

Article

Spatiotemporal Variations in the Agricultural Water Footprint and Its Socioeconomic Adaptability Across Ecological Function Zones in Xinjiang, China

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Abstract

Agricultural water footprint is an important indicator for assessing water-use efficiency and resource carrying capacity in agricultural systems, especially in arid regions. From the perspective of ecological function zones, this study examines the spatiotemporal dynamics of the agricultural water footprint in Xinjiang, China, and evaluates its adaptability to socioeconomic factors. The blue and green water footprints of crop production and the water footprint of animal products during 2000–2020 were quantified to estimate the total agricultural water footprint. The Gini coefficient and imbalance index were used to quantitatively evaluate the spatial adaptability between the agricultural water footprint and socioeconomic factors, including sown area, population, and agricultural Gross Domestic Product (GDP) across different ecological function zones. The results indicate that the agricultural water footprint increased from $2.54 \times 10^{10} \text{ m}^3$ to $5.85 \times 10^{10} \text{ m}^3$, with a clear spatial gradient characterized by higher values in southwestern Xinjiang and lower values in the northeastern region. Crop production accounted for more than 85% of the total footprint, with cotton as the dominant contributor, while beef consumption drove the growth in the animal product water footprint. The adaptability between the agricultural water footprint and sown area improved overall, whereas coordination with population distribution remained weak, and notable regional differences were observed in water footprint intensity relative to agricultural GDP. These findings indicate that the spatiotemporal differentiation of the agricultural water footprint is closely linked to resource endowments and development characteristics across ecological function zones, providing support for region-specific agricultural water management in arid areas.

Keywords: agricultural water footprint; ecological function zones; spatiotemporal variation; socioeconomic adaptability; Gini coefficient; imbalance index; Xinjiang

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1. Introduction

Water resources, as a fundamental element sustaining human survival, occupy a central position in regional development processes [1]. Since the twentieth century, rapid population growth has led to a substantial increase in water demand from socioeconomic

systems [2]. To further elucidate the extent to which human activities appropriate freshwater resources from natural capital, Hoekstra [3] pioneered the water footprint concept, providing a systematic and comprehensive approach to assess the sustainability of freshwater resource utilization in human production and consumption activities [4]. Within this framework, crop water use is classified into blue, green, and grey water footprints, encompassing both direct and indirect water consumption during crop growth [3]. Specifically, the blue water footprint quantifies the use of surface and groundwater resources for irrigation, whereas the green water footprint reflects the contribution of soil-stored precipitation available for crop evapotranspiration. In contrast, the grey water footprint measures the freshwater volume necessary to assimilate agricultural pollutants and ensure compliance with environmental water quality criteria [5,6].

In recent years, water footprint theory has been extensively expanded and widely applied. Numerous studies have investigated water footprints under diverse regional contexts. For example, the water footprints of typical crops in Xinjiang have been quantitatively estimated, and the influence of technological factors on water consumption has been examined [7]; strategies for improving the sustainable use of water footprints in Shandong Province have been proposed [8]; and the indirect impacts of food consumption structures on water resource use in Tunisia have been identified [9]. These studies have not only enriched the theoretical framework of water footprint analysis but have also provided practical insights for optimizing regional water resources management.

Efficient utilization and sustainable management of water resources have become core global concerns. Water footprint theory plays a critical role in evaluating regional water-use efficiency, revealing water flow characteristics, and informing water management policies [10–12], and has gradually been extended to integrated analyses of the water–energy–food nexus. Existing research indicates that energy production and food production often compete for limited water resources [13], while factors such as urbanization level, effective irrigated area, and industrial structure exert significant influences on the spatiotemporal dynamics of water footprints [14]. In particular, rapid urbanization has profoundly reshaped water supply–demand relationships [15], further confirming the applicability of water footprint and virtual water theories in assessing the sustainability of water use in regional food production systems [16]. Overall, substantial progress has been made in applying water footprint theory to issues of water resource management, security, and sustainability, providing a scientific basis for optimizing resource allocation [17,18]. However, existing studies on agricultural water footprints and their spatial distribution have primarily focused on conventional spatial scales such as global, national, and river basin levels [19–22]. Relatively few studies have incorporated local ecological functional planning into their analyses. Moreover, when socioeconomic factors are considered, insufficient attention has been paid to the synergistic interactions between natural ecosystem resource constraints and socioeconomic dynamics, which represent a critical bottleneck for achieving sustainable development of regional social–ecological systems [23,24].

Ecological function zoning integrates natural geography, climatic conditions, ecological environments, and socioeconomic factors to provide a comprehensive spatial framework for regional planning [25]. It plays an important role in optimizing natural resource allocation, clarifying ecosystem types and functions, and identifying key driving forces of regional differentiation [26]. Such zoning not only lays the foundation for formulating development strategies and ecological protection measures tailored to local characteristics, but also offers a novel spatial perspective for water resources management [27–28]. Over the past decade, both water supply and total water consumption in Xinjiang have exhibited a gradual upward trend [29], and water scarcity has become a critical limiting factor for socioeconomic development in the region [30]. Under China's 14th Five-Year Plan, Xinjiang has been delineated into four ecological function zones, which differ mark-

edly in resource endowments and ecosystem service functions, leading to substantial heterogeneity in water demand and utilization patterns.

In this context, this study systematically quantifies the agricultural water footprint of Xinjiang from 2000 to 2020 based on ecological function zoning, analyzes its spatiotemporal evolution, and evaluates the adaptability between the relationship between the agricultural water footprint and socioeconomic development was evaluated using Gini coefficient and imbalance index approaches, considering sown area, population, and agricultural Gross Domestic Product (GDP). This study aims to establish a theoretical and analytical foundation for improving the coordinated management and sustainable interaction between agricultural water resources and socioeconomic systems in arid regions, to expand the analytical perspective of water resource optimization and ecological function-based zonal management, and ultimately to offer decision-making references for improving water-use efficiency and promoting sustainable agricultural development in Xinjiang.

2. Materials and Methods

2.1. Study Area

Situated in northwestern China, Xinjiang covers approximately one-sixth of the country's total land area and represents the largest provincial-level administrative region [31], giving it considerable geographical and strategic significance. The region is characterized by complex topography, consisting of mountains, basins, and plateaus, and exhibits a typical continental arid climate, with cold and dry winters and hot summers with limited precipitation [32]. Annual precipitation in most areas is less than 200 mm, and water resources are scarce and unevenly distributed both spatially and temporally [33], posing substantial challenges for regional water resource development and management. To optimize resource allocation, Xinjiang was delineated into four ecological function zones under China's 14th Five-Year Plan based on ecological characteristics (Figure 1), providing a spatial framework for water resource utilization and ecological conservation.

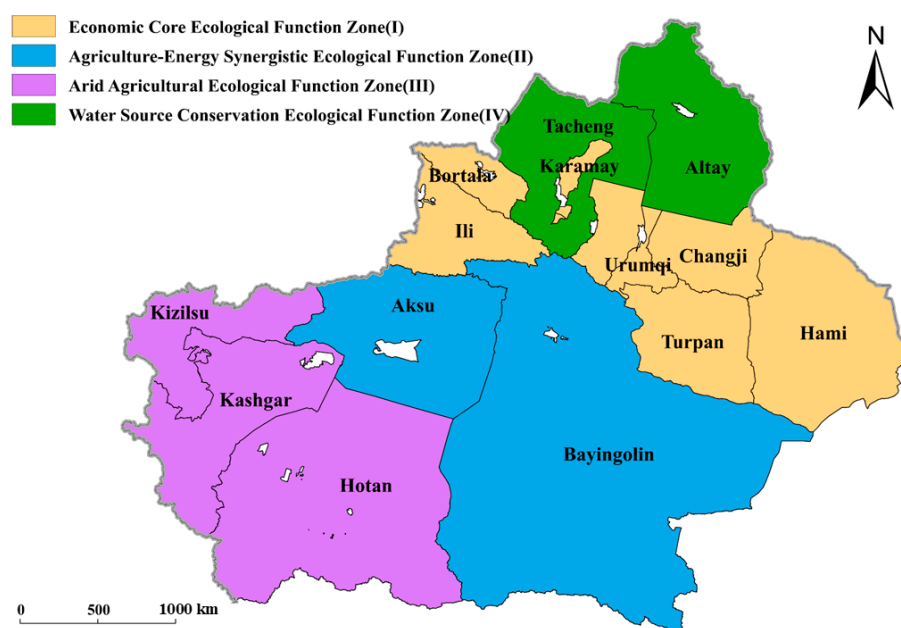


Figure 1. Geographical location and ecological function zoning map of Xinjiang Uygur Autonomous Region. (White areas represent jurisdictions administered by the Xinjiang Production and Construction Corps (XPCC). These areas were not included in the ecological functional zone classification)

because their agricultural statistics are reported as aggregated units and cannot be consistently disaggregated for zonal analysis).

2.2. Data Sources

Meteorological variables, including relative humidity, sunshine duration, wind speed, mean maximum temperature, mean minimum temperature, and precipitation, were obtained from the China Meteorological Administration (CMA) (<http://www.cma.gov.cn/>) (Accessed on 1 May 2025). These data were derived from 42 meteorological stations distributed across Xinjiang, ensuring full coverage of the four ecological functional zones. To minimize potential spatial bias arising from uneven station distribution, Thiessen polygon interpolation was applied to derive spatially representative climatic inputs for each prefecture and ecological functional zone prior to CropWat 8.0 modeling.

Agricultural production data, including crop sown area and yield, as well as socioeconomic variables such as population and agricultural GDP, were derived from the Xinjiang Uygur Autonomous Region Statistical Yearbook (2000–2020) (<https://tjj.xinjiang.gov.cn/>) (Accessed on 10 May 2025) and the Xinjiang Water Resources Bulletin (<https://slt.xinjiang.gov.cn/xjslt/>) (Accessed on 12 May 2025). These official statistical sources use standardized definitions and consistent accounting methods across years, ensuring the reliability and comparability of the dataset. Furthermore, since the adaptability assessment is based on proportional distributions and relative indices, such as the Gini coefficient and imbalance index, the analysis primarily reflects spatial relationships rather than absolute values, thereby ensuring temporal and spatial consistency throughout the study period.

2.3. Agricultural Water Footprint

2.3.1. Crop Water Footprint

Given that the grey water footprint reflects pollution-related dilution requirements rather than actual crop water consumption, this study considered only blue and green water footprints [34–35]. Crop water demand is influenced by climatic conditions, crop characteristics, soil properties, and crop growth duration. The CropWat 8.0 model, recommended by the Food and Agriculture Organization (FAO), was applied to quantify crop water requirements.

In CropWat 8.0, climatic, rainfall, and crop growth information are first input into the climate, rainfall, and crop modules. The crop water requirement (CWR) module then provides crop evapotranspiration (ET_c), calculated at 10-day intervals. In this study, when effective precipitation exceeded ET_c , crop water consumption was assumed to rely solely on rainfall, corresponding to green water. When effective precipitation was lower than ET_c , all effective precipitation was assumed to be fully consumed by crop growth.

(1) Blue Water Footprint

The blue water footprint (BWF) was calculated based on irrigation water consumption during crop growth [35–36] as follows:

$$BWF = W \times \eta \quad (1)$$

where W represents actual irrigation water use, and η denotes the effective utilization coefficient.

(2) Green Water Footprint

The green water footprint (GWF) was calculated using the CropWat 8.0 model as follows:

$$ET_g = \sum \min(ET_c, P_e) \quad (2)$$

$$GWF = 10A \times ET_g \quad (3)$$

where ET_g (mm) represents green water evapotranspiration calculated at 10-day intervals during the growing period; ET_c (mm) denotes crop evapotranspiration over each 10-day period; P_e (mm) is effective precipitation over each 10-day period; A is the crop sown area; and the factor 10 represents the unit conversion from water depth (mm) to water volume (m^3).

2.3.2. Animal Water Footprint

The animal water footprint (WF_{ani}) is influenced by multiple factors, including animal species, breeding practices, and production regions, making direct calculation complex [37]. Therefore, this study adopted the reference values reported by Hoekstra and Chapagain [38] (Table 1), this approach ensures methodological consistency and comparability across ecological functional zones and over time. The animal water footprint was calculated as follows:

$$WF_{ani} = UWF_n \times Y \quad (4)$$

where n refers to the animal product category, UWF represents the virtual water content per kilogram of animal product (m^3/kg), and Y denotes the total production quantity of the corresponding product (kg).

Table 1. The unit water footprint content of main animal products.

Animal Products	Beef	Mutton	Pork	Poultry and Rabbit Meat	Equine Meat	Aquatic Products
UWF (m^3/kg)	12.56	5.20	2.21	3.12	5.67	5.00

2.4. Evaluation of the Adaptability Between the Agricultural Water Footprint and Socioeconomic

2.4.1. Gini Coefficient Between the Agricultural Water Footprint and Socioeconomic Factors

The Gini coefficient, developed by Corrado Gini in 1912 based on the Lorenz curve framework [39], provides a quantitative measure of spatial inequality. In this study, it was used to evaluate the degree of spatial correspondence between the agricultural water footprint and socioeconomic indicators, thereby identifying regional imbalances in the distribution of water use relative to socioeconomic factors. The calculation is expressed as follows:

$$Gini = \sum_{i=1}^n X_i Y_i + 2 \sum_{i=1}^n X_i (1 - V_i) - 1 \quad (5)$$

where n denotes the number of ecological function zones (or prefecture-level administrative units); X represents the proportional share of socioeconomic factors (sown area, population, and agricultural GDP); Y denotes the proportional share of the water footprint in ecological function zone (or prefecture) i ; and V represents the cumulative percentage of the water footprint across ecological function zones (or prefectures) [35].

2.4.2. Imbalance Index Between the Agricultural Water Footprint and Socioeconomic Factors

The Gini coefficient reflects the overall level of spatial alignment between the agricultural water footprint and socioeconomic indicators. To further characterize the imbalance status of individual ecological function zones in Xinjiang, an imbalance index between the agricultural water footprint and socioeconomic factors was introduced. The calculation is expressed as follows:

$$I_i = \frac{Y_i}{X_i} \quad (6)$$

where I_i represents the imbalance index of ecological function zone i . When $I_i > 1$, it indicates that the agricultural water footprint per unit of sown area (per capita or per unit of agricultural GDP) is higher than the Xinjiang average; when $I_i < 1$, the corresponding water footprint is lower than the regional average. Values of I_i closer to 1 indicate a higher level of adaptability between the agricultural water footprint and socioeconomic factors.

3. Results

3.1. Dynamic Changes in the Agricultural Water Footprint

Between 2000 and 2020, the agricultural water footprint (AWF) in Xinjiang increased from $2.54 \times 10^{10} \text{ m}^3$ to $5.85 \times 10^{10} \text{ m}^3$, reflecting a sustained intensification of agricultural water use (Figure 2). Crop production consistently dominated total AWF, accounting for more than 85% of the total throughout the study period. The crop water footprint rose to $4.97 \times 10^{10} \text{ m}^3$ in 2020, largely driven by the expansion of sown area, which nearly doubled over the same period. Meanwhile, the animal water footprint increased by 62%, indicating a growing contribution of livestock development and dietary transitions to agricultural water demand.

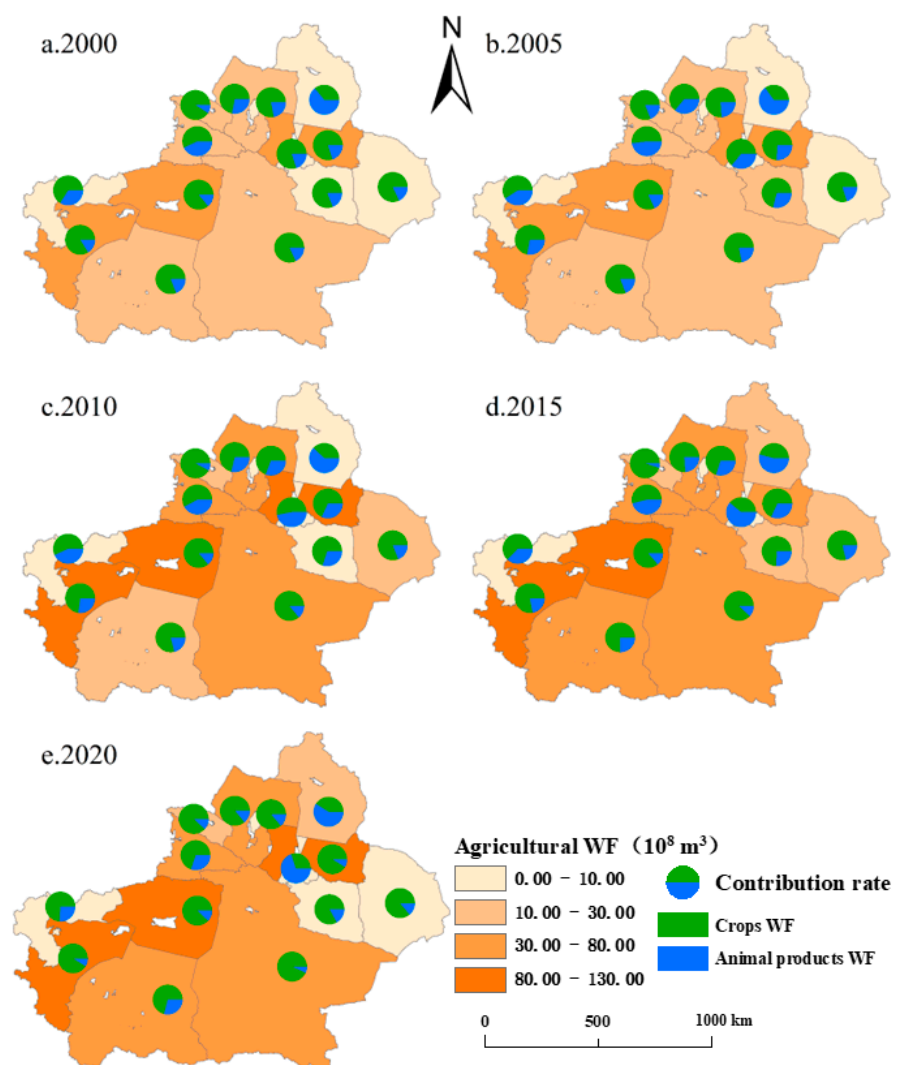


Figure 2. The agricultural water footprint in Xinjiang Uygur Autonomous Region, including 2000 (a), 2005 (b), 2010 (c), 2015 (d), 2020 (e).

A pronounced spatial gradient was observed, with higher values concentrated in southwestern Xinjiang and comparatively lower levels observed in the northeastern region. By 2020, Aksu Prefecture recorded the highest AWF ($1.22 \times 10^{10} \text{ m}^3$), whereas Karamay City exhibited the lowest ($2.00 \times 10^8 \text{ m}^3$). When examined from the perspective of ecological functional zoning, distinct differentiation emerges.

The agriculture–energy synergy zone (Zone II) and the arid agricultural zone (Zone III) represent the core irrigated production areas of Xinjiang. These zones are characterized by large-scale cultivation, a high proportion of water-intensive crops (particularly cotton), and strong dependence on irrigation infrastructure, which collectively result in elevated agricultural water consumption. In contrast, the economic core zone (Zone I) is subject to urban–industrial water competition and land-use constraints, leading to relatively limited agricultural expansion and a gradual shift toward more intensive, high-value agricultural systems. The water conservation zone (Zone IV), primarily oriented toward ecological protection and pastoral development, possesses limited cropland and lower irrigation intensity, resulting in a comparatively smaller agricultural water footprint.

Therefore, the spatial distribution of AWF is not solely determined by agricultural scale, but is structurally shaped by the differentiated functional roles, resource constraints, and development orientations embedded within the ecological functional zoning system.

3.2. Spatiotemporal Variations in the Crop WF

3.2.1. Composition of the Crop WF

During 2000–2020, the overall structure of the crop water footprint (CWF) in Xinjiang remained largely stable, with no substantial shifts in its composition, with cotton consistently representing the dominant component. The water footprint of cotton increased substantially from $9.69 \times 10^9 \text{ m}^3$ to $2.73 \times 10^{10} \text{ m}^3$, and its contribution rose from 49% to 55% (Figure 3), reinforcing its central role in regional agricultural water use. This trend reflects the continued expansion of cotton cultivation, driven by its economic importance and its strategic role in supporting Xinjiang’s agricultural economy. In contrast, potatoes accounted for the smallest share of CWF throughout the study period, declining from 0.76% to 0.33%, primarily due to their relatively limited cultivation scale and lower production priority.

At the prefectural level, CWF increased in nearly all regions except Urumqi and Turpan, reflecting the overall expansion of agricultural production across Xinjiang (Figure 4). The spatial center of gravity of the CWF shifted gradually from Kashgar Prefecture in southern Xinjiang ($4.34 \times 10^9 \text{ m}^3$) to Aksu Prefecture ($1.07 \times 10^{10} \text{ m}^3$), indicating the increasing concentration of irrigated crop production in this region. Prefectures such as Aksu, Bayingolin, and Kashgar exhibited persistently high CWF values due to their extensive cropland areas and intensive irrigation systems, whereas cities such as Urumqi and Karamay showed relatively low CWF levels due to limited agricultural land and greater influence of urban development and industrial activities.

These spatial patterns are closely associated with the functional roles and resource constraints of ecological functional zones. The agriculture–energy synergy zone (Zone II), which includes major cotton-producing areas such as Aksu and Bayingolin, exhibited the highest cotton dominance, with its share increasing from 58% to 66%. This reflects the zone’s role as a key agricultural production base supported by irrigation infrastructure, favorable climatic conditions, and strong policy support for cotton cultivation. Similarly, the arid agricultural zone (Zone III), including Kashgar, maintained a high CWF due to its large agricultural scale and importance in regional food and cotton production. However, the share of cotton declined slightly from 44% to 40%, primarily due to the rapid

expansion of orchards, which reflects crop diversification in response to market demand and regional agricultural restructuring.

In contrast, the economic core zone (Zone I), which includes highly urbanized areas such as Urumqi and Karamay, experienced a notable increase in cotton share from 49% to 60%, despite relatively limited cropland availability. This reflects a transition toward more efficient and economically valuable agricultural production under land and water resource constraints. Meanwhile, the water conservation zone (Zone IV), characterized by ecological protection priorities and pastoral land use, showed the lowest overall CWF, contributing only 10% of the regional total in 2020. The increase in cotton share from 32% to 45% in this zone reflects localized agricultural adjustments, although overall agricultural intensity remained relatively low due to ecological conservation objectives and limited cropland expansion.

Overall, the spatiotemporal variation in crop water footprint reflects both prefectural-level differences in agricultural production intensity and the structural influence of ecological functional zoning, which defines regional agricultural roles, resource availability, and development pathways.

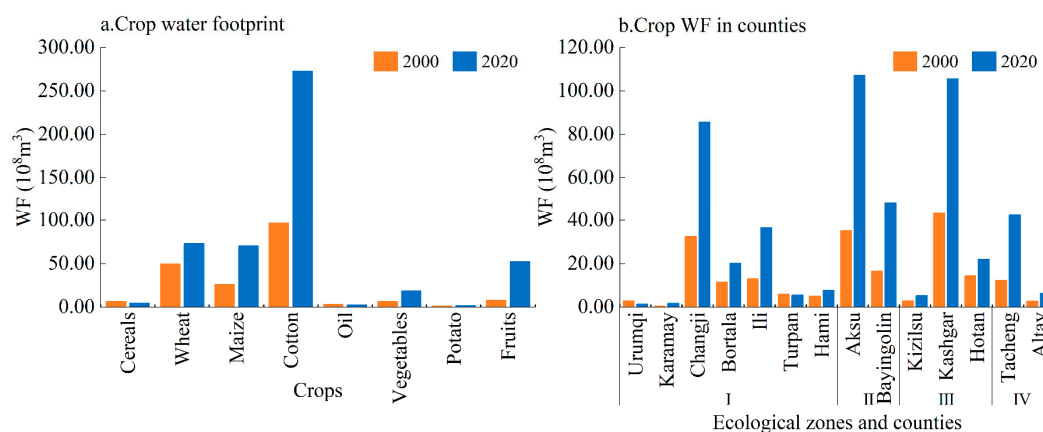


Figure 3. Crop water footprint in Xinjiang Uygur Autonomous Region, including Crop water footprint 2000 and 2020 (a), Crop water footprint in counties 2000 and 2020 (b).

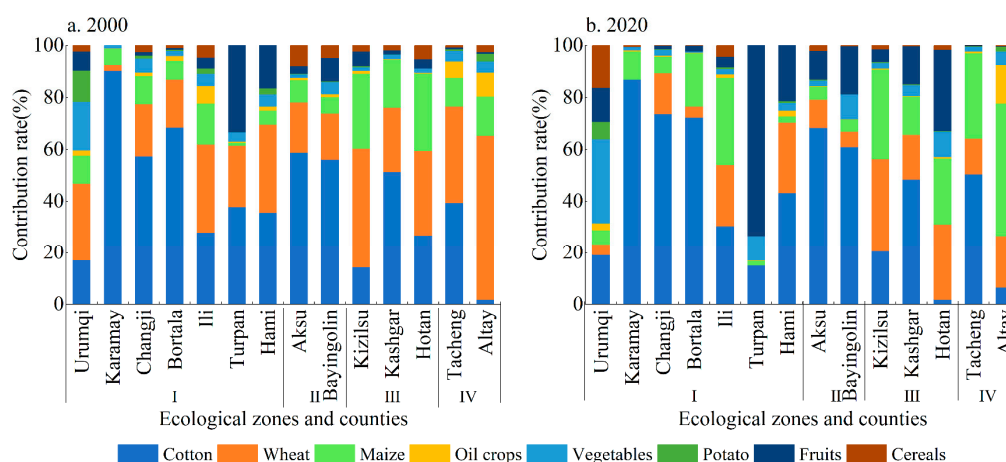


Figure 4. The contribution rate of crop water footprint in Xinjiang Uygur Autonomous Region, including 2000 (a), 2020 (b).

3.2.2. Blue and Green Water Footprints

From 2000 to 2020, the blue water footprint consistently accounted for the dominant share of agricultural water use in Xinjiang, increasing slightly from 86% to 88% of the total crop WF, whereas the share of the green water footprint decreased from 14% to 12% (Figure 5). This pattern reflects the structural dependence of agricultural production on irrigation under the region's arid climatic conditions and limited effective precipitation.

At the prefectural scale, blue water dominated agricultural water use in most regions, although substantial spatial variation existed. In 2000, the blue water proportion exceeded 90% in Turpan (99%), Hami (96%), Bayingolin (95%), and Tacheng (95%), indicating extremely high irrigation dependence. By contrast, Ili (60%) and Altay (76%) exhibited relatively higher green water contributions, reflecting greater utilization of precipitation. A similar spatial pattern was observed in 2020. Turpan remained almost entirely dependent on irrigation, with blue water accounting for 100% of total agricultural water use, while Hami (98%), Bayingolin (96%), and Aksu (92%) also maintained high irrigation dependence. Meanwhile, Ili continued to exhibit the highest green water proportion (56%), followed by Altay (19%) and Tacheng (15%), highlighting regional differences in precipitation availability, cropping systems, and agricultural intensity.

These prefectural-scale differences correspond closely with ecological functional zoning and regional resource constraints. The agriculture–energy synergy zone (Zone II), including major agricultural areas such as Aksu and Bayingolin, exhibited persistently high blue water proportions due to extensive irrigated cotton production and limited precipitation. Similarly, the arid agricultural zone (Zone III), which includes Kashgar and surrounding regions, also showed strong irrigation dependence, reflecting its role as a major agricultural production base under severe climatic water limitations.

In contrast, the economic core zone (Zone I), which includes Urumqi and surrounding areas, exhibited relatively higher green water proportions in some locations, reflecting more diversified agricultural systems and localized precipitation advantages. However, agricultural production in this zone remains constrained by urban expansion and competition for water resources. The water conservation zone (Zone IV), primarily oriented toward ecological protection and pastoral activities, exhibited relatively low green water utilization overall due to limited cropland and low precipitation, although localized variation exists depending on natural conditions and land use.

Overall, the spatial distribution of blue and green water footprints reflects both prefectural-level differences in climatic conditions and agricultural intensity, as well as the structural influence of ecological functional zoning, which defines regional agricultural roles, water resource constraints, and patterns of irrigation dependence.

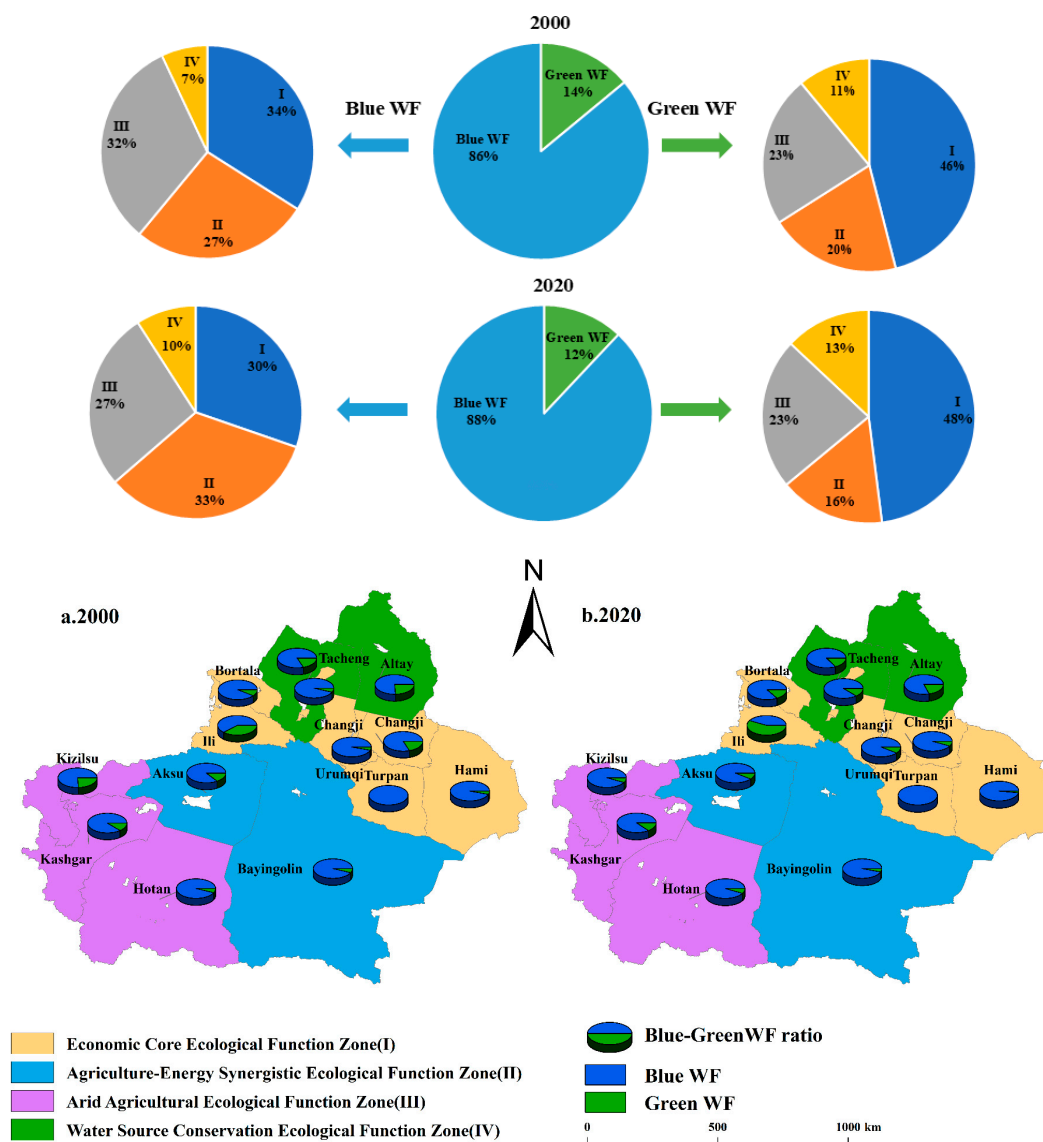


Figure 5. Share of crops' blue and green water footprint, including 2000 (a), 2020 (b).

3.3. Spatiotemporal Variations in the Animal Products' Water Footprint

From 2000 to 2020, the animal product water footprint in Xinjiang increased significantly from $5.44 \times 10^9 \text{ m}^3$ to $8.83 \times 10^9 \text{ m}^3$ (Figure 6), reflecting the overall expansion of livestock production and increasing demand for animal-derived food. Among all animal products, beef consistently accounted for the largest share, with its water footprint increasing from $2.64 \times 10^9 \text{ m}^3$ to $4.65 \times 10^9 \text{ m}^3$, and its proportion rising from 48% to 53%. This reflects both the relatively high water intensity of beef production and its growing importance in regional dietary structure. In contrast, the water footprint of equine meat increased from $1.97 \times 10^8 \text{ m}^3$ to $3.85 \times 10^8 \text{ m}^3$, but its overall contribution remained relatively low, accounting for less than 5% throughout the study period.

At the prefectural scale, the animal water footprint increased in most regions, although the magnitude of growth varied considerably. Turpan exhibited the highest animal water footprint, increasing from $9.70 \times 10^8 \text{ m}^3$ to $1.59 \times 10^9 \text{ m}^3$, reflecting its relatively intensive livestock production and agricultural activity. In contrast, Karamay recorded the lowest value, reaching only $2.8 \times 10^7 \text{ m}^3$ in 2020, due to limited livestock production and strong constraints from urban land use and industrial development. Most other prefec-

tures, including Kashgar, Aksu, and Bayingolin, also exhibited increasing trends, reflecting the gradual expansion of livestock production across Xinjiang.

These spatial differences correspond closely with ecological functional zoning and regional livestock production systems. The water conservation zone (Zone IV), which is characterized by extensive grassland resources and pastoral production systems, exhibited a notable increase in poultry and rabbit water footprints, with their share rising from 2% to 17% (Figure 7). This reflects adaptive adjustments in livestock structure under ecological protection constraints and the utilization of natural grazing resources.

Similarly, the arid agricultural zone (Zone III), which includes traditional pastoral and mixed farming regions such as Kashgar, exhibited increases across all animal categories. However, the share of mutton declined from 50% to 34%, reflecting gradual diversification of livestock production and shifts toward more varied animal product systems under changing economic and livelihood conditions.

In contrast, the agriculture–energy synergy zone (Zone II), which prioritizes irrigated crop production, exhibited relatively lower livestock water footprint shares, with pork and poultry–rabbit proportions declining to below 1% by 2020. This reflects land and water resource allocation favoring irrigated crop production rather than livestock expansion. Meanwhile, the economic core zone (Zone I), characterized by urban dominance and limited grazing land, exhibited declining shares of pork and poultry–rabbit water footprints, falling below 5% by 2020. However, equine meat maintained a relatively stable proportion of 5–8%, reflecting localized livestock production adapted to regional resource constraints.

Overall, the spatiotemporal variation in animal product water footprint reflects both prefectural-level differences in livestock production scale and the structural influence of ecological functional zoning, which defines regional livestock production patterns, resource availability, and agricultural development priorities.

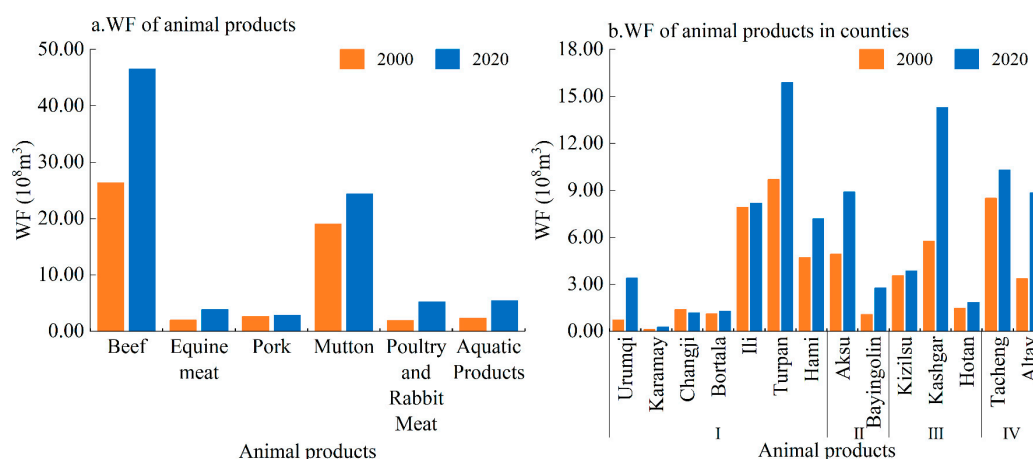


Figure 6. The water footprint of animal products in Xinjiang Uygur Autonomous Region, including the WF of animal products 2000 and 2020 (a), the WF of animal products in counties 2000 and 2020 (b).

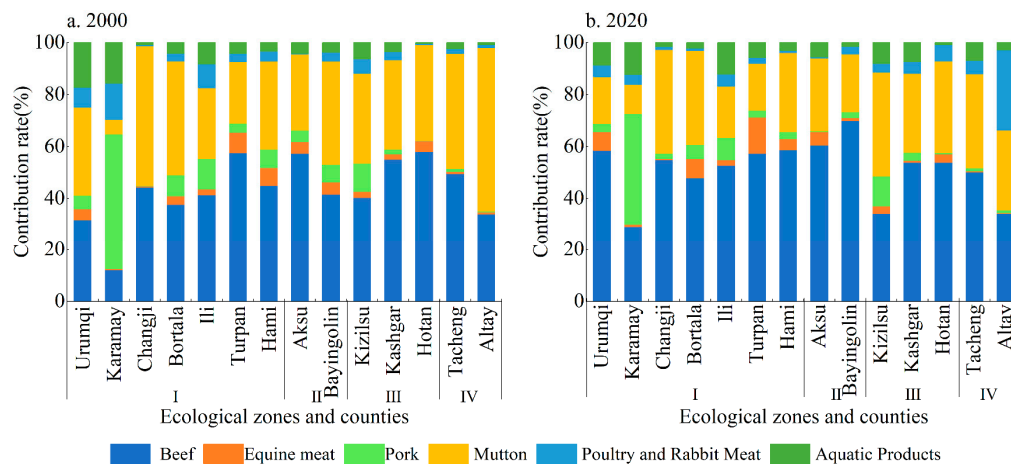


Figure 7. The contribution rate of animal products WF in Xinjiang Uygur Autonomous Region, including 2000 (a), 2020 (b).

3.4. Adaptability Between the AWF and Socioeconomic Factors

3.4.1. Gini Coefficients Between the AWF and Socioeconomic Factors

(1) AWF and Sown Area

As shown in Figure 8a,b, the spatial adaptability between the agricultural water footprint and sown area in Xinjiang improved markedly during 2000–2020. The Gini coefficient of the crop water footprint declined from 0.40 to 0.31, indicating a transition from a relatively uneven to a more balanced spatial distribution. This trend reflects a gradual improvement in the spatial coordination between agricultural water use and cultivated land expansion, suggesting enhanced efficiency in regional water resource allocation.

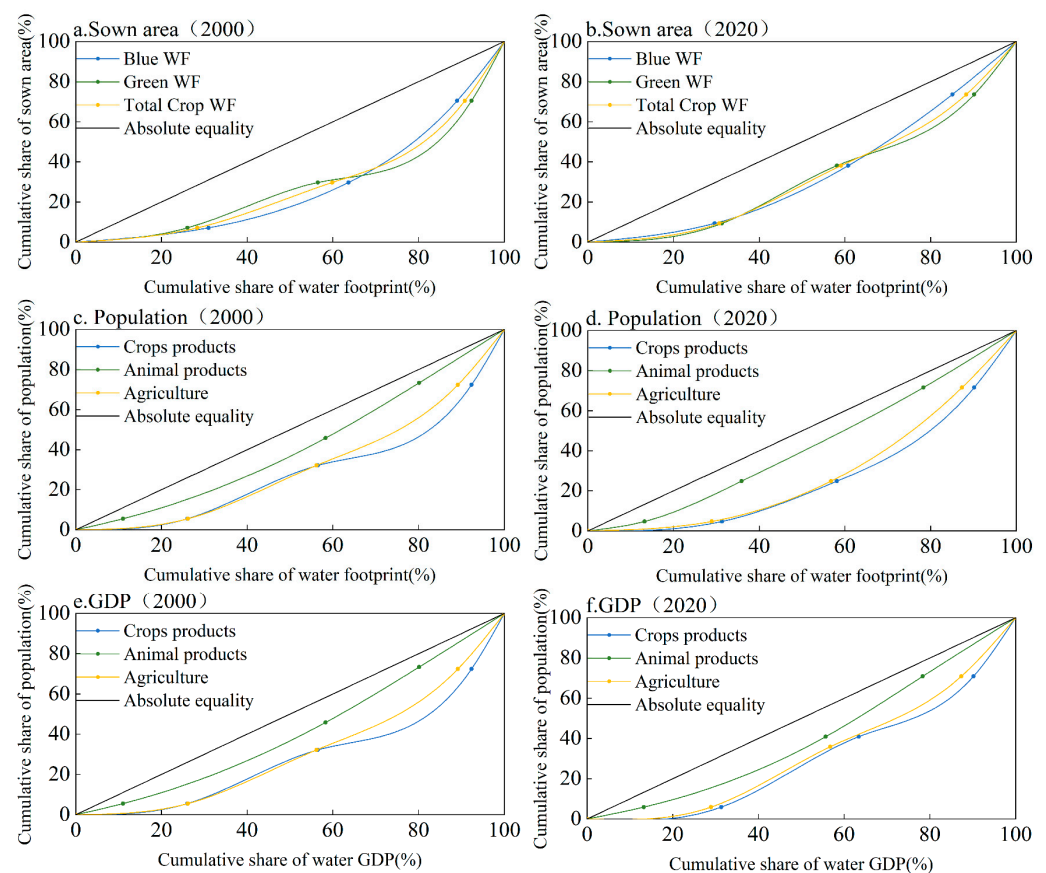


Figure 8. Lorentz curve of water footprint and socioeconomic in Xinjiang Uygur Autonomous Region, including relationships with sown area (a,b), population (c,d), and agricultural GDP (e,f).

The improvement was more pronounced for blue water. Specifically, the Gini coefficient between the blue water footprint and sown area declined from 0.40 to 0.34, suggesting that the spatial distribution of irrigation water became increasingly consistent with cropping patterns. This pattern was especially pronounced in the agricultural energy synergy zone (Ecological Zone II) and the arid agricultural zone (Ecological Zone III), where large-scale irrigated agriculture dominates regional production. In these zones, continued investment in irrigation infrastructure, implementation of water-saving technologies such as drip irrigation, and improvements in water management systems contributed to enhanced coordination between irrigation supply and agricultural expansion.

In contrast, the spatial distribution of the green water footprint remained relatively stable. Its Gini coefficient declined slightly from 0.27 to 0.23 and remained within the relatively balanced range throughout the study period. This stability reflects the strong dependence of green water availability on climatic conditions, which vary relatively little in spatial structure over time. In the water conservation zone (Ecological Zone IV), ecological protection priorities and limited cropland extent constrained large-scale changes in green water utilization. Similarly, in the economic core zone (Ecological Zone I), urbanization and competition with industrial water use limited agricultural expansion, resulting in relatively stable rainfed water-use patterns.

Despite overall improvements, the Gini coefficient of blue water remained consistently higher than that of green water, indicating persistent spatial inequality in irrigation water allocation. This reflects the concentration of irrigation-dependent agricultural production in Zones II and III, where intensive cotton and grain cultivation requires substantial irrigation inputs. These results highlight the importance of functional zoning in shaping the spatial allocation of agricultural water resources and underscore the need for differentiated water management strategies to improve irrigation efficiency while maintaining regional agricultural productivity.

(2) AWF and Population

The spatial adaptability between the agricultural water footprint and population distribution exhibited a slight weakening trend from 2000 to 2020 (Figure 8c,d). The Gini coefficient of the total AWF increased marginally from 0.38 to 0.39, remaining within the relatively balanced range but indicating a modest decline in spatial coordination between agricultural water use and population distribution.

The Gini coefficient between crop WF and population rose from 0.41 to 0.43, reflecting a growing spatial separation between major agricultural production areas and population centers. This pattern is closely related to the functional positioning of the agricultural energy synergy zone (Ecological Zone II) and the arid agricultural zone (Ecological Zone III), which serve as the primary agricultural production bases of Xinjiang. These regions prioritize large-scale cultivation of water-intensive crops such as cotton and grain under national and regional agricultural policies, despite relatively low population densities.

By contrast, the spatial adaptability between animal water footprint and population remained relatively high. Although its Gini coefficient increased slightly from 0.11 to 0.15, it remained within the highly balanced range. This reflects the closer spatial linkage between livestock production and consumption demand, particularly in the economic core zone (Ecological Zone I), where livestock production supports urban markets and population centers.

These patterns demonstrate that ecological functional zoning significantly influences the spatial relationship between agricultural water use and population distribution. While

agricultural production zones are primarily organized based on resource availability and production suitability, livestock production exhibits stronger alignment with population demand. This functional differentiation contributes to the observed spatial mismatch between crop water use and population distribution while maintaining relatively balanced livestock water use patterns.

(3) AWF and Agricultural GDP

As illustrated in Figure 8e,f, the spatial adaptability between AWF and agricultural GDP improved slightly during the study period. The overall Gini coefficient declined from 0.34 to 0.32, indicating improved coordination between agricultural water use and economic output.

However, structural differences were evident between crop and animal production systems. The Gini coefficient between crop WF and agricultural GDP increased from 0.30 to 0.36, which indicates relatively lower economic returns per unit of water in crop production. This pattern was particularly evident in the agricultural energy synergy zone (Ecological Zone II) and the arid agricultural zone (Ecological Zone III), where agricultural production is dominated by large-scale cultivation of water-intensive crops such as cotton. Although these regions contribute significantly to total agricultural output, the economic value generated per unit of water remains relatively limited due to the resource-intensive nature of bulk crop production.

In contrast, the animal water footprint exhibited a higher degree of spatial alignment with agricultural GDP. Its Gini coefficient increased slightly from 0.15 to 0.17 but remained within the highly balanced range. This reflects the higher economic value and stronger market integration of livestock production, particularly in the water conservation zone (Ecological Zone IV), where ecological livestock systems contribute to local economic development under ecological protection constraints.

Meanwhile, the economic core zone (Ecological Zone I) exhibited relatively higher water-use efficiency due to its transition toward high-value and technology-intensive agricultural systems, including facility agriculture and specialized crop production. These structural transformations improved the economic efficiency of agricultural water use.

Overall, these results demonstrate that the spatial relationship between agricultural water use and economic output is strongly influenced by ecological functional zoning, agricultural structure, and regional development priorities. Improving agricultural water-use efficiency requires region-specific strategies that account for functional roles, resource constraints, and economic development pathways.

3.4.2. Imbalance Index Between the AWF and Socioeconomic Factors

(1) AWF and Sown Area

As shown in Figure 9a, significant spatial differences existed between the agricultural water footprint and sown area across ecological function zones in Xinjiang during 2000–2020. The imbalance indices for the blue WF in Ecological Zones I and IV remained persistently below 1, indicating relatively lower irrigation water consumption per unit of sown area compared with the regional average. This suggests a relatively water-saving pattern of irrigation water allocation, with Ecological Zone I exhibiting a particularly stable imbalance index over time, reflecting sustained regulation capacity in irrigation water management. In contrast, the imbalance index of Ecological Zone II remained consistently above 1, indicating substantially higher irrigation water consumption per unit of sown area than the Xinjiang average, which is consistent with its role as a core irrigated agricultural zone with strong dependence on artificial irrigation.

The spatial imbalance of the green water footprint was more pronounced (Figure 9b). In 2000, only Ecological Zone IV exhibited an imbalance index below 1, while by 2020, the

indices of Ecological Zones I and II remained persistently above the regional average. This indicates a relatively high intensity of green water use per unit of sown area in these zones. Such patterns are closely associated with regional cropping structures and water-use practices. Ecological Zones I and II are dominated by water-intensive crops and frequently rely on supplemental irrigation, leading to localized concentration of green water use. In contrast, Ecological Zone IV, characterized by a livestock-oriented production system and limited cropland area, exhibited relatively low pressure on green water resources.

Overall, blue water allocation showed a tendency toward improved interregional coordination, whereas green water use remained characterized by notable spatial concentration and efficiency gaps. These results indicate the necessity of differentiated water allocation strategies that account for regional resource conditions and cropping characteristics, with enhanced regulation of irrigation water in high-consumption areas and improved efficiency of precipitation utilization in rainfed agricultural systems.

(2) AWF and Population

As presented in Figure 9c, the per capita AWF imbalance index exhibited clear spatial differentiation among ecological function zones during the study period. Ecological Zones II and III consistently showed imbalance indices above 1, indicating higher per capita agricultural water consumption relative to the regional average. This reflects sustained agricultural production intensity under water resource constraints. In contrast, the imbalance indices of Ecological Zones I and IV generally remained below 1, indicating a relatively higher degree of alignment between population distribution and agricultural water use. In Ecological Zone I, this pattern is associated with a transition toward more efficient and intensive agricultural systems, while in Ecological Zone IV it is constrained by limited agricultural scale and its ecological functional orientation.

From a temporal perspective, the imbalance indices of Ecological Zones II and IV showed an increasing trend, indicating that the growth rate of agricultural water footprint outpaced population growth. This pattern may be associated with continued expansion of agricultural production, water-intensive cropping structures, and relatively slow population growth. In contrast, the imbalance indices of Ecological Zones I and III declined over time, suggesting a gradual alleviation of pressure between agricultural water use and population. In Ecological Zone I, this trend is primarily associated with water-saving practices and structural upgrading of agriculture, while in Ecological Zone III it may be linked to population growth, technological progress, and partial adjustments in cropping structure.

Overall, the spatial relationship between agricultural water footprint and population distribution in Xinjiang remains uneven, reflecting the combined effects of resource endowments, development trajectories, and demographic dynamics across ecological function zones.

(3) AWF and Agricultural GDP

As shown in Figure 9d, significant differences were observed in the imbalance index of agricultural water footprint per unit of agricultural GDP across ecological function zones in Xinjiang during 2000–2020. The imbalance index of Ecological Zone II consistently exceeded 1, indicating that agricultural water consumption per unit of economic output in this zone remained higher than the regional average. This pattern corresponds to its irrigation-intensive agricultural structure and the allocation of water resources within agriculture–energy coupled systems. In contrast, the imbalance indices of Ecological Zones I and IV consistently remained below 1, indicating relatively high economic conversion efficiency of agricultural water use. In Ecological Zone I, this is associated with technology- and capital-intensive high value-added agriculture, whereas in Ecological

Zone IV it reflects limited agricultural scale and a gradual shift toward specialized and quality-oriented livestock production.

The imbalance index of Ecological Zone III exhibited a declining trend, indicating a gradual improvement in the economic efficiency of agricultural water use under severe water resource constraints. This improvement is associated with structural adjustment and the diffusion of water-saving technologies.

These spatial differences indicate that variations in the economic efficiency of agricultural water use are shaped not only by water availability, but also by differences in functional positioning, industrial structure, and policy regulation across ecological function zones. The results suggest that further improvements in the economic efficiency of agricultural water use require integrated, zone-specific management approaches aligned with regional development objectives.

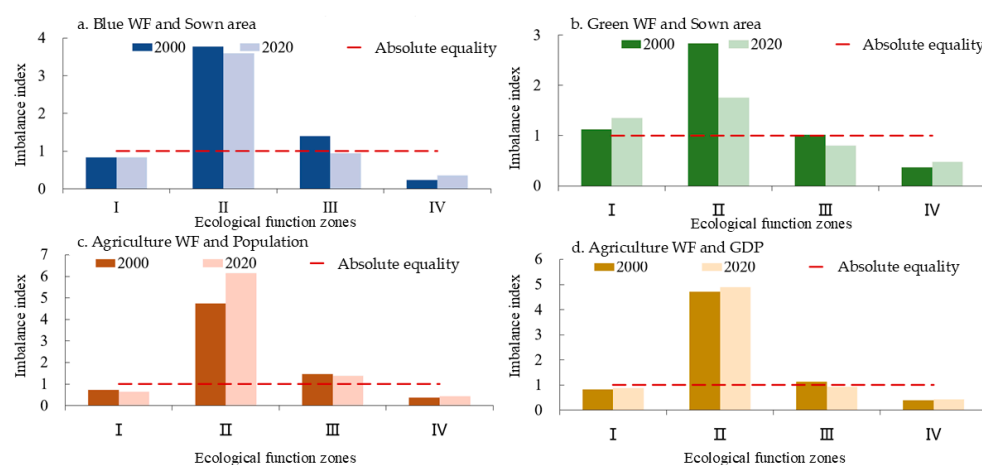


Figure 9. The imbalance index of agricultural water footprint relative to socioeconomic factors across ecological functional zones in Xinjiang Uygur Autonomous Region in 2000 and 2020, including relationships with sown area (a,b), population (c), and agricultural GDP (d).

4. Discussion

4.1. AWF and Sustainable Development

The AWF in Xinjiang increased substantially from $2.54 \times 10^{10} \text{ m}^3$ in 2000 to $5.85 \times 10^{10} \text{ m}^3$ in 2020, reflecting a sustained intensification of agricultural water demand [40–43]. This trend is consistent with previous studies conducted in Xinjiang, which reported a continuous increase in agricultural water consumption driven primarily by crop production, particularly cotton cultivation [44–45]. Cotton remained the dominant contributor in this study, with its water footprint increasing from $9.69 \times 10^9 \text{ m}^3$ to $2.73 \times 10^{10} \text{ m}^3$, accounting for more than half of the total crop water footprint. Similar findings have been widely reported in arid agricultural systems, where irrigation-dependent cash crops significantly intensify blue water consumption [46]. These consistencies with previous research further confirm the reliability and representativeness of the results obtained in this study.

From a sustainability perspective, the observed increase in AWF reflects the long-term interaction between agricultural expansion and water resource constraints under the ecological functional zoning framework. Ecological Zones II and III, which serve as major agricultural production bases, have experienced sustained expansion of irrigated cotton cultivation due to their strategic roles in ensuring cotton supply and supporting regional economic development. These zones rely heavily on irrigation and exhibit high blue water dependence, indicating elevated vulnerability to water scarcity. In contrast, Ecological Zone I, functioning as the regional economic core, faces intensified competition for water resources from urban and industrial sectors, which has constrained agricultural expansion

and promoted a gradual transition toward higher-value and more water-efficient agricultural systems. Ecological Zone IV, primarily designated for ecological conservation and pastoral development, maintains relatively limited cropland area and lower irrigation intensity, resulting in comparatively lower water consumption and greater long-term sustainability potential.

Spatially, the pronounced gradient of higher AWF in southwestern Xinjiang and lower values in northeastern regions reflects the combined influence of natural resource endowment, functional positioning, and policy orientation. Prefectures such as Aksu, located within the agriculture–energy synergy zone, exhibit persistently high water consumption due to extensive irrigated agriculture and policy-supported crop specialization. Conversely, economically developed urban regions such as Karamay have shifted toward less water-intensive agricultural structures in response to competing water demands and structural economic transformation. These spatial differences highlight that agricultural water use patterns are shaped not only by climatic and hydrological conditions but also by region-specific development priorities and governance frameworks.

Policy mechanisms have played a critical role in shaping the spatiotemporal evolution of agricultural water use. Cotton subsidy programs have reinforced regional specialization in cotton production, particularly in southern Xinjiang, contributing to concentrated irrigation demand and increased blue water consumption. Meanwhile, irrigation water pricing reforms and water management policies have promoted the adoption of water-saving technologies, such as drip irrigation, which have improved irrigation efficiency and moderated water use intensity in some areas. However, the effectiveness of these measures varies across ecological functional zones due to differences in infrastructure conditions, economic capacity, and institutional implementation.

From a water sustainability perspective, achieving long-term balance between agricultural production and water resource availability requires integrating ecological functional zoning into water governance. Practical implementation should include optimizing crop structure according to regional water availability, improving irrigation efficiency through technological upgrading, strengthening water rights allocation and quota management systems, and promoting region-specific agricultural development strategies aligned with ecological functions. Such spatially differentiated management approaches can help reconcile agricultural production demands with water resource constraints and enhance the resilience of agricultural water systems under increasing environmental and socioeconomic pressures.

Nevertheless, several barriers may hinder the effective implementation of these sustainability-oriented strategies. Financial constraints may limit farmers' capacity to invest in water-saving technologies, particularly in less economically developed regions. Institutional fragmentation and coordination challenges across administrative and functional boundaries may reduce the efficiency of water resource governance. Additionally, entrenched cropping practices and market-driven incentives may perpetuate water-intensive agricultural patterns. Addressing these barriers requires coordinated policy support, improved institutional integration, targeted financial incentives, and strengthened technology extension programs. By aligning economic incentives with water conservation objectives, ecological functional zoning can provide a critical framework for promoting sustainable agricultural water use and enhancing long-term water security in arid regions.

4.2. Compatibility Between Agricultural Water Footprint and Socioeconomic Factors

The spatial relationship between AWF and socioeconomic factors exhibited clear differentiation across ecological functional zones. The improved compatibility between AWF and sown area indicates that irrigation infrastructure expansion and agricultural development have become increasingly aligned spatially. This improvement is particularly ev-

ident in Ecological Zones II and III, where irrigation investments and agricultural expansion have enhanced the coordination between water use and land resources.

In contrast, the weaker spatial compatibility between AWF and population reflects the functional specialization of agricultural production regions. Major agricultural production zones generally have lower population densities, resulting in spatial separation between agricultural water consumption and population centers. Meanwhile, livestock production showed stronger alignment with population distribution, reflecting its closer relationship with local consumption and market access.

The relationship between AWF and agricultural GDP also reflects structural differences in regional development. Ecological Zones II and III, dominated by bulk agricultural production, exhibit relatively high water consumption but lower economic output per unit of water, indicating lower water-use efficiency. In contrast, Ecological Zone I has achieved higher economic returns per unit of water due to its transition toward higher-value agricultural production. Ecological Zone IV has also shown improved economic efficiency through the development of ecological livestock production.

Socioeconomic transformation has further influenced the structure and spatial distribution of AWF. Rising incomes and dietary changes have increased demand for animal products, contributing to the expansion of livestock production and associated water consumption. However, livestock production tends to be more closely linked to market demand and population distribution, resulting in relatively stronger spatial coordination compared with crop production.

Improving compatibility between AWF and socioeconomic development requires regionally differentiated management strategies. Strengthening coordination between water allocation, agricultural planning, and industrial policy is essential in agricultural production zones. In economic core zones, promoting high-value agriculture and improving water productivity can enhance economic efficiency. In ecological conservation zones, optimizing livestock production systems while maintaining ecological water requirements is critical.

4.3. Limitations and Future Research Directions

Although this study presents a comprehensive analysis of the spatiotemporal dynamics of AWF and its socioeconomic adaptability, several limitations remain. First, the analysis is based on selected representative years due to data availability constraints, which may limit the ability to capture short-term variability. Second, the assessment focused on blue and green water footprints, while grey water footprint was not included. Future studies should incorporate grey water footprint to provide a more comprehensive evaluation of water resource sustainability.

In addition, future research should further integrate water resource carrying capacity indicators, including available water resources and ecological water requirements, to better assess the sustainability of agricultural water use under ecological functional zoning. Such integration would provide a more complete understanding of the balance between water demand and environmental constraints.

Refining livestock water footprint estimation by incorporating region-specific feed composition, feed conversion efficiency, and technological factors would also improve accuracy [47–48]. Expanding the temporal and spatial resolution of datasets would enhance the ability to assess long-term trends and regional heterogeneity.

These improvements would strengthen the scientific basis for agricultural water resource management and provide more robust decision support for sustainable agricultural development in Xinjiang and other arid regions.

5. Conclusions

This study quantified the spatiotemporal evolution of the AWF in Xinjiang from 2000 to 2020 based on an ecological functional zoning framework and evaluated its compatibility with socioeconomic development. The total AWF increased significantly, with crop production—particularly cotton—remaining the dominant contributor. Animal product water footprint also increased, reflecting structural changes in agricultural production. Spatially, AWF exhibited a clear southwest–northeast gradient, driven by differences in ecological functional positioning, agricultural development intensity, and water resource endowment. Agricultural production relied heavily on blue water, indicating strong dependence on irrigation in this arid region.

Compatibility between AWF and sown area improved, reflecting enhanced coordination between agricultural expansion and water allocation, while compatibility with population and economic output remained relatively weak. These findings highlight the importance of function zone-based water management. Improving irrigation efficiency, optimizing agricultural structure, and strengthening water allocation mechanisms are essential for promoting sustainable agricultural water use in arid regions.

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