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Sustainable Development of Water Resources and Food Security in Northwest China

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Abstract: Northwest China has abundant light, heat, and land resources, but its water resources are limited, which has restricted the sustainable development of food security in this region. Water-use efficiency in crop production, water resource stress, and virtual water output of crops in Northwest China are evaluated using water footprint and virtual water as analysis tools. Grain production and agricultural water use in Northwest China are predicted. Furthermore, policy suggestions are proposed to guarantee the sustainable development of water resources and food security in Northwest China, including gradually reducing the scale of agricultural water use in this region, optimizing the crop planting structure, and implementing a virtual water project along the Silk Road Economic Belt. This study is hoped to provide a reference for the rational utilization of regional water resources and the formulation of food security strategies.
Keywords: Northwest China; food security; water resource; sustainable development

1 Introduction

Food production in Northwest China has experienced remarkable progress in recent years. At present, the output of food per capita, such as grain, vegetables, and fruits, exceeds average national output. However, the Northwest region suffers from an extreme shortage of water resources, and the large scale of food production has brought disaster to the region's fragile ecological environment [1]. The region's water crisis is further exacerbated by sustained population growth, an increase in the proportion of animal food consumption, and an increase in evapotranspiration because of climate change. Limited water resources have become a bottleneck in sustainable development for regional food security [2]. At the same time, Northwest China produces considerable agriculture water waste, and water productivity is lower than the national average.

With the rapid development of the Southern China economy, an increasing amount of once-cultivated land is now occupied, meaning that the arid Northwest will continue to be the country's primary grain producing area into the future. Meanwhile, agricultural production in Northwest China is faced with the challenge of increased agricultural output with the same amount of, or less, water input as a result of increased water consumption because of economic and social development, urbanization, and ecological disruption. In addition, climate change and an increase in extreme weather events also pose a potential threat to future food production in Northwest China [3].

In the context of internationalization and greenization, and considering the overall strategic layout of the development of modern agriculture in China and the structure of agricultural production, as well as its macro-layout

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in Northwest China, this study analyzed the relationship between agricultural water use and food security in the region. The aim of this paper is to present measures to improve agricultural water use in Northwest China and promote food security within the context of the sustainable development of regional agricultural production.

2 Current status of water resources and evaluation of agricultural water use in Northwest China

2.1 Current status of water resources in Northwest China

Northwest China covers a vast territory that is rich in light, heat, and land resources, accounting for approximately 41.4% of the country's total area. It is an important reserve base for grain production in China, accounting for 12% of the country's gross grain production. Water resources and arable land account for 10% and 15%, respectively, of the Chinese total. Grain production in Northwest China is of great significance to China's food security. However, the region is also the most arid in the country, characterized by infrequent precipitation and high evaporation. Precipitation generally occurs between June and September, mostly in the form of heavy rain, meaning that soil erosion is a serious issue in the region. Water shortage is also significant, with the average quantity of water per mu (1 mu equals to 666.67 m^2) being less than half the national average. In addition, the spatial distribution of arable land and water resources is not commensurate. The lack of precipitation means that agricultural production in Northwest China is highly dependent on irrigation. Because of a lag in economic development, the cultivation of agriculture and animal husbandry in Northwest China consumes a large quantity of water resources, and the utilization rate of water resources is high. The utilization rate of water resources in some river basins, such as the Shiyang River basin, exceeds 100% and has resulted in a series of ecological problems [1,4]. The depletion of headwaters further aggravates the problem of water scarcity. As glaciers retreat and snow lines move to higher altitudes, there is reduced surface water runoff [5]. As resource-based water shortage deteriorates in Northwest China, so does water quality [6].

2.2 Evaluation of agricultural water use in Northwest China

Agriculture plays an important role in the economic development of Northwest China. Agricultural irrigation accounts for almost 70% of the total water consumption. In some areas, the proportion is more than 90%. In parts of the region, particularly Xinjiang, Ningxia, and Gansu, the percentage of water consumption for agricultural irrigation is higher than the national average. In recent years, the proportion of irrigation water used in agricultural production has gradually decreased to coincide with an increase in water consumption by other sectors of the economy, as shown in Table 1.

Table 1. General situation of agricultural irrigation in Northwest China.

Indicators	Year	Inner Mongolia	Ningxia	Gansu	Qinghai	Shaanxi	Shanxi	Xinjiang	Northwest China	China
Proportion of irrigated area to total sown area of crops (%)	2000	40	39	25	38	29	27	91	41	34
	2005	43	45	28	37	30	29	86	43	35
	2010	43	37	26	48	31	34	85	45	38
	2015	41	39	31	33	29	39	84	45	40
	2016	40	40	31	36	29	40	85	46	40
Proportion of farmland irrigation water to total water consumption (%)	2000	87	92	80	72	73	65	95	87	62
	2005	82	93	79	69	66	55	91	84	57
	2010	70	92	79	60	59	56	91	80	55
	2015	66	88	81	51	54	61	94	81	63
	2016	73	87	80	75	53	62	94	83	62
Irrigation water consumption per mu (m^3)	2000	446	1213	619	644	303	210	829	609	479
	2005	378	979	559	616	287	209	753	540	448
	2010	362	981	559	597	305	217	673	528	421
	2015	327	705	497	565	300	186	617	457	394
	2016	305	636	487	565	312	188	617	444	380

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The production water footprint of nine main crops in Northwest China was analyzed to investigate the utilization of precipitation (green water) and irrigation water (blue water) and to analyze the spatial–temporal evolution of crop production water footprint. The water footprint of a region's crop production is the amount of water consumed per unit of crop production (including blue water and green water).

The water footprint of comprehensive grain crop production in Northwest China shows a fluctuating and declining trend (Fig. 1), with the proportion of blue water footprint in crop production showing the same trend but with the extent of decrease being relatively small.

In general, the water footprint of comprehensive grain crop production in Northwest China was larger than the national average prior to 2010. It then became slightly lower than the national average. During the study period, Northwest China's blue water production footprint was consistently higher than the national average; however, the gap has reduced considerably. The green water production footprint has been consistently lower than the national average, and the gap between the two shows an increasing trend. This suggests that grain production in Northwest China consumes a greater quantity of blue water resources.

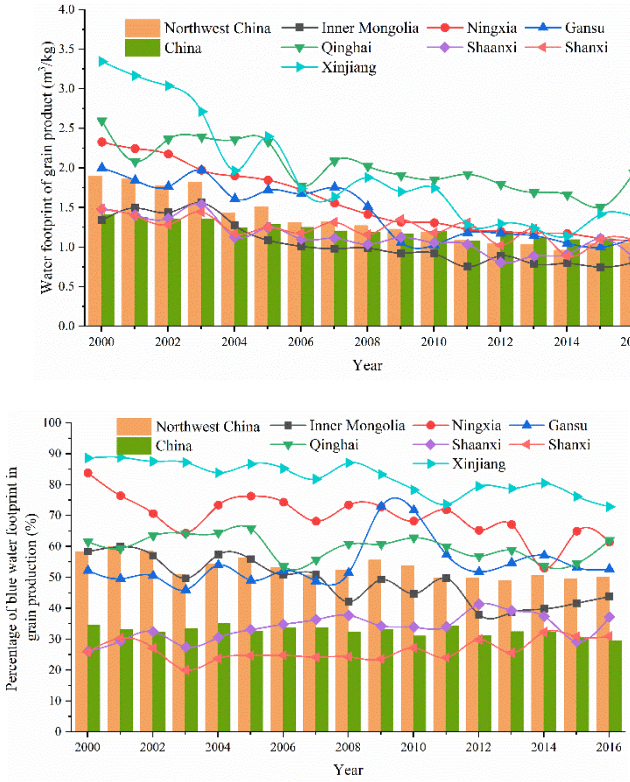

Fig. 1. Water footprint and its composition evolution trend for integrated grain crop production in Northwest China (2000–2016).

Analysis of the water footprints of the nine dominant crops in Northwest China reveals significant differences between different crops in the same region; that is to say, there is an absolute comparative advantage. The difference of the same crop between different regions is also significant; in other words, there is a relative comparative advantage.

Virtual water refers to the amount of water required to produce goods and services. When the production of a certain crop product in an area cannot meet or exceed the needs of the region, trade in crop products can be generated between regions, in turn creating a flow of virtual water between regions. Northwest China plays a role in exporting grain to other regions of China, and this export is both fluctuating and growing. In 2016, Northwest China exported more than 10 million tonnes of grain and more than 29 million tonnes of cash crops. With the trade in crop products, the annual output of virtual water exported from Northwest China exceeded 10 billion m^3 after 2008 and reached 25.27 billion m^3 in 2016, as shown in Table 2.

3 Evaluation of water stress in Northwest China

This study used the utilization of water resources to measure regional water stress. When the utilization ratio of water resources is less than 10%, water stress is low; when the utilization ratio is between 10% and 20%, water stress

is middle-low; when the utilization ratio is between 20% and 40%, water stress is medium-high; and when the utilization ratio is greater than 40%, water resource stress is high.

Water stress in Northwest China fluctuates between the medium-high and the high stress levels. For the average of China, in comparison, water stress fluctuates between the middle-low and medium-high stress levels. This shows that the shortage of water resources in Northwest China is already very grim (Table 3).

Table 2. Virtual water trade produced by crop trade between Northwest China and the rest of China. ($\times 10^8$ m^3)

Year	Rice	Wheat	Maize	Beans	Potato	Grain	Cotton	Oil	Vegetables	Fruit	Economic crops	Total
2000	–255.3	111.7	109.4	16.4	2.3	–15.5	46.2	–4.7	–53.9	42.7	30.3	14.8
2001	–235.2	114.1	102.4	8.4	0.9	–9.5	43.6	–27.1	–68.4	34.2	–17.8	–27.3
2002	–227.5	130.1	127.5	18.0	2.9	51.0	43.4	–8.4	–65.9	41.2	10.3	61.3
2003	–214.1	107.6	169.1	2.0	4.7	69.3	46.2	–3.0	–58.2	18.1	3.1	72.4
2004	–227.7	82.3	147.0	14.1	3.6	19.3	37.9	–11.8	–50.7	18.6	–6.0	13.3
2005	–228.7	82.4	154.5	23.6	2.4	34.2	48.7	–10.6	–52.8	25.3	10.7	44.9
2006	–224.6	58.1	123.5	23.9	5.5	–13.7	41.0	–2.2	–33.2	34.4	40.0	26.3
2007	–225.2	33.3	143.7	33.8	5.1	–9.4	60.5	–17.2	–25.0	39.8	58.2	48.8
2008	–227.9	47.7	158.2	21.4	5.6	5.1	65.7	0.2	–30.8	59.4	94.6	99.7
2009	–230.6	71.4	153.0	18.6	2.9	15.3	47.9	–0.8	–17.4	69.6	99.4	114.6
2010	–238.1	70.9	165.2	24.0	2.9	25.1	49.0	1.5	–13.6	74.0	110.9	13.6
2011	–223.9	54.9	179.6	22.8	4.2	37.7	45.4	0.9	–8.3	72.2	110.2	147.8
2012	–250.2	58.3	194.6	26.2	4.1	32.9	55.6	0.2	–12.8	74.9	117.8	150.7
2013	–239.7	41.7	232.2	21.2	4.5	59.8	54.6	0.6	–11.9	84.1	127.4	187.2
2014	–238.8	45.0	219.1	7.8	3.8	36.9	51.8	2.6	–16.6	91.4	129.2	166.1
2015	–229.8	67.2	247.5	10.3	3.2	98.5	62.1	7.9	5.6	110.2	185.9	284.4
2016	–236.5	73.4	263.9	12.5	4.5	124.2	63.3	0.7	–0.7	120.8	128.5	252.7

Note: The negative sign indicates that virtual water flowed into Northwest China.

Table 3. Agricultural water use in Northwest China and China, and the contribution rate to water resources stress (%).

	Ratio of total water use to total water resources		Ratio of irrigation water use to total water use	
Year	Northwest China	China	Northwest China	China
2000	42.4	19.8	86.9	68.8
2001	39.9	20.7	83.8	68.7
2002	40.8	19.5	88.2	68.0
2003	33.2	19.4	84.7	64.5
2004	40.8	23.0	74.1	64.6
2005	33.0	20.1	84.1	63.6
2006	42.6	22.9	70.3	63.2
2007	41.4	23.0	70.3	61.9
2008	43.3	21.5	81.5	62.0
2009	38.6	24.7	82.0	62.4
2010	35.0	19.5	80.6	61.3
2011	36.2	26.3	68.3	61.3
2012	37.1	20.8	69.9	63.3
2013	34.5	22.1	70.8	63.4
2014	41.4	22.4	70.4	63.5
2015	42.7	21.8	80.7	63.1
2016	41.7	18.6	82.9	62.4
Average value	39.1	21.5	78.2	63.9

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4 Prediction of grain production and agricultural water use in Northwest China

The grey system GM (1,1) model and linear regression were used to predict grain yield, crop production water footprint, and precipitation in Northwest China. According to predicted grain yield per unit and grain output, Northwest China's future grain planting area will increase to a certain extent. Even according to conservative estimates of grain planting area, the Northwest's future grain output per capita will still be higher than the national average. In other words, Northwest China's role as a food export area will not change in the future. A small increase in precipitation is predicted in the region; however, temperature increases due to future climate change are likely to lead to an increase in evapotranspiration. It is necessary, therefore, to control the arable land area and crop planting structure and to develop appropriate dry farming that will ensure that the future blue water footprint of crops is reduced and that agricultural water stress does not increase (Table 4).

Table 4. Population, grain yield, grain production, blue water footprint of crops, and precipitation forecast for Northwest China.

Year	Population ($\times 10^4$)	Grain yield per unit (kg/hm^2)	Grain yield ($\times 10^4$ t)	Blue water footprint ($\times 10^8$ m^3)	Precipitation amount (m)
2017	16 371	4717	8886	588	0.310
2018	16 470	4917	9180	584	0.311
2019	16 570	5019	9432	579	0.311
2020	16 670	5121	9684	575	0.312
2021	16 770	5223	9936	571	0.313
2022	16 869	5325	10 187	567	0.314
2023	16 969	5427	10 439	563	0.315
2024	17 069	5529	10 691	559	0.316
2025	17 168	5631	10 943	555	0.317
2026	17 268	5734	11 195	551	0.318
2027	17 368	5836	11 447	547	0.319
2028	17 468	5938	11 699	544	0.320
2029	17 567	6040	11 951	540	0.321
2030	17 667	6142	12 203	536	0.322
2031	17 767	6244	12 455	532	0.323
2032	17 866	6346	12 707	528	0.324
2033	17 966	6448	12 958	525	0.325
2034	18 066	6550	13 210	521	0.326
2035	18 165	6652	13 462	517	0.327

5 Policy suggestions

5.1 Gradually reduce total agricultural water use

According to the requirements of organic food, the comprehensive impact of factors such as land resource reserves, cultivated land quality conservation, water resource stress, and ecological carrying capacity, Northwest China should be developed to a reasonable degree. As this is the most arid region in China, it also experiences the most serious soil erosion. The region's ecosystem is heavily dependent on water resources, while the utilization rate of water resources exceeds 40%, leading to high water resource stress. The proportion of total water consumption is high; hence it is recommended that the scale of agricultural water use be gradually reduced to promote regional sustainable development.

5.2 Optimize crop planting structure

To ensure continued food supply, on the basis of the absolute comparative advantages of different crops in the same region and the relative comparative advantages of the same crop in different regions, it is recommended that adjustments be made to the crop planting structure of Northwest China. Such adjustment would reduce the area of high-water-consuming crops, increase the proportion of crop precipitation utilization, improve water use efficiency, reduce regional water consumption, and alleviate regional water stress. It is recommended that the proportion of forage crops be increased and that the current dual-crop structure of grain–economic crops be transformed to a

structure of grain–economic–forage crops.

5.3 Implement the "Silk Road Economic Belt" virtual water project

China's ongoing population growth and the full liberalization of the second-child policy will, inevitably, lead to an increase in food consumption. By 2035, the country will require an additional 100 million tonnes of food. Restrictions on cultivated land and water resources, as well as food quality and structural diversity requirements, have made it difficult to develop domestic production in order to meet the growing demand for food. For a long time, China has imported much of its grain from relatively fixed countries, with long transportation distances, thus increasing risks to the country's food security. The implementation of the Belt and Road initiative has provided a new opportunity to improve China's food security. Most of the countries along the Belt and Road are developing nations, with common demands for the development of agricultural cooperation and the promotion of agricultural transformation and upgrading. A comparison of the cultivated land resources per capita and food production status of five Central Asian nations, Kazakhstan, Uzbekistan, Kyrgyzstan, Turkmenistan, and Tajikistan, reveals their potential as future strategic reserve granaries for China.

These five nations have much in common with Northwest China, given their abundant light and heat resources. They have a total land area of approximately 4 million km^2, of which 32.41 million hm^2 is cultivated land. This is equivalent to one quarter of China's total cultivated land area. In addition, they have a combined grassland area of 250 million hm^2, which is equivalent to three quarters of China's grassland area [7–9]. Some arable land in these countries has not yet been utilized. The five countries have annual precipitation between 160 mm and 700 mm, and water resources per capita of a little less than 8000 m^3, which is higher than Northwest China's water resources per capita of 2310 m^3.

Agriculture in these five Central Asian countries is dominated by farming and animal husbandry. Each agricultural laborer has, on average, 5 hm^2 of cultivated land and 39 hm^2 of pasture. The crop industry is dominated by three land-intensive products: grains (wheat, corn, and rice), oilseed, and cotton. The livestock industry is dominated by sheep, cattle, and horse husbandry. Agricultural investment is currently insufficient, production technology is backward, grain yield is low, the irrigation quota is large, and water use efficiency is low [9].

These five Central Asian countries and Northwest China have good complementarity, and the potential for agricultural cooperation can lead to mutual benefits. These countries are adjacent to Northwest China, which has an international border of more than 3 000 km and is home to nine cross-border ethnic groups, meaning that the region shares similar languages and customs and that the cultural life of Northwest China and these five countries is widely connected [9]. Relying on this geographical advantage, the Northwest region has become a frontier for China's opening to the West, as well as being an important grounding and convergence point for foreign economic cooperation with Central Asia. In addition, the integration of the Eurasian Continental Bridge, the establishment of the Shanghai Cooperation Organization, and the implementation of the National Western Development and the Silk Road Economic Belt Policy have provided opportunities for the Northwest's food trade and have laid a solid foundation for the food virtual water project as outlined below.

(1) Increase agricultural production and water use efficiency in the five Central Asian countries. Despite the huge potential that remains to be tapped, the agricultural input of these five countries is generally inadequate, the development of agricultural machinery is slow, and labor productivity is low. The current grain planting area of the five countries is 17.741 million hm^2, which is equivalent to 19% of China's planting area and 234% of Northwest China's planting area. The total annual grain output is 29.007 million tonnes, which is equivalent to 5% of China's grain output and 74% of the Northwest region's grain output. The yield per unit is 1635.0 kg/hm^2, which is equivalent to 27% of China's yield and 32% of the Northwest region's yield. If the yield per unit of the five countries is raised to the level of Northwest China, annual output will increase by 61.640 million tonnes. If the yield per unit is raised to the national average, the annual increase in production will be 78.426 million tonnes, which is close to the quantity of China's current total grain imports. The five countries have a small area of water-saving agricultural irrigation, water use efficiency is low, and irrigation water use efficiency is less than 20% that of Northwest China; hence, there is a strong demand for water-saving agricultural irrigation technology. China's Northwest region has the advantages of higher levels of capital, agricultural mechanization rate, and agriculture science and technology over the five Central Asian countries. Xinjiang, for example, has more mature experience, higher technical experience in mulching technology and under-film drip irrigation technology, and a slew of independently developed water-saving irrigation products and technologies. Therefore, the Silk Road Economic Belt food virtual water project should first strengthen technical and financial support for agriculture in the five Central Asian countries so as to improve

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agricultural production levels and water consumption levels without increasing agricultural water resource utilization and cultivated land area. This, in turn, will increase food production.

(2) Optimize industrial structures and planting structures in Northwest China and the five Central Asian countries. Precipitation in Central Asia mainly occurs in winter and spring, while precipitation in Northwest China mainly occurs from June to September. Therefore, the proportion of precipitation utilization for wheat and oil crop production in the five Central Asian countries is relatively high, and the demand for irrigation water is relatively low. These countries are rich in grassland resources, which is conducive to the development of animal husbandry. However, because of the underdevelopment of the food processing industry, there are few processed livestock products. China's livestock and poultry industries use more feed grains and require more water resources. Therefore, it is recommended that the food industry in Northwest China and the five Central Asian countries be considered as a whole, that regional coordination be strengthened, and that water resources be considered as a key to the optimization and adjustment of the industrial and planting structures of the entire region. The region has already established a water-friendly industrial structure and planting structure.

(3) Establish virtual food water trade in Northwest China and the five Central Asian countries. To develop the food trade between Northwest China and the five Central Asian countries and to further improve transportation infrastructure within the region, it is recommended that perfect bilateral and multilateral trade coordination mechanisms be established, with the establishment of an "Internet + modern agriculture" business marketing model, so as to lay the foundation for virtual food water trade between Northwest China and the five nations of Central Asia.

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