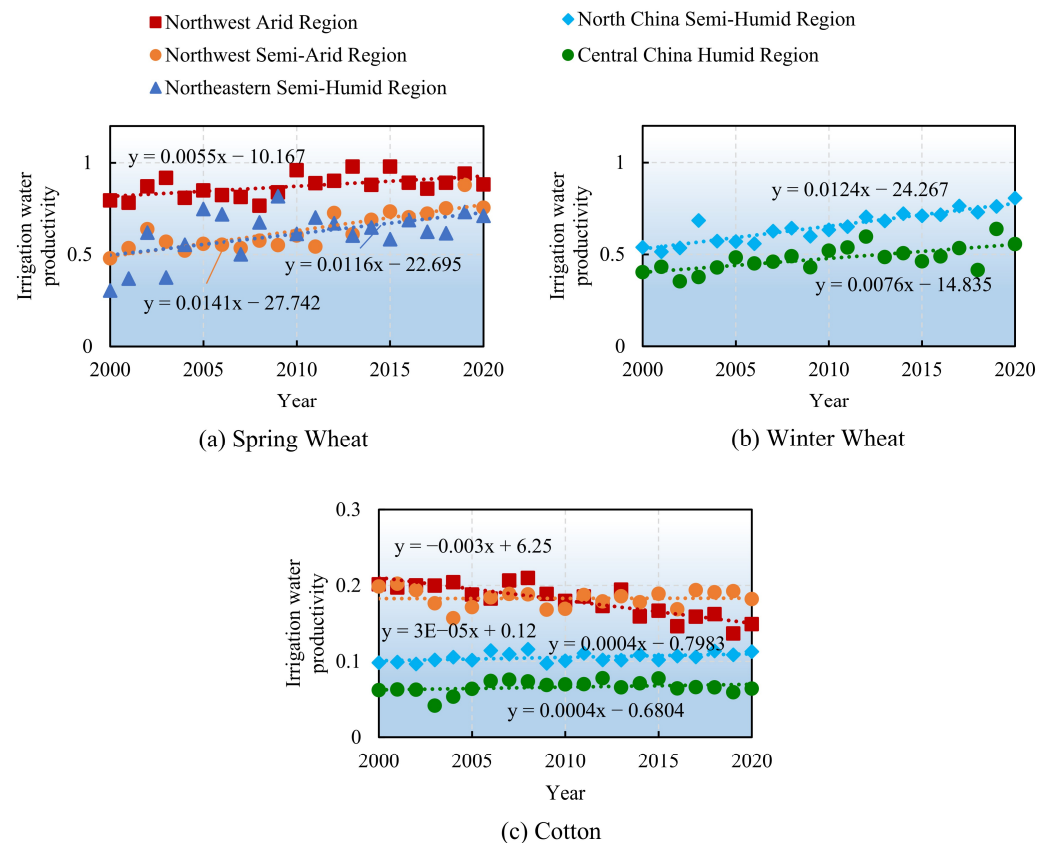


Figure 4. Analysis of changes in irrigation water productivity in wheat and cotton in arid and humid regions from 2000 to 2020.

4. Discussion

4.1. Reliability

The research results in this article are all based on the assumption that crops in all regions are grown under fully irrigated conditions, which brings uncertainty to this study. In particular, the green water yield that can be obtained for crops under rainfed (no irrigation) conditions, which is calculated entirely using the Doorenbos–Kassam model, is the key part of this study. There are more studies on the water consumption characteristics of wheat during growth and development in China, so we take spring wheat and winter wheat as an example and combine the results of previous research to demonstrate the reliability of this study.

Many scholars in China have studied the relationship between water consumption and the yield of wheat in some depth. In the Northeastern Semi-Humid Region, Liu et al. [40] and Zhao et al. [41] not only collected relevant data in the China National Knowledge Infrastructure (CNKI) database but also carried out experiments to explore the relationship between water consumption and the yield of spring wheat, finally giving formulas for the relationship between yield and water consumption of spring wheat. In this study, the green water yield Y_g of spring wheat in the Northeastern Semi-Humid Region was calculated based on their research formulas (Table 4), and the calculated results differed from the results of this study ($Y_g = 0.19 \text{ kg} \cdot \text{m}^{-2}$) by 4.8% and 8.3%. In addition, this study calculated the average multi-year green water yields of spring wheat in the arid and semi-arid regions of Northwest China and found them to be $0 \text{ kg} \cdot \text{m}^{-2}$ and $0.01 \text{ kg} \cdot \text{m}^{-2}$, respectively, which is basically in line with the local crop production situation.

Table 4. Annual average green water yield of spring wheat in Northeast China from 2000 to 2020, based on the formula of Jiang Liu and Funian Zhao.

	Formula	Y_g	Difference
Jiang Liu	$Y = 16.30(ET_c - 156.00)$	0.20	4.8%
Funian Zhao	$Y = 13.73(ET_c - 130.36)$	0.21	8.3%

In North and Central China, scholars have studied the mechanism of the effect of irrigation patterns on the water consumption characteristics and yield of winter wheat. Wang [42] investigated the effects of different tillage methods, different irrigation patterns, and different nitrogen application rates on water consumption characteristics and the yield of wheat through a multi-group controlled trial. Zhang et al. [43] designed three water-saving irrigation experiments to reveal the yield formation mechanism and water and nitrogen utilization characteristics of winter wheat. Cao et al. [44] designed five irrigation pattern experiments to investigate the effects of different irrigation patterns on the water consumption characteristics, yield, and irrigation water use efficiency of wheat. Zhang et al. [45] and Huang et al. [46] studied the effects of different irrigation rates and nitrogen application on the water consumption characteristics, seed yield, and water use efficiency of winter wheat. Xin [47] studied the effects of different plowing methods and irrigation patterns on the water consumption characteristics, population microenvironment, and yield of winter wheat. Based on the experimental data of the above authors, a first-order linear relationship between water consumption and the yield of winter wheat in the North China Semi-Humid Region and the Central China Humid Region can be established (Figure 5). Based on this relationship equation, the multi-year average green water yield Y_g of winter wheat in the North China Semi-Humid Region and the Central China Humid Region from 2000 to 2020 can be obtained as $0.055 \text{ kg} \cdot \text{m}^{-2}$, $0.315 \text{ kg} \cdot \text{m}^{-2}$, respectively, which are different than the results of this study ($0.059 \text{ kg} \cdot \text{m}^{-2}$, $0.292 \text{ kg} \cdot \text{m}^{-2}$ in the semi-wet region of North China and the wet region of Central China, respectively) by -6.1% and 7.8% .

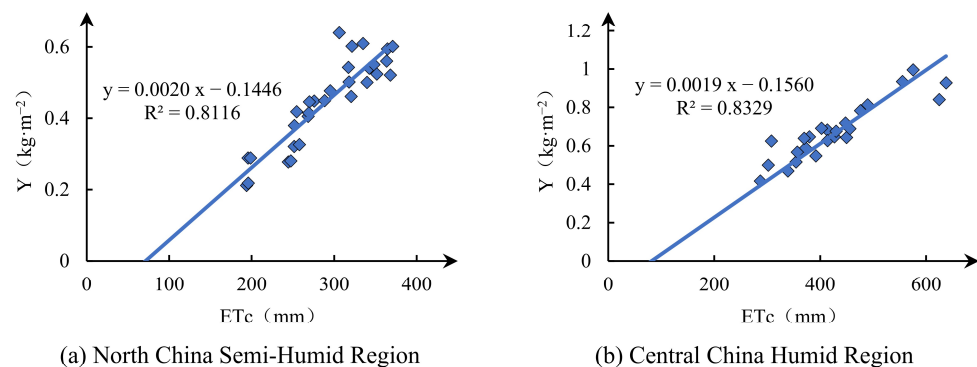


Figure 5. First-order linear relationship between water consumption and the yield of winter wheat in the North China Semi-Humid Region and the Central China Humid Region.

The above findings indicate that the results of this study are not differ much from the results of domestic scholars, and the difference is below 10%, which is within the acceptable range, so it can be considered that the results of this study have a high degree of reliability.

4.2. Correlation

The meteorological and production factors of arid and humid regions from 2000 to 2020 are shown in Table 5, and the efficiency factors of the study area have been analyzed in detail in Section 2.3, so they will not be repeated here. The arid and semi-arid regions of Northwest China, due to their geographical location, have longer sunshine hours, which is favorable for the growth of crops, but a lower annual precipitation restricts the agricultural

development of the region [48]. The Northeastern Semi-Humid Region has rich black soil resources compared with other regions due to the more fertile land, and the fertilizer input is significantly lower; however, due to the region's lower winter temperatures and other environmental phenomena, only cold crops such as spring wheat and soybean can be planted in this region [49,50]. The North China Semi-Humid Region has a high level of agricultural mechanization, which optimizes the agricultural production process and increases crop yields and productivity [51]. Sufficient rainfall and suitable temperatures in the Central China Humid Region are favorable in terms of crop growth but also lead to more serious problems with weeds and pests, therefore requiring more use of pesticides [52]. The characteristics of these regions reveal the specific impacts of different climatic conditions and resource endowments on agricultural production, reflecting the different needs and challenges of resource use and agricultural management in each region.

Table 5. The status of meteorological and production factors in arid and humid areas from 2000 to 2020.

Region	Meteorological Factor			Production Factor		
	Sun	P	T	Machinery	Fertilizer	Pesticide
Northwest Arid Region	7.83	111.82	9.29	3.50	329.72	4.00
Northwest Semi-Arid Region	7.63	290.18	7.38	3.68	222.53	8.19
Northeastern Semi-Humid Region	6.76	570.13	4.31	3.68	234.23	7.35
North China Semi-Humid Region	6.64	490.25	10.31	9.04	335.10	8.38
Central China Humid Region	4.61	1052.45	16.02	5.54	377.65	11.62

The correlation of the indicators of each influencing factor for typical crops in the study area is shown in Figure 6. In terms of the correlation between the efficiency factors, the blue water productivity of each crop showed a significant positive correlation with the water productivity, while a significant negative correlation with the green water productivity was observed. This indicates that, in crop production, water use efficiency mainly depends on irrigation water use efficiency rather than natural precipitation use efficiency [53]. This inspires us to give priority to improving the efficiency of irrigation water use in crop production in order to strengthen the management and regulation of irrigation water resources, further optimize irrigation technology, implement efficient water-saving measures, make better use of limited water resources, improve the efficiency of agricultural production, and realize the sustainable development of agriculture [4,54].

In terms of the correlation of each efficiency factor with meteorological factors, wheat and cotton showed striking consistency in regard to the correlation between water productivity and sunshine hours and precipitation. Blue water productivity was significantly positively correlated with sunshine hours and significantly negatively correlated with precipitation. Green water productivity showed a completely opposite trend to blue water productivity, being significantly negatively correlated with sunshine hours and significantly positively correlated with precipitation. This indicates that, in the Northwest Arid Region, which has less precipitation but more sunshine hours, crop blue water productivity is higher and green water productivity is lower; that is, irrigation water is used more efficiently while natural precipitation is used less efficiently. In the humid eastern regions, where precipitation is higher and sunshine hours are fewer, the opposite is true. Therefore, in the arid zone, the focus should be on optimizing the use of irrigation water and improving irrigation techniques and efficiency, while, in the humid zone, more efficient use of natural precipitation should be made in order to reduce the dependence on irrigation water [55]. Understanding the differences in the efficiency of water use in different regions can help promote sustainable agriculture [56,57]. Through adjusting the way water resources are used, it is possible to increase the efficiency of agricultural production without increasing water consumption [58].

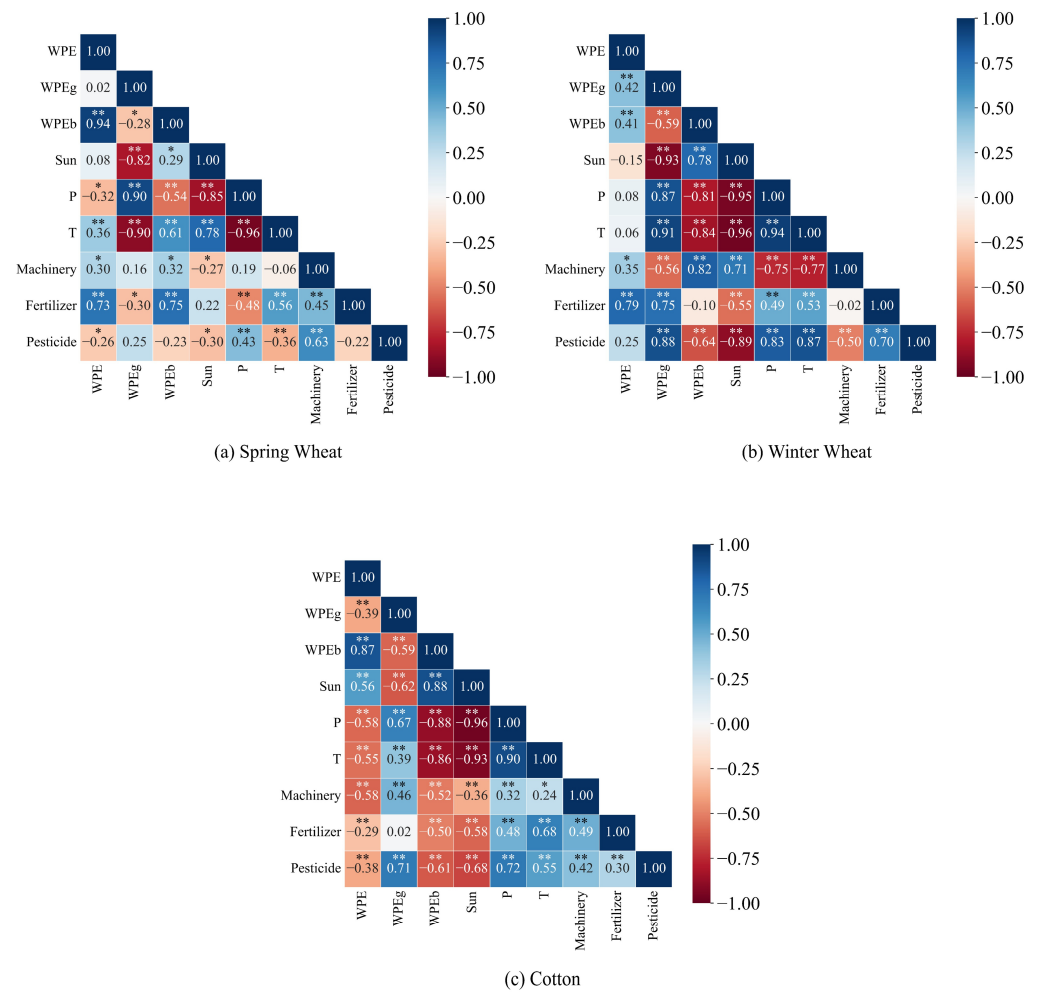


Figure 6. Heat map of correlation between regional crop water productivity and indicators of influencing factors. Note: * indicates significant correlation at the 0.05 level, ** indicates significant correlation at the 0.01 level.

The correlations between the efficiency factors and the agricultural production factors did not show significant consistency between the water productivity of the typical crops and the agricultural inputs in the study area. This suggests that the role of increased inputs in agricultural machinery, fertilizers, and pesticides in improving overall crop water productivity (i.e., water use efficiency) is controversial [59]. However, it is clear that these inputs can significantly increase overall yield or production value [60,61]. Therefore, there is a need to reassess and optimize these agricultural input strategies, to explore and introduce more diversified agricultural technologies and methods, and to rationally allocate agricultural input resources so as to avoid over-reliance on a particular type of input and to maximize the optimal benefits of each type of resource [62].

4.3. Limitations and Future Studies

The initial objectives of this study have been largely achieved, but many limitations remain. First, as extensive field trials across the country are labor-intensive and operationally too complex, this study adopted a simulation and calculation method based on the water footprint and the Doorenbos–Kassam model. Although we compared the results of this study with those of others and tested its reliability, the accuracy and rigor could be further improved. Future studies can validate the results of this study through field trials to enhance its credibility. Second, this study was limited to calculating the water productivity of typical crops, thus representing the production efficiency of agricultural water use. Future studies could be further extended by not only calculating the water productivity

of major crops in each region but also combining it with the economic value of crops to assess the economic efficiency of agricultural water use. Finally, this study has limitations in the selection of influencing factors. Future research could incorporate additional variables, such as regional water source conditions, dietary culture, socioeconomic conditions, and local management policies, to provide a more comprehensive understanding of the spatiotemporal variations in agricultural water use efficiency and the underlying driving mechanisms. Expanding the scope of these factors would enhance the scientific rigor and practical applicability of the research.

Overall, although this study provides a valuable reference for the study of agricultural water use efficiency in the arid and humid regions of China, it needs to be further explored and improved. It provides a rich research direction for subsequent scholars, and it is expected that future studies will achieve more in-depth and systematic results in this field.

5. Conclusions

For a long time, when discussing the efficiency of irrigation water use (from irrigation quotas to production efficiency), it has been assumed that the humid and economically developed regions of China are more advanced than the arid and semi-arid regions of the northwest. However, this ignores the beneficial effects of the natural conditions of these areas on agricultural production. In the humid regions, crops receive sufficient water without irrigation during their growth and development stages, and the gains from this are considerable, with relatively limited gains being associated with a small amount of supplemental irrigation. In arid and semi-arid regions, on the other hand, where natural conditions do not provide sufficient water and large amounts of supplementary irrigation are necessary, the benefits are quite significant. However, this has given rise to the misconception that irrigation quotas in the arid and semi-arid regions of the northwest are much higher than in the humid regions, while the final crop yields and the benefits of agricultural production are not much different from—or even less than—those in the humid regions.

This study measured the production water footprint, yield structure and water productivity of wheat, a typical grain crop, and cotton, a typical cash crop, in the Northwest Arid Region, Northwest Semi-Arid Region, Northeastern Semi-Humid Region, North China Semi-Humid Region, and Central China Humid Region from 2000 to 2020. Using a comparative analysis, it was found that, from the Central China Humid Region to the Northwest China Arid Region, the average dependence of wheat and cotton on blue water increased gradually from 49.9% to 93.6% as the degree of regional aridity intensified. Likewise, the proportion of blue water yield rose from 31.0% to 100% and irrigation water productivity increased from $0.27 \text{ kg} \cdot \text{m}^{-3}$ to $0.53 \text{ kg} \cdot \text{m}^{-3}$. These findings led to the following conclusions:

- (1) The higher the degree of aridity, the higher the dependence on blue water and the lower the dependence on green water for crop growth and development. At the same time, this will lead to a higher yield of blue water and a lower yield of green water for crops in arid areas.
- (2) Crop water productivity is related to regional climatic conditions and agricultural production conditions. Based on the same level of agricultural production, the crop blue water productivity and irrigation water productivity are higher in the Northwest Arid Region, represented by Xinjiang, compared with the humid regions.
- (3) For arid zones, the focus should be on improving the way in which irrigation water is used and on improving irrigation technology and efficiency; in humid zones, natural precipitation should be used more fully and efficiently, thus reducing dependence on irrigation water. Understanding the differences in water use efficiency in different regions and adjusting the ways in which water is used can improve agricultural productivity and promote sustainable agricultural development without increasing water consumption.

Author Contributions: Y.Z. wrote the main manuscript text and prepared the figures. A.L. advised on the study design and supervised the study. P.Z. and X.D. collected primary data and performed part of the data analyses. X.G. calculated the water footprint of the water footprint of typical crop production. The authors offered their total contribution to this work. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (grant numbers 52309041 and 52179028) and the Third Xinjiang Scientific Expedition (grant number 2022xjkk0103).

Data Availability Statement: The original contributions presented in this study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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