Spatiotemporal Characteristics and Influencing Factors of Crop Water Footprint in the Guanzhong Region at the County Scale (Postprint)

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Abstract

Investigating the water footprint of regional crops and its spatiotemporal distribution patterns and driving factors can improve agricultural production efficiency and water resource utilization benefits. This study quantifies and analyzes the water footprint of winter wheat and summer maize in 54 counties (districts) of the Guanzhong region from 2000 to 2020, and employs path analysis to explore the driving factors influencing the spatiotemporal changes in green water footprint, blue water footprint, and grey water footprint. The results show that: (1) The total crop water footprint in the Guanzhong region decreased from 2.232\$$\times 10^{8} m$^{3}\$ in 2000 to 2.003\$$\times 10^{8} m$^{3}\$ in 2020, with blue water being the primary form of water resource use, followed by grey water, and green water being the least used, accounting for 37.261%, 36.254%, and 26.485%, respectively; (2) The total crop water footprint shows significant spatial differences, exhibiting characteristics of high in the east and low in the west, and agglomeration distribution in similar areas (high-high, low-low); (3) Yield per unit area, average wind speed, and fertilizer application amount are the most significant factors affecting green water footprint, blue water footprint, and grey water footprint, respectively. The results of this study are beneficial for helping the Guanzhong region conserve water resources and improve water use efficiency, expanding perspectives on sustainable utilization of agricultural water resources.

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Abstract: Exploring the regional crop water footprint and its spatiotemporal distribution patterns and driving factors can enhance agricultural production efficiency and water resource utilization benefits. This study quantified and analyzed the water footprint of winter wheat and summer corn in 54 counties (districts) of the Guanzhong region from 2000 to 2020, and employed path analysis to investigate the drivers influencing spatiotemporal changes in green water footprint, blue water footprint, and gray water footprint. Results showed that: (1) The total crop water footprint in the Guanzhong region decreased from 2.232×10^{8} m^3 to 2.003×10^{8} m^3, with blue water being the dominant form of water resource use, followed by gray water, and green water being the least used, accounting for 37.261%, 36.254%, and 26.485%, respectively. (2) The total crop water footprint exhibited significant spatial variation, showing an east-high west-low pattern and agglomeration characteristics in similar regions (high-high or low-low clusters). (3) Yield per unit area, average wind speed, and fertilizer application amount were the most significant factors affecting green water footprint, blue water footprint, and gray water footprint, respectively. These findings can help the Guanzhong region conserve water resources, improve water use efficiency, and expand approaches for sustainable agricultural water utilization.

Keywords: crop; water footprint; influencing factors; spatiotemporal distribution; Guanzhong region

China faces severe water scarcity, with per capita water availability less than one-third of the global average. Agricultural development is inseparable from water resources. In 2021, national agricultural water consumption reached 3644.3×10^{8} m^3, accounting for 61.5% of total water use. Water resource shortages constrain agricultural development and threaten food security. Therefore, comprehensively evaluating water resource utilization in agricultural production can reveal water supply-demand conditions and existing problems, thereby improving agricultural water use efficiency and promoting coordination between agricultural development and sustainable water resource utilization. The concept of water footprint is significant for promoting sustainable water resource use and achieving sustainable development.

The “water footprint” is defined as the total water volume required to produce a product, divided into green water footprint, blue water footprint, and gray water footprint. Green water footprint refers to rainwater stored in soil and evaporated during production; blue water footprint refers to surface water or groundwater used during crop production; and gray water footprint refers to the freshwater volume needed to dilute pollutants to standard water quality levels. The water footprint concept broadens traditional agricultural water consumption calculations that only considered irrigation water, refining the accounting of water resources consumed during crop production.

As water footprint theory and methods have matured, increasing research has adopted water footprint to assess crop water resource utilization. International scholars primarily conduct water footprint studies from global or national perspectives. Mekonnen and Hoekstra assessed the green, blue, and gray water footprint of global wheat. Hoekstra evaluated the water footprint of global rice production. Sangam et al. used the DSSAT (CERES Rice) model to quantify the potential impact of climate change on rice production water footprint. Yang et al. analyzed the physical versus economic water footprints of crop production in China from 1980 to 2016, revealing relationships between crop water productivity and economic value.

Domestic scholars mainly investigate spatiotemporal evolution patterns and influencing factors of single or multiple crops at national, provincial, and basin scales. Sun et al. analyzed spatial characteristics of wheat production water footprint in mainland China, finding that fertilizer and agricultural machinery inputs were the main agricultural factors affecting wheat water footprint, while solar radiation and precipitation were the primary climatic factors. Guo et al. analyzed spatiotemporal distribution and influencing factors of crop water footprint in China, identifying population density, per capita net income, and fertilizer application amount as main driving factors. Fan et al. quantified spatiotemporal characteristics of grain crop production water footprint in the Sanjiang Plain, revealing that phenological conditions affect grain crop water footprint. These studies demonstrate that water footprint characteristics and change patterns vary spatiotemporally across regions. Investigating the spatiotemporal patterns and influencing factors of crop green, blue, gray, and total water footprints is essential for improving water resource utilization efficiency.

As a typical agricultural region, the Guanzhong region has an agricultural water consumption of 18.52$×10^{8}$ m^3, accounting for 35.18% of Shaanxi Province’s total water use, facing water scarcity pressure and severe water consumption with low utilization efficiency. While numerous studies have explored crop water footprint and structural characteristics in different regions, research on crop production water footprint in the Guanzhong region at county scale remains insufficient.

Winter wheat and summer corn are the most extensively planted crops in the Guanzhong region. Improving water use efficiency for these two crops can alleviate regional water scarcity. Based on water footprint theory, this study analyzes the water footprint of major crops in the Guanzhong region to address three questions: (1) quantify crop water footprint in the Guanzhong region; (2) analyze spatiotemporal characteristics of crop water footprint; and (3) identify driving factors affecting water use for major crop production. The results can help conserve water resources, improve water use efficiency, and provide guidance for regional agricultural sustainable development.

1.1 Study Area Overview

The Guanzhong region is located in central Shaanxi Province [Figure 33: see original paper], between 33°30 –35°40 N and 106°30 –110°30 E, including Xi'an, Baoji, Weinan, Tongchuan, Xianyang, and Yangling District. Situated in the lower Yellow River basin, the region has a warm temperate semi-humid to semi-arid climate with an average annual temperature of 12–14°C, average annual precipitation of 600 mm, and elevation of 460–850 m. The region has a total water resource volume of 185.02$×10^{8}$ m^3 and per capita water availability of 181.03 m^3 per person. The main cropping system is winter wheat-summer corn rotation, gradually developing into a diversified system with oil crops such as rapeseed and beans as supplements. The Guanzhong region concentrates 65% of the province's irrigated area with complete irrigation facilities, high agricultural production potential, and is a major agricultural production area in Shaanxi and nationally.

1.2 Methods

1.2.1 Crop Water Footprint Accounting Method This study employed the WAT 8.0 model to calculate crop water footprint, using crop coefficients from the "Irrigation Water Quotas for Major Crops in Northern China" and FAO Report No. 56. Nitrogen was used as the indicator for gray water footprint calculation.

1.2.2 Spatiotemporal Distribution Characteristics Measurement
Spatial Autocorrelation. Spatial autocorrelation analysis reflects the spatial dependency degree of variables within a geographic region and has been widely applied in water footprint research. Global Moran's I was used to determine the spatial clustering or dispersion degree of regional variables.

Center of Gravity Migration and Cold-Hot Spot Analysis. Center of gravity migration reflects interannual spatial change trends of elements. This study mapped the migration trajectory of crop water footprint centers using ArcGIS software. However, the center of gravity model only illustrates spatiotemporal changes in weighted average values of crop water footprint, not distribution characteristics of similar attribute clusters. Cold-hot spot analysis can reveal spatial aggregation patterns of high values (hot spots) or low values (cold spots), and has been applied in ecosystem service value spatial heterogeneity and environmental pollution distribution studies. Based on the natural breaks method, the study area was divided into four categories according to crop water footprint values: hot spot areas, sub-hot spot areas, sub-cold spot areas, and cold spot areas, to reveal local spatial aggregation characteristics and provide basis for targeted water footprint management.

1.2.3 Path Analysis Path analysis decomposes correlation coefficients into direct, indirect, and total path coefficients based on multiple regression, representing each independent variable's direct, indirect, and total effects on dependent variables. This study used path analysis to quantify the influence intensity and mechanisms of different factors on crop water footprint, understand agricultural water resource utilization, and formulate corresponding management strategies.

1.3 Data Sources

Meteorological data from 2000–2020 were obtained from the National Earth System Science Data Center (http://www.geodata.cn/data/), including precipitation, maximum temperature, minimum temperature, relative humidity, average wind speed, and sunshine hours. Agricultural production data at prefecture and county levels, including crop yield, sown area, fertilizer application amount, agricultural plastic film usage, and pesticide usage, were sourced from the "Shaanxi Statistical Yearbook," "Baoji Statistical Yearbook," "Xianyang Statistical Yearbook," "Xi'an Statistical Yearbook," "Weinan Statistical Yearbook," and "Tongchuan Statistical Yearbook."

2 Results and Analysis

2.1 Temporal Evolution Characteristics of Crop Water Footprint in Guanzhong Region

From 2000 to 2020, the total crop water footprint in the Guanzhong region fluctuated across years [Figure 2: see original paper]. The lowest value was 2.003$×10^{8}$ m^{3} in 2020, a decrease of 10.27% from the highest value of 2.232$×10^{8}$ m^{3} in 2000. The multi-year average total water footprint was 2.431$×10^{8}$ m^{3}. The multi-year averages of green water footprint, blue water footprint, and gray water footprint were 0.825$×10^{8}$ m^{3}, 0.848$×10^{8}$ m^{3}, and 0.603$×10^{8}$ m^{3}, respectively. During the study period, green water footprint and gray water footprint increased, while blue water footprint decreased from 0.716$×10^{8}$ m^{3} to 0.667$×10^{8}$ m^{3}, with an average annual decrease of 0.139$×10^{8}$ m^{3}.

The total water footprint showed an upward trend from 2000 to 2010, with the most significant difference of 0.335$×10^{8}$ m^{3} in 2010, and a downward trend from 2010 to 2020, with a difference of 0.139$×10^{8}$ m^{3}. During the study period, crop planting area continuously decreased while yield continuously increased [Figure 3: see original paper]. The total crop planting area decreased from 1.727$×10^{6}$ hm^{2} to 1.421$×10^{6}$ hm^{2}, while yield increased from 8.228$×10^{6}$ t to 10.104$×10^{6}$ t. Wheat planting area decreased from 6.46×10^{5} hm^2 to 5.98×10^{5} hm^2, with yield increasing from 3.595×10^{6} t to 6.236×10^{6} t. Corn planting area decreased from 3.682×10^{5} hm^2 to 2.866×10^{5} hm^2, with yield increasing from 3.452×10^{6} t to 5.980×10^{6} t. In 2010, fertilizer application amount and yield per unit area reached their maximum values, resulting in the maximum gray water footprint value, which accounted for 43.247% of the total water footprint, making the total water footprint value reach its maximum.

In terms of crop types [FIGURE:4, FIGURE:5], winter wheat total water footprint decreased at a rate of 0.059×10^{8} m^3 per year, from 1.558×10^{8} m^3 to 1.274×10^{8} m^3, with an average reduction of approximately 5.842%. Summer corn total water footprint increased from 0.674×10^{8} m^3 to 0.730×10^{8} m^3, an increase of 8.265%. Summer corn green water footprint, gray water footprint, and total water footprint all increased, while blue water footprint decreased.

[Figure 6: see original paper] shows the overall composition of crop water footprint. Blue water footprint dominated, accounting for 37.261%, followed by gray water footprint at 36.254%, and green water footprint at 26.485%. The proportion of green water footprint in total water footprint increased annually from 20.954% to 30.226%, while blue water footprint proportion decreased from 49.179% to 34.016%. During the study period, the continuously rising proportion of gray water footprint indicated increasing pollution.

Winter wheat water footprint was dominated by blue water footprint, with a multi-year average proportion of 44.114%, followed by gray water footprint at 36.852%, and green water footprint at 22.542%. As a cross-year crop, winter wheat's two growth peaks before and after winter coincide with two water shortage peaks in the Guanzhong region, making it water-deficient with strong irrigation demand. Summer corn water footprint composition was dominated by gray water footprint (41.052% multi-year average), followed by green water footprint (33.537%), and blue water footprint (25.411%). With a short growth cycle that largely overlaps with the local rainy season, summer corn has relatively low water deficit throughout its growth period, as natural precipitation can meet its water needs.

2.2 Spatial Distribution Characteristics of Crop Water Footprint in Guanzhong Region

2.2.1 Spatial Distribution Features As shown in [Figure 7: see original paper], the highest total crop water footprint was in Fuping County at 6.874×10^{8} m^3, while the lowest was in Beilin District at 0.494×10^{8} m^3, showing an east-high west-low trend with high-value areas concentrated in the eastern region and low-value areas in the western region. Green water footprint showed a south-high north-low pattern, with high-value areas concentrated in southern regions; Chang'an District had the highest green water footprint at 1.861×10^{8} m^3, while Beilin District had the lowest at 0.098×10^{8}

m^3. Blue water footprint showed similar east-high west-low characteristics, with high-value areas concentrated in Weinan City; Pucheng County had the highest blue water footprint at 3.364$\times10^{8}$ m^3, while Beilin District had the lowest at 0.396$\times10^{8}$ m^3. Gray water footprint high-value areas were concentrated in central-eastern regions, with low-value areas in western regions; Fuping County had the highest gray water footprint at 2.926$\times10^{8}$ m^3, while Yanta District had the lowest at 1.492$\times10^{8}$ m^3.

Southern regions have complex terrain with numerous mountains and hills, high natural vegetation coverage, and strong soil water retention capacity, resulting in relatively high green water footprint. Eastern regions have flat terrain, abundant groundwater resources, and relatively abundant precipitation influenced by the Yellow and Wei Rivers, making them suitable for irrigated agriculture with sufficient surface water resources. Weinan City is an agricultural planting area with large crop sown area and yield, resulting in high water demand, thus its blue water footprint and gray water footprint are high while green water footprint is low. Western regions have low yield, small crop sown area, and low fertilizer application, with green water footprint generally consistent with precipitation distribution, while blue water footprint shows the opposite pattern to precipitation distribution. Gray water footprint values are consistent with fertilizer application amounts in spatial distribution. Crop water footprint in the Guanzhong region shows certain spatial agglomeration characteristics, with high-value areas of winter wheat and summer corn total water footprint consistent with their yield spatial distribution.

2.2.2 Spatial Clustering Analysis Winter wheat and summer corn water footprints in the Guanzhong region show agglomeration distribution patterns. To accurately explore spatial correlation relationships, Global Moran's I was used to analyze the spatial pattern of crop water footprint. Moran's I values for representative years were calculated , with results showing that both winter wheat and summer corn passed significance tests, indicating that crop water footprints in the Guanzhong region show significant agglomeration distribution in similar areas (high-high or low-low). Moran's I values showed an increasing trend, indicating that spatial agglomeration degree of crop water footprint gradually strengthened rather than being randomly distributed. This phenomenon demonstrates that crop cultivation water resource utilization is more concentrated in certain areas rather than randomly dispersed. The gradually strengthening spatial agglomeration also implies that more effective monitoring and management measures are needed to ensure rational allocation and utilization of water resources, avoiding excessive concentration that leads to water resource depletion and waste in some regions.

2.2.3 Center of Gravity Migration and Cold-Hot Spot Changes During the study period, the center of gravity of crop water footprint in the Guanzhong region changed [Figure 8: see original paper]. The green water footprint center was in Liquan County, gradually moving northward and approaching Jingyang County. The blue water footprint center shifted from Jingyang County to Sanyuan County. The gray water footprint center and winter wheat water footprint center remained within Jingyang County. The summer corn water footprint center moved from Liquan County to Jingyang County, gradually approaching Sanyuan County. The overall center of gravity of crop water footprint moved northward around Jingyang County in Xianyang City, maintaining relative stability, indicating that agricultural production methods and crop planting structures in the Guanzhong region remained relatively stable without large-scale agricultural structural adjustments. Special attention should be paid to water resource consumption in Jingyang County, Liquan County, and Sanyuan County.

Cold-hot spot analysis results show distinct distribution patterns of high and low value clusters of crop water footprint [Figure 9: see original paper]. Total water footprint hot spots showed little spatial variation during the study period, concentrated in eastern regions, while cold spots were concentrated in western regions and sub-hot spots in southern regions. Some regions remained stable, while cold spot areas decreased, indicating that agricultural production water demand shows an increasing trend. Therefore, strengthened water resource management and protection are needed in these areas, encouraging farmers to adopt more water-saving agricultural practices to reduce water resource pressure and improve resource use efficiency. Weinan City had large total water footprint values, and combined with crop yield and sown area data, this region has high yield but high water consumption, thus requiring water use control.

Green water footprint showed significant spatial differences. In 2000, green water footprint hot spots were concentrated in western and southern regions, gradually shifting to eastern regions. During the study period, cold spot areas increased while hot spots showed no obvious change, indicating that green water footprint utilization patterns have undergone certain transfer and adjustment. Some regions have low green water resource utilization, leading to increased green water footprint cold spots, requiring strengthened green water resource allocation and management for more rational and sustainable utilization. The lack of obvious change in hot spots indicates that agricultural production levels and green water resource use efficiency in these areas have reached relatively stable levels, requiring attention to green water consumption.

Blue water footprint spatial differences were not obvious. Crop blue water footprint hot spots remained concentrated in eastern regions, while cold spots remained in western regions, with hot spots and sub-hot spots decreasing and cold spots increasing. This represents reduced blue water footprint consumption during the study period, indicating that the Guanzhong region has strengthened blue water resource management and allocation, optimized agricultural production structure, and improved irrigation water use efficiency, thereby achieving rational allocation and utilization of blue water resources and reducing waste and overuse.

Gray water footprint hot spots gradually shifted to eastern regions, with sub-hot spots increasing, representing increased pollution areas. During the study period, cold spots and sub-cold spots of total crop water footprint, blue water footprint, and green water footprint were concentrated in north-central regions with little change, indicating low water resource use efficiency in these areas. Water-saving technologies should be promoted, agricultural structure optimized, and scientific water resource utilization plans formulated to improve water resource use efficiency and address future water resource challenges.

2.3 Analysis of Influencing Factors of Crop Water Footprint

2.3.1 Correlation Analysis Correlation analysis was conducted between crop water footprint and influencing factors to establish a correlation matrix and explore relationships . Crop green water footprint showed significant positive correlations with yield per unit area and pesticide use, and significant negative correlations with relative humidity, average wind speed, and fertilizer application amount. Crop blue water footprint showed significant positive correlation with average wind speed, and significant negative correlations with relative humidity, yield per unit area, fertilizer application amount, agricultural plastic film usage, and pesticide use. Gray water footprint showed significant positive correlations with yield per unit area, fertilizer application amount, agricultural plastic film usage, and pesticide use.

2.3.2 Path Analysis Crop water demand is affected by local climate conditions and agricultural input factors. Meteorological factors such as precipitation, temperature, and humidity influence crop water consumption during growth, while agricultural inputs such as effective irrigation area, agricultural mechanization power, and agricultural plastic film usage affect crop yield, thereby influencing crop water footprint. This study used path analysis to quantify the impacts of meteorological and agricultural input factors on crop water footprint in the Guanzhong region. To analyze the main factors causing differences in crop water footprint, and referring to relevant literature [8-9, 19], eight factors were selected: average temperature, relative humidity, average wind speed, sunshine hours, yield per unit area, nitrogen fertilizer application per unit area, agricultural plastic film usage, and pesticide usage.

Path analysis of factors influencing crop green water footprint. Direct path coefficients showed that crop green water footprint had positive correlations with relative humidity and yield per unit area, and negative correlation with pesticide use [Figure 10: see original paper]. Yield per unit area had the greatest direct impact on green water footprint. Indirect path coefficient analysis showed that yield per unit area still had the greatest total impact on green water footprint, followed by relative humidity and pesticide use. Higher yield per unit area means higher water use efficiency and higher water resource demand, consuming more green water. Relative humidity mainly indirectly affects crop green water footprint through precipitation—higher relative humidity means higher atmospheric water content, leading to increased water vapor and green water footprint. Excessive pesticide use pollutes soil and water environments, affecting water resource quality and availability.

Path analysis of factors influencing crop blue water footprint. Direct path coefficient analysis showed that crop blue water footprint had positive correlation with average wind speed and negative correlations with relative humidity, yield per unit area, fertilizer application amount, and pesticide use [Figure 11: see original paper]. Average wind speed had the greatest direct impact on blue water footprint. Indirect path coefficient analysis showed that average wind speed remained the largest influencing factor on crop blue water footprint, followed by relative humidity, pesticide use, yield per unit area, and fertilizer application amount. Wind speed directly affects water vapor diffusion rate in crop canopies, influencing evapotranspiration and thus crop water footprint. Excessive pesticide use pollutes soil and water bodies, affecting water resource quality and quantity.

Path analysis of factors influencing crop gray water footprint. Direct path coefficient analysis showed that crop gray water footprint had positive correlations with fertilizer application amount, agricultural plastic film usage, and pesticide use, and negative correlation with yield per unit area [Figure 12: see original paper]. Fertilizer application amount had the greatest direct impact on gray water footprint. Indirect path coefficient analysis showed that fertilizer application amount remained the most significant factor affecting crop gray water footprint. Appropriate fertilizer input can improve crop yield and quality, but excessive application leads to nutrient loss and soil pollution, increasing crop gray water footprint. Agricultural plastic film can improve soil temperature and water retention, promoting crop growth, but excessive use causes soil pollution and plastic waste pollution, increasing crop gray water footprint. Increased yield per unit area can reduce production area and thus land use, while also meaning higher water resource demand. Efficient crop varieties and planting techniques enable crops to achieve higher yields with the same water amount, thereby reducing gray water footprint.

In summary, yield per unit area is the most significant factor affecting green water footprint, average wind speed has the greatest impact on blue water footprint (followed by pesticide use and relative humidity), and fertilizer application amount most significantly affects gray water footprint. Agricultural input factors have significantly greater influence on crop water footprint than meteorological factors, indicating that regional water footprint differences are primarily caused by production levels and agricultural input factors.

3 Discussion

From 2000 to 2020, the total crop water footprint in the Guanzhong region showed a decreasing trend, with green water footprint increasing, blue water footprint decreasing, and gray water footprint increasing. This is consistent with findings from Cao et al., Yan et al., and Jiang et al. The results differ from

Feng et al. and Xue et al. because this study expanded the research scope to include gray water footprint, and differs in data sources and spatial calculation units. Additionally, the Guanzhong region primarily relies on irrigation water, and topographic characteristics vary.

The water footprint pattern in the Guanzhong region shows blue water as the main source and green water as supplementary for crop production, indicating that irrigation water is the primary water consumption during crop growth, related to scarce precipitation in northwestern China that requires irrigation or groundwater supplementation. The total crop water footprint shows an east-high, west-low spatial pattern. Similar crop water footprint areas show significant agglomeration distribution in space. The center of gravity of crop water footprint gradually migrated northward around Jingyang County in Xianyang City, indicating relatively stable agricultural production methods and crop planting structures without large-scale agricultural restructuring. However, water resource pressure remains significant with population growth and economic development, requiring focused attention on water resource consumption in this area. As the center of gravity moves northward, and with longstanding drought issues in northern China, future water resource challenges will increase with rising water demand and climate change impacts, affecting local agricultural production and ecological environments. Therefore, strengthened water resource protection and management are needed, appropriately reducing high water-consuming crop planting and improving agricultural water resource use efficiency.

Cold-hot spot analysis shows that cold spots and sub-cold spots of total crop water footprint, blue water footprint, and green water footprint are concentrated in north-central regions with little change, indicating low water resource use efficiency in these areas. Water-saving technologies should be promoted, agricultural structure optimized, and scientific water resource utilization plans formulated to improve efficiency and address future water resource challenges. Weinan City has large total water footprint values, and combined with crop yield and sown area data, this region has high yield but high water consumption, thus requiring water use control.

Precipitation directly affects water content stored in soil, while evapotranspiration affects groundwater and surface water content and flow. Relative humidity and average wind speed are the main meteorological factors affecting evapotranspiration, thus becoming primary meteorological factors influencing crop water footprint in the Guanzhong region. In addition to meteorological factors, agricultural production input factors also affect crop water footprint. The Guanzhong region has abundant but unevenly distributed precipitation, causing inconsistent water demand timing during crop growth stages, thereby affecting crop growth and yield and resulting in low green water utilization efficiency. Rational allocation of precipitation is an effective measure to improve green water utilization efficiency.

Irrigation water increase is a major factor contributing to water footprint growth. Improving irrigation water use efficiency to reduce blue water footprint and agricultural water consumption is essential. Measures such as windbreaks, efficient water-saving irrigation technologies, reasonable fertilizer use standards, and water-saving mechanized operations can achieve sustainable blue water resource utilization. Gray water footprint accounts for a high proportion in both winter wheat and summer corn water footprints, indicating that large fertilizer use causes agricultural non-point source pollution. Reducing fertilizer and pesticide use in crop production can mitigate negative impacts on water environments. Gray water footprint high-value areas are concentrated in eastern regions, with fertilizer application amounts increasing during the study period, posing great threats from agricultural non-point source pollution. Fertilizer and pesticide are important agricultural production input factors—appropriate use can improve crop yield and quality, increase production benefits, and promote agricultural modernization, but abuse leads to soil fertility decline, reduced cultivated land productivity, agricultural non-point source pollution, and decreased agricultural product quality. Scientific fertilizer application should be implemented to improve utilization efficiency, applying only when crop nutrient requirements are not yet met, reducing fertilizer and pesticide use while ensuring crop yield, optimizing nutrient management to achieve precision fertilization and reduce water resource consumption caused by water environmental pollution.

Yield per unit area is positively correlated with green water footprint and negatively correlated with blue and gray water footprints. Moderately increasing agricultural production input and adopting scientific planting management, promoting water-saving technologies, circular agriculture technologies, and establishing pollutant treatment systems can effectively manage the impacts of yield per unit area on green, blue, and gray water footprints.

Recommended measures for regulating crop water footprint include:

1. **Rational allocation of precipitation** is an effective measure to improve green water utilization. Water resource exchange between different regions through water conservancy projects and water resource allocation projects can transfer water from water-rich areas to water-scarce areas for optimal allocation. Building reservoirs to store rainwater during wet seasons for use during dry seasons can reduce precipitation consumption. Strengthening soil conservation, such as improving land quality and increasing organic matter, can enhance soil water retention capacity, reducing crop irrigation water demand and water footprint.

2. **Improving irrigation facilities** to enhance agricultural water resource utilization efficiency. Irrigation consumes the most blue water footprint in agricultural production. Improving irrigation facilities, such as promoting drip and sprinkler irrigation, optimizing irrigation pipeline networks, and strengthening irrigation facility management and maintenance can reduce water evaporation and soil evaporation, improve irrigation efficiency, reduce irrigation water resource consumption, and decrease blue water

footprint.

3. **Strengthening agricultural waste treatment and utilization**, such as producing organic fertilizer and biomass fuel, can reduce gray water discharge and pollution in agricultural production. Rational fertilization techniques can improve nutrient use efficiency and reduce nutrient loss and pollution. Precision fertilization, organic fertilizer application, and strengthened agricultural pollution prevention and control, such as enhanced farmland environmental monitoring and pollution source control, can reduce gray water discharge and pollution.

4 Conclusion

This study analyzed spatiotemporal evolution characteristics of water footprint for major crops in the Guanzhong region from 2000 to 2020 using water footprint theory, and employed path analysis to deeply investigate factors influencing regional differences in crop water footprint, revealing regional water resource pressure from agricultural production and providing reference for optimizing crop planting structure, conserving water resources, and improving water use efficiency. Main conclusions are:

1. From 2000 to 2020, the total crop water footprint in the Guanzhong region showed an overall decreasing trend, from 2.232×10^{8} m^3 to 2.003×10^{8} m^3. Within the crop water footprint structure, blue water footprint dominated, followed by gray water footprint, with green water footprint being the smallest, accounting for 37.761%, 36.254%, and 26.485%, respectively.
2. The total crop water footprint showed significant spatial variation, presenting an east-high west-low pattern, with similar areas (high-high or low-low) showing agglomeration distribution.
3. Yield per unit area, average wind speed, and fertilizer application amount were the most significant factors affecting green water footprint, blue water footprint, and gray water footprint, respectively. Agricultural input factors had significantly greater influence on crop water footprint than meteorological factors.

References

[1] Yan C, Li M, Zhuo L, et al. Spatiotemporal evolution of water footprint and water saving potentials of crop production in Shaanxi Province during 1989-2019[J]. Resources Science, 2023, 45(1): 158-173.

[2] Zhang L, Deng X, Long A, et al. Spatiotemporal assessment of water resource security based on the agricultural water footprint: A case in the Hotan Prefecture of Xinjiang[J]. Arid Zone Research, 2022, 39(2): 436-447.

[3] Fan X, Chen B. Spatiotemporal patterns and influencing factors of the water footprint of grain crop production in the Sanjiang Plain[J]. Acta Ecologica Sinica, 2022, 42(15): 6368-6380.

[4] Mekonnen M M, Hoekstra Y. A global and high resolution assessment of the green, blue and grey water footprint of wheat[J]. Hydrology and Earth System Sciences, 2010, 14(7): 1259-1276.

[5] Hoekstra A Y, Chapagain A K. Water footprints of nations: Water use by people as a function of their consumption pattern[J]. Water Resources Management, 2007, 21(1): 35-48.

[6] Sangam S, Ranju C, Mukand S B. Quantifying the impact of climate change on crop yield and water footprint of rice in the Nam Oon Irrigation Project, Thailand[J]. Science of the Total Environment, 2017, 599-600: 689-699.

[7] Yang X, Zhuo L, Xie P, et al. Physical versus economic water footprints in crop production: A spatial and temporal analysis for China[J]. Hydrology and Earth System Sciences, 2021, 25(1): 169-191.

[8] Sun S, Wang Y, Wu P, et al. Spatial variability and attribution analysis of water footprint of wheat in China[J]. Transactions of the Chinese Society of Agricultural Engineering, 2015, 31(13): 142-148.

[9] Guo X, Gao S, Wu M, et al. Analysis of temporal and spatial distribution and influencing factors of water footprint in crop production system of China[J]. Transactions of the Chinese Society of Agricultural Machinery, 2018, 49(5): 295-302.

[10] Shaanxi Provincial Bureau of Statistics, Shaanxi General Investigation Team of the National Bureau of Statistics. Shaanxi Statistical Yearbook 2021[M]. Beijing: China Statistics Press, 2022.

[11] Department of Water Resources of Shaanxi Province. 2021 Shaanxi Water Resources Bulletin[M]. Xi'an: Department of Water Resources of Shaanxi Province, 2022.

[12] Duan A. Water Quotas for Irrigation of Major Crops in the Northern Region[M]. Beijing: China Agricultural Science and Technology Press, 2004.

[13] Yin M, Zhu H, Hu Y, et al. Analysis of various characteristics and driving factors of gray water footprint in Gansu Province[J]. Arid Zone Research, 2022, 39(6): 1810-1818.

[14] Du H, Wang G, Ran G, et al. Agricultural gray water footprint in the Tarim River Basin using SDGs analysis[J]. Arid Zone Research, 2023, 40(7): 1184-1193.

[15] Wang Y, Jia H, Lu J, et al. Water footprint and water consumption structure of peanut production in Yellow-Huaihe-Hai agricultural area[J]. Acta Agronomica Sinica, 2022, 48(12): 3203-3214.

[16] Ding X, Wu Q, Wen G, et al. Migration trajectory and spatial pattern of farmland non-point source pollution in Dongting Lake Plain from 2000 to 2020[J]. Transactions of the Chinese Society of Agricultural Engineering, 2021, 37(15): 258-266.

[17] Zhang P, Geng W, Yang D, et al. Spatiotemporal evolution of land use and ecosystem service value in the Lower Reaches of the Yellow River Region[J]. Transactions of the Chinese Society of Agricultural Engineering, 2020, 36(11): 277-288.

[18] Zhang G, Shao J, Wang J, et al. Spatial and temporal variations of agricultural non-point source pollution in the Three Gorges Reservoir area of Chongqing[J]. Journal of Natural Resources, 2015, 30(7): 1197-1209.

[19] Feng Q, Bi Z, Liu J. Spatial and temporal evolution of water footprint of main crops in Huaihe River Basin and analysis of influencing factors[J]. Journal of Water Resources & Water Engineering, 2022, 33(6): 213-219.

[20] Xue B, Dong S, Huang Y, et al. Spatiotemporal evolution of water footprint during the production of main grain crops in Liaoning Province from 1980 to 2016[J]. Chinese Journal of Ecology, 2019, 38(9): 2813-2820.

[21] Gao H, Li W, Li C, et al. Water footprints of main crops and their change in Ningxia[J]. Journal of Irrigation and Drainage, 2020, 39(3): 110-118.

[22] Jiang Q, Wu Y, Wang Z, et al. Spatiotemporal distribution and spatial equilibrium analysis of water footprint in Heilongjiang Province[J]. Water Resources Protection, 2022, 38(5): 122-131.

[23] Li X, Zhang Y, Shan Y. Sustainable utilization of water resources in Yulin City based on an emergy ecological footprint model[J]. Arid Zone Research, 2022, 39(4): 1066-1075.

[24] Zhang S. Dynamic Risk and Driving Force of Agricultural Drought in Shaanxi Province[D]. Xi'an: Xi'an University of Technology, 2023.

[25] Gao J, Wu P, Xie P, et al. Quantitative analysis of multi-spatial and temporal distribution of blue-green water resources and crop production water footprint in irrigated areas[J]. Transactions of the Chinese Society of Agricultural Engineering, 2021, 37(5): 105-112.

[26] Feng B, Liu X, Zhao Y, et al. Estimation of blue and green water footprint of crop production and analysis of its influencing factors in Shanxi Province[J]. Research of Soil and Water Conservation, 2018, 25(4): 200-205.

[27] Tian J, Dang X, Yang Z, et al. Analysis of water security risk of cash forest expansion in the Loess Plateau in terms of water footprint: A case study of apple planting[J]. Journal of Natural Resources, 2022, 37(10): 2750-2762.

[28] Ruttan V W. The transition to agricultural sustainability[J]. Proceedings of the National Academy of Sciences of the United States of America, 1999, 96(11): 5960-5967.

[29] Cao X, Zeng W, Wu M, et al. Water resources efficiency assessment in crop production from the perspective of water footprint[J]. Journal of Cleaner Production, 2021, 309: 127371.

Note: Figure translations are in progress. See original paper for figures.