Postprint: Spatiotemporal Evolution of Water Footprint and Water-saving Potential Assessment for Typical Grain Crop Production in Ningxia

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Abstract

In recent years, the grain and vegetable production capacity of Ningxia Hui Autonomous Region (hereinafter referred to as Ningxia) has significantly improved. However, as one of the provinces with the most scarce water resources in China, assessing the water footprint of agricultural production and its water-saving potential is conducive to promoting the sustainable utilization of agricultural water resources. Taking the production water footprint of five typical grain crops as the research object, combined with the Mann-Kendall trend test method, this study explores the spatiotemporal evolution trends of grain crop production water footprint in this region from 2006 to 2020, and further reveals the crop water-saving potential using a water-saving potential model. The results show that: (1) In the past 15 years, the production water footprint of typical grain crops in Ningxia showed an overall decreasing trend, among which the crop production water footprint in Guyuan City decreased by 42.97%, while the blue and green water footprint of grain crop production showed an overall fluctuating trend. (2) The blue water and grey water footprints of various crop production both showed decreasing trends. The green water footprint of the same crop production showed significant differences among cities, with soybeans having the largest contribution rate to the production green water footprint. (3) In typical years, the engineering water-saving potential of crop production, and the real water-saving potential of blue water and green water could reach 44.81%, 46.43%, and 45.10%, respectively. The research results can provide theoretical reference for the sustainable development of water-saving agriculture in Ningxia.

Full Text

Spatio-temporal Evolution and Water-saving Potential Evaluation of Water Footprint of Typical Grain Crops Production in Ningxia

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Abstract

In recent years, the grain and vegetable production capacity of Ningxia Hui Autonomous Region (Ningxia) has increased significantly. However, as one of the most water-scarce provinces in China, evaluating the water footprint of agricultural production and its water-saving potential is crucial for promoting the sustainable use of agricultural water resources. Focusing on the production water footprint of five typical food crops, this study explored the spatiotemporal evolution trends of the production water footprint in the region from 2006 to 2020 using the Mann-Kendall trend test. Additionally, a water-saving potential model was employed to further analyze the water-saving potential of these crops. The results indicated that: (1) The production water footprint of typical grain crops in Ningxia exhibited a decreasing trend over the past 15 years, with the production water footprint in Guyuan City decreasing by 42.97%. (2) The blue water and gray water footprints of each crop showed a consistent downward trend, while the green water footprint of the same crop varied significantly across cities, with soybean contributing the most to the green water footprint. (3) The water-saving potential of crop engineering, true water-saving potential of blue water and true water-saving potential of green water could reach 44.81%, 46.43% and 45.10%, respectively, in typical year crop production projects. These findings provide a theoretical foundation for the sustainable development of water-saving agriculture in Ningxia.

Keywords: crop production water footprint; spatiotemporal evolution; water saving potential; Ningxia

1 Introduction

Water resource deficit represents a primary constraint on sustainable agricultural development in Ningxia. Agricultural water consumption accounts for 76.3% of total water consumption, with the effective utilization coefficient of irrigation water being only 0.7-0.8, significantly lower than that of advanced water-saving countries [?]. Therefore, developing efficient water-saving agriculture is a key measure to transform agricultural production methods, enhance comprehensive agricultural production capacity, and promote modern agricultural development [?]. In recent years, Ningxia has adhered to the principle of "determining city size, land use, population, and production based on water availability," establishing a regional agricultural economic and social development model adapted to water resource carrying capacity to support high-quality agricultural development.

Falkenmark [?] proposed the concepts of "blue water" and "green water." Blue water footprint represents the consumption of surface and groundwater during crop growth, while green water footprint represents the consumption of water stored in soil, typically characterized by effective rainfall. Gray water footprint is a pollution-related index referring to the freshwater volume required to assimilate pollutant loads to meet current environmental quality standards and natural background concentrations [?]. Compared with traditional water resource utilization indices, water footprint incorporates blue, green, and gray water into agricultural water assessment, providing a more comprehensive reflection of water resource utilization impacts in agricultural production. Thus, comprehensive analysis of water resource consumption during agricultural production based on agricultural water footprint can provide data support for regional efficient water-saving efforts.

Agricultural water-saving potential is crucial for agricultural production, efficient water utilization, and ecological health in arid regions [?]. Scholars have investigated the formation mechanisms [?], theoretical frameworks [?], and calculation methods of agricultural water-saving potential. Zhou [?] calculated theoretical water productivity, irrigation efficiency, and water-saving potential of crops. Yan et al. [?] analyzed water-saving potential of crops in typical years in Shaanxi Province based on blue and green water footprints. Current research on water-saving potential for different regions and crops has yielded some results, but studies deeply exploring crop water-saving potential from the perspective of production water footprint remain relatively scarce.

Ningxia, located in northwest inland China, has arid and semi-arid areas accounting for over 75% of its total area. Issues such as low agricultural water use efficiency, insufficient utilization of rainfall resources, and fertilizer misuse severely constrain regional socio-economic development and ecological security [?]. Therefore, this study takes prefecture-level cities as research units to calculate the production water footprint of five typical grain crops in Ningxia, combines the Mann-Kendall trend test to explore spatiotemporal evolution trends from 2006 to 2020, and further estimates water-saving potential of crop production in typical years (wet, normal, and dry years) through a water-saving potential model, aiming to provide theoretical references for vigorously developing water-saving agriculture and strictly implementing the "four water determinations" policy in Ningxia.

1.1 Study Area Overview

Ningxia Hui Autonomous Region (104°17 ~107°39 E, 35°14 ~39°23 N) is located in the upper Yellow River region of northwest China, characterized by a temperate continental climate with uneven water resource distribution. The average temperature across cities is 11.4°C, average sunshine duration is 2071-3086 hours, making it one of the regions with the most abundant sunshine and solar radiation in China [?]. Annual average precipitation ranges from 164.1 to 647.3 mm. Typical grain crops include potatoes, corn, wheat, soybeans, and rice. By 2020, the total crop sown area in Ningxia was 1.78$×10^{6}$ hm^2, with Guyuan City and Wuzhong City having the highest proportions at 30.24% and 26.45%, respectively. The sown area of five typical grain crops accounts for 70.6% of the total sown area, with grain crop sown area accounting for 57.8% and grain yield accounting for 64.6%.

Figure 1 [Figure 1: see original paper] Proportion of average crop planting area and distribution of meteorological stations in Ningxia

Note: Based on the standard map from the Ministry of Natural Resources (Approval No. GS(2024)0650), with no modifications to boundary lines. The same applies below.

1.2 Data Sources

Data on precipitation, evaporation, air pressure, temperature, ground temperature, humidity, wind speed, wind direction, and sunshine hours were obtained from the Daily Climate Dataset (V3.0) compiled by the China Meteorological Data Service Center (http://data.cma.cn). Data on planting area, yield, and nitrogen fertilizer application were sourced from the Ningxia Statistical Yearbook [?]. Crop coefficients and irrigation water utilization coefficients were obtained from literature statistics [?]. Benchmark values for crop production water footprint were derived from indicators recommended by the Food and Agriculture Organization (FAO) [?]. Natural background concentrations and maximum allowable concentrations for Class III surface water quality standards from the Environmental Quality Standards for Surface Water of China [?] were used for gray water footprint calculations.

1.3 Methods

1.3.1 Calculation of Grain Crop Water Footprint This study adopted the water footprint calculation method proposed by Hoekstra [?] to measure the production water footprint of typical crops in Ningxia. Crop water requirement is defined as the product of reference crop evapotranspiration and crop coefficient. Crop evapotranspiration was calculated using the FAO-recommended Penman-Monteith formula (see **Table 1**). Crop coefficients vary during growth, gradually increasing from small values in early stages, reaching maximum during vigorous growth periods (around 1.2), and decreasing in later stages [**?**]; specific values are referenced in **Table 2** . Ji [**?**] studied influencing factors of irrigation water utilization coefficients in Ningxia and proposed different coefficients for various irrigation conditions (see **Table 3**). The irrigation water utilization coefficient reflects comprehensive effects of irrigation district engineering conditions, irrigation technology, and management levels [**?**].

Table 1 Calculation process of water footprint of typical grain crops in Ningxia

Parameter	Formula	Description
Reference crop evapotranspiration	$ET_0 = \frac{0.408\Delta(R_n-G)+\gamma\frac{900}{T+273}u_2(e_s-e_a)}{\Delta+\gamma(1+0.34u_2)}$	ET_0 is reference crop evapotranspiration; R_n is net radiation; G is soil heat flux; γ is psychrometric constant; T is mean daily temperature; e_s is saturation vapor pressure; e_a is actual vapor pressure; u_2 is wind speed at 2m height
Crop evapotranspiration	$ET_c = K_c \times ET_0$	ET_c is crop evapotranspiration; K_c is crop coefficient
Effective precipitation	$P_e = \begin{cases} P(125-0.2P)/125 & P \le 250 \\ 125+0.1P & P > 250 \end{cases}$	P_e is effective precipitation; P is monthly precipitation
Crop blue/green water evapotranspiration	$ET_g = \min(ET_c, P_e)$, $ET_b = \max(ET_c - P_e, 0)$	ET_g, ET_b are green and blue water evapotranspiration
Grain production water footprint	$WF_g = 10 \times ET_g/Y$, $WF_b = 10 \times ET_b/Y$	WF_g, WF_b are green and blue water footprints; Y is crop yield

Parameter	Formula	Description
Grain production gray water footprint	$WF_{grey} = \max(\beta \times AR/(C_{max} - C_{nat}) - ET_b(1-\alpha)/\eta, 0)$	WF_{grey} is gray water footprint; β is leaching rate; AR is nitrogen fertilizer application; C_{max} is maximum allowable concentration; C_{nat} is natural background concentration; α is 0.002 kg · m^{-3}; η is irrigation water utilization coefficient

Table 2 Crop coefficient in effective months of crop growth

Shows crop coefficients for different growth stages of wheat, corn, rice, soybean, and potato

Table 3 Irrigation water utilization coefficient in Ningxia

Shows coefficients for different cities and years

1.3.2 Time Series Trend Analysis Method The Mann-Kendall test is a non-parametric test method applicable to type and ordinal variables [?], widely used by scholars for temporal variation studies [?]. This study employed the Mann-Kendall test using MATLAB to quantitatively analyze water footprint changes of major crops in Ningxia cities from 2006-2020, with 2006 as the baseline year.

The test procedure is as follows: The null hypothesis H_0 states that the time series data $(x_1, x_2, ..., x_n)$ are independent and identically distributed random samples; the alternative hypothesis H_1 is a two-sided test: for all $i, j \leq n$ and $i \neq j$, the distributions of x_i and x_j are different [?]. The test statistic S is calculated as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i)$$

where x_j and x_i are values in years j and i, n is the sample length (number of years), and sgn is the sign function:

$$\operatorname{sgn}(x_j - x_i) = \begin{cases} 1 & \text{if } x_j - x_i > 0 \\ 0 & \text{if } x_j - x_i = 0 \\ -1 & \text{if } x_j - x_i < 0 \end{cases}$$

The standard normal variable Z is calculated as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\mathrm{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\mathrm{Var}(S)}} & \text{if } S < 0 \end{cases}$$

where $\mathrm{Var}(S)$ is the variance of S. $Z > 0$ indicates an increasing trend, $Z < 0$ indicates a decreasing trend. When $|Z| > 1.96$ and $|Z| > 2.58$, the trend passes significance tests at 95% and 99% confidence levels, respectively.

1.3.3 Water-saving Potential Calculation This study adopted the calculation method recommended in the local standard "General Rules for Agricultural Water-saving Potential Evaluation Based on Crop Production Water Footprint Regulation"[**?**] to assess crop production water-saving potential in Ningxia cities, including engineering water-saving potential and true water-saving potential. Engineering water-saving potential is the difference in total agricultural water use before and after irrigation implementation, primarily focusing on irrigation water savings [**?**]. Benchmark values for crop production water footprint are shown in **Table 4** .

Table 4 Crop production water footprint benchmark

Shows benchmark values for different crops

The engineering water-saving potential (WSP_e) is calculated as:

$$WSP_e = (WF_b - WF_B) \times S/\eta$$

where WSP_e is engineering water-saving potential (m^3); WF_b and WF_g are blue and green water footprints ($\mathrm{kg} \cdot \mathrm{hm}^{-2}$); WF_B is crop production water footprint benchmark ($\mathrm{kg} \cdot \mathrm{hm}^{-2}$); S is actual irrigated area (hm^2); Y is crop yield ($\mathrm{kg} \cdot \mathrm{hm}^{-1}$); and η is irrigation water utilization coefficient.

True water-saving potential refers to the difference in agricultural water use before and after water-saving implementation during production, further divided into blue water and green water true water-saving potentials for more accurate assessment [**?**]. The calculations are:

$$WSP_{a-b} = (WF_b - WF_B) \times (WF_b - WF_g)/Y$$

$$WSP_{a-g} = (WF_g - WF_B) \times (WF_b - WF_g)/Y$$

where WSP_{a-b} is blue water-saving potential and WSP_{a-g} is green water-saving potential.

2 Results and Analysis

2.1 Interannual Variation of Grain Crop Production Water Footprint

The production water footprint of typical grain crops in Ningxia showed an overall decreasing trend (except for wheat), with significant increases in crop yields and notable decreases in blue-green water footprints (Figure 2 [Figure 2: see original paper]). During the study period, the mean blue-green water footprint of soybean and potato showed the largest decreases, dropping by 33.18% and 42.69%, respectively, from 8.24 $m^3 \cdot kg^{-1}$ and 4.61 $m^3 \cdot kg^{-1}$ to 5.51 $m^3 \cdot kg^{-1}$ and 2.11 $m^3 \cdot kg^{-1}$. In contrast, the mean blue-green water footprint of wheat increased by 20.71% and 3.43 $m^3 \cdot kg^{-1}$.

The blue water footprint of all crops showed a decreasing trend, with the most significant decrease in corn in Yinchuan City (32.08%). The green water footprint of soybean passed significance tests in Shizuishan, Guyuan, and Zhongwei cities, with Guyuan showing a 23.53% decrease. The green water footprint of potato decreased in all cities (though not significant in Wuzhong), while wheat green water footprint increased in Wuzhong and Zhongwei. By 2020, the green water footprint of corn in Yinchuan decreased by 10.34%, while in Guyuan it increased to 1.86 times its original value. The gray water footprint of soybean and potato (except in Yinchuan and Shizuishan) showed decreasing trends and passed significance tests in all cities. The gray water footprints of wheat, corn, and rice in Yinchuan and rice in Wuzhong showed decreasing trends, while other cities showed increasing trends (except Guyuan), though not significant.

2.2 Spatial Distribution and Evolution of Grain Crop Production Water Footprint Among Cities

Based on spatial variation characteristics of crop production water footprint during the study period (Figures 3-5 [Figure 3: see original paper][Figure 4: see original paper][Figure 5: see original paper]), significant differences existed among Ningxia cities. The mean blue water footprint ranged from 6.80-17.61 $m^3 \cdot kg^{-1}$, with inter-city standard deviation reaching 91.22% of the mean. The mean green water footprint ranged from 1.72-4.26 $m^3 \cdot kg^{-1}$, with inter-city standard deviation at 4.57% of the mean. In 2020, soybean green water footprint proportion remained as high as 85.58% in Yinchuan and Shizuishan, while Guyuan’ s proportion only decreased by 5.12%. Shizuishan showed increased blue water footprint proportion for soybean but decreased for other crops, while Wuzhong and Zhongwei showed increased blue water footprint proportion for wheat but decreased for other crops.

Soybean had the largest gray water footprint, ranging from 0.30-0.14 $m^3 \cdot kg^{-1}$. The lowest gray water footprint was in Guyuan. In 2020, Yinchuan and Shizuishan had the highest contributions from soybean gray water footprint at 76.54% and 70.37%, respectively.

2.3 Water-saving Potential of Grain Crops

Based on precipitation frequency, typical wet, normal, and dry years were identified to calculate engineering and true water-saving potentials. **Table 6** shows that potato contributed most to Guyuan' s water-saving potential, accounting for 48.05% of the city' s total. The ranking of average true water-saving potential for the five crops was: potato (5.22$×10^{8}$ m^{3}), corn (3.51$×10^{8}$ m^{3}), wheat (3.15$×10^{8}$ m^{3}), rice (0.71$×10^{8}$ m^{3}), and soybean (2.22$×10^{8}$ m^{3}). Overall, soybean' s engineering, green water, and blue water-saving potentials were largest in normal years (42.07%, 45.30%, and 45.00%, respectively). Potato' s three types of water-saving potentials were largest in dry years (42.15%, 39.44%, and 49.60%, respectively). Corn' s three water-saving potentials were largest in wet years (36.05%, 39.22%, and 35.96%, respectively).

Figure 6 [Figure 6: see original paper] shows the spatial distribution of water-saving potential in typical years. Yinchuan, Wuzhong, and Guyuan had larger water-saving potentials, with Guyuan accounting for 26.52% of total provincial potential. Yinchuan ranked second (22.18%), followed by Wuzhong (21.98%). Zhongwei and Shizuishan had smaller potentials, accounting for only 16.70% and 12.62% of total water-saving potential, respectively.

3 Discussion

3.1 Trends and Causes of Water Footprint Changes in Typical Grain Crops in Ningxia

The different proportions of blue and green water footprints among Ningxia cities are closely related to climate conditions, fertilization practices, irrigation rates and technologies, and crop yields. The results show that while the proportion of soybean blue-green water footprint is continuously decreasing across cities, other crops show increasing proportions. With future climate change impacts and increasing agricultural water demand, public awareness of water conservation in agricultural products needs to be enhanced, and ecological compensation standards or mechanisms based on water footprint should be established.

The sharp increase in crop production blue-green water footprints in 2020 may be attributed to the fact that most areas in Ningxia experienced the lowest precipitation since 2000, with cumulative precipitation in southern mountainous areas from May to July being more than 60% below historical averages. This resulted in slow growth and poor conditions for corn, potato, and other autumn grain crops, significantly affecting yields.

The ranking of gray water footprints for grain crop production across Ningxia cities is: Shizuishan > Yinchuan > Wuzhong > Zhongwei > Guyuan. All crops showed decreasing trends in gray water footprint that passed significance tests. The gray water footprints of wheat, corn, and rice in Yinchuan and rice in

Wuzhong showed decreasing trends, while other cities showed increasing trends (except Guyuan), though not significant. This indicates that excessive fertilizer and pesticide use still exists in Ningxia crop production, undoubtedly increasing ecological pressure. Scientific application of fertilizers and pesticides can not only promote grain yield increases but also advance agricultural modernization and reduce farmland gray water footprint [?].

Ningxia' s crop production water footprint is dominated by blue water footprint, supplemented by green water footprint, consistent with other studies [?]. The green water footprint shows an increasing trend in Zhongwei and Wuzhong (Table 3), which is closely related to evapotranspiration and average wind speed [?]. The increasing proportion of blue water footprint for wheat in Wuzhong and Zhongwei (Figure 3), with increases of 23.23% and 24.88% respectively, reflects that irrigation water dominates agricultural water use in Ningxia. Due to low precipitation in northwest China, agricultural water use relies primarily on irrigation water and groundwater.

3.2 Regional Differences and Changes in Water-saving Potential of Typical Grain Crops in Ningxia

The results indicate that potato has the largest water-saving potential in Ningxia, while soybean has the smallest (7.46$×10^{8}$ m^3 and 0.55$×10^{8}$ m^3, respectively). Ningxia experiences scarce precipitation, abundant sunshine, and high evaporation, with relatively short water resources. Potato shows the greatest potential for water demand, and vigorously developing agricultural water-saving measures plays a positive role in addressing local water shortages and promoting economic development [?]. Guyuan has the largest water-saving potential but the smallest engineering water-saving potential. Due to improved canal system conditions, flow rates, operational conditions, soil conditions along canals, irrigation methods, and systems, Guyuan has achieved highly efficient utilization of agricultural irrigation water.

Crop water-saving potential is closely related to water resource availability, regional climate conditions, soil characteristics, agricultural technology, market demand, and policy orientation. Based on local conditions, optimizing planting structures according to regional advantages can greatly improve water use efficiency and water-saving potential. Future research should focus on establishing scientific water resource utilization amounts and water-saving potentials for crops under multi-objective conditions including food security and production stability [?]. Combining field management and biological water-saving technologies can alleviate regional agricultural water contradictions, prevent soil erosion, effectively protect farmland quality, increase groundwater recharge, and improve regional ecological environments.

4 Conclusions

1) During the study period, the production water footprint of typical grain crops in Ningxia showed a decreasing trend (except for wheat). Crops with higher production water footprints (soybean) exhibited significant decreasing trends, with the production water footprint decreasing by 33.18%.

2) Significant differences existed in crop production water footprint between regions and cities. In 2020, the mean blue-green water footprint of soybean was 3.11 $\mathrm{m}^3 \cdot \mathrm{kg}^{-1}$, 2.72 times that of corn. Corn and rice had the smallest production water footprints, while soybean had the largest. Due to sharp declines in soybean yield, Shizuishan had the largest soybean production water footprint in 2020.

3) The ranking of average water-saving potential for the five crops was: potato > corn > wheat > rice > soybean. During the study period, Guyuan had the largest crop production water-saving potential but the smallest engineering water-saving potential. Shizuishan had the smallest crop production water-saving potential, accounting for 11.50% of the provincial total, despite having the largest increase in irrigation water utilization coefficient (45.89%).

4) Ningxia has substantial water-saving potential. Two preliminary recommendations are: support water-saving renovation of large and medium-sized irrigation districts; and implement precision fertilization to reduce environmental pollution.

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