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The Water–Soil Resource Matching Pattern of Grain Crops in the North China Plain from the Perspective of the Physical Water–Water Footprint

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Abstract: The agricultural water–soil matching coefficient is a key factor for reflecting regional grain production status, which can be used to evaluate the reasonableness of water–soil allocation in certain areas. Taking the North China Plain (NCP) as the study area, in this study, we constructed a framework from a "physical water–water footprint" standpoint. The binary matching characteristics of "water–soil–grain" were then analyzed, and the water–soil matching coefficient method was employed to evaluate the pattern of water–soil matching for the years 1984, 1998, 2003, and 2022. Through the perspective of physical water–water footprint coupling, field trials of grain were utilized to calculate the range of water–soil matching coefficients under high yields. The results showed the following: ① From 1949 to 2022, the grain yield and planting areas increased. Wheat, the dominant crop, required substantial irrigation. Precipitation, cultivated land, and irrigation water exhibited spatial mismatches over the last ten years. ② The total water footprint showed an increasing trend, and the blue water footprint accounted for 19.47%. The spatial distribution of the water and land footprints of grain crops largely overlapped, and their values were higher in the central and southern regions, and lower in the north. ③ The current water–soil matching coefficient was in the range of [0.28, 1.75], which fell outside the optimal range of [0.534, 0.724]. The soil–water matching coefficients of wheat and rice were overall higher than those of other crops. We found higher values in the southwestern region and lower values in the northern areas, which aligns with the boundary of the groundwater funnel area. To address the identified challenges, we recommend implementing a tiered regulatory zone system based on the matching coefficient. The government should encourage a reduction in water-intensive crops like wheat and rice in high-value regions by providing subsidies. Additionally, a monitoring mechanism for water and soil compatibility should be established, considering the specific growth requirements of various crops.

Keywords: grain; physical water; water footprint; land footprint; water–soil matching pattern; North China Plain

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1. Introduction

Due to the rapid rise in the global population, natural resources are facing increasing pressure. Meanwhile, traditional agriculture based on high inputs and outputs from natural resources, the use of intensive farming practices, and the extensive usage of irrigation are having a significant impact on the global environment. Ensuring food security is thus the primary issue for global development [1–4], which centers on the efficient use of agricultural water–soil resources [5]. Indeed, many global regions, such as arid and semi-arid areas, face similar resource scarcity challenges, and solutions including increased agricultural mechanization and the optimization of irrigation practices have already been proposed worldwide [6–8]. Globally, 20% of arable land is currently irrigated, contributing 40% of food production, while agriculture accounts for 90% of the total water consumption [6]. With the liberalization of global food trade and rising food demand, the importance of matching water–soil resources has become more prominent, and food security and sustainable agricultural development are global challenges [8,9]. China is one of the largest agricultural countries globally, but its spatial distribution of water–soil resources is inefficient, with major grain-producing areas located in northern regions where water–soil resources are limited. This adversely affects the country's food security and significantly hinders the development of the regional economy [10,11]. The effective allocation of water–soil resources is therefore crucial to dynamic and spatial distribution in grain production.

However, there is still limited understanding of how the interplay between water and soil resources affects food production, particularly from a spatial perspective that integrates physical water and water footprint. This understanding is essential to the effective planning of water–soil resources to ensure sustainable food production and food security. The water footprint, bridging physical and virtual water, is commonly used to quantify the relationship between food production and water consumption, offering insights into agricultural water use and its utilization efficiency [12]. It has been widely employed to estimate water consumption for various crops at both global and regional scales [13]. In this study, we therefore examine regional grain–water–soil resource matching from a "physical water–water footprint" perspective, aiming to thoroughly understand the matching characteristics and relationships among them.

Water–soil matching is a quantitative relationship that characterizes the appropriate alignment of the water required for agricultural production and cultivated land in time and space, which plays a decisive role in agricultural production [2]. Its spatial distribution pattern is the foundation for sustainable socio-economic development and agricultural production, and plays an important role in guaranteeing regional food security. Existing research has explored the relationship between water–soil and grain production at global and regional levels, focusing on analyzing single resources, such as water and soil, as well as the coupling relationships and interaction among these elements [10,14,15]. Additionally, researchers have explored the patterns and characteristics of water–soil resource matching in specific regions across different spatial and temporal scales [16,17]. Most studies have adopted the Gini coefficient [18,19], Markov chain [20], and water–soil resource matching coefficient [10,21] methods, focusing on global water shortage regions and major grain-producing areas such as the Bima River Basin, the arid areas of northwestern China, the Yellow River Basin, northeastern China, and typical mountainous areas in India; emphasizing regional grain production, cultivated land changes, and the matching of water–soil resources with socio-economic factors; and proposing targeted suggested measures.

Previous studies have made substantial progress in understanding the matching of water–soil and spatial heterogeneity in grain production. However, the following research gaps still exist: (1) From a research perspective, the binary matching characteristics of the three key elements of "water–soil–grain" in grain production have not been thoroughly explored, particularly from the integrated physical water–water footprint perspective. (2) From the methodological perspective, traditional econometric models often overlook the definition of a reasonable range for water–soil matching across different regions, typically assuming that a larger matching coefficient always leads to better outcomes; however, this is actually not the case. In contrast, this study abandons the simplistic notion that a higher water–soil matching coefficient is always advantageous. Instead, we calculate the range of reasonable water–soil matching coefficients for high-yield targets by using field trial data, an approach that defines the optimal scope of the crop-planting structure from the water footprint perspective. By doing so, we provide critical data for assessing the degree of water–soil matching in grain production and enhance the understanding of water–soil utilization across various grain crop production systems. Moreover, this methodology lays the foundation for agricultural zoning and planting strategies in irrigated regions.

The NCP is the region with the highest degree of development of water and soil resource utilization in China [22]. As the primary grain-producing area, it has the world's largest groundwater drop funnel. Groundwater, which accounts for approximately 70% of the total water supply, serves as the main water source [23]. However, the overexploitation of groundwater for agricultural production has led to various environmental geological issues, thereby restricting the sustainable development of the social economy [19]. In response, in this study, we comprehensively analyzed key agricultural and water-related data in the NCP, including precipitation, the yield of five major grain crops (wheat, corn, rice, soybean, and potato), the planting area, the cultivated area, and irrigation from 1950 to 2022. Firstly, the binary matching characteristics of the three elements of water, soil, and agricultural development were determined from the perspective of "physical water". Secondly, based on the "water footprint" approach, the water–soil matching coefficient method was applied to quantitatively analyze the water–soil matching patterns of these five major grain crops for the years 1984, 1998, 2003, and 2022. Finally, from the "physical water–water footprint" coupling perspective, field experimental data on wheat, corn, soybean, and potato were used to calculate the range of reasonable water–soil matching coefficients for high yields. The spatial distribution of groundwater funnels was analyzed, providing a scientific basis for evaluating the matching of water–soil resources and supporting their sustainable use. The research framework is shown in Figure 1.

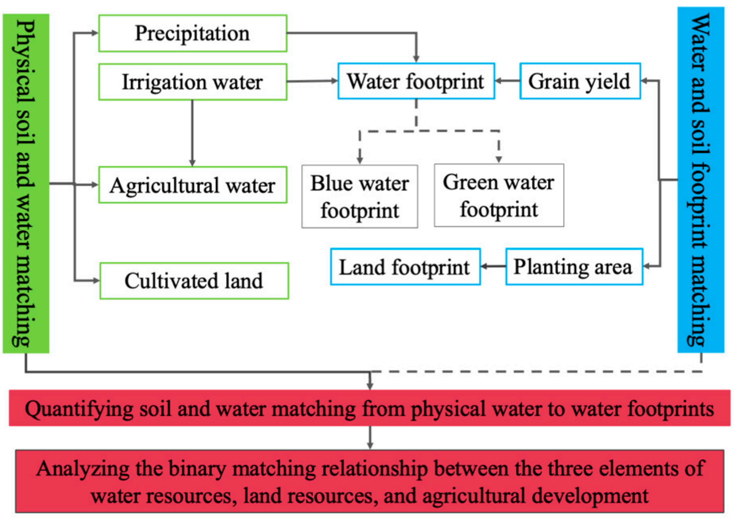

Figure 1. Study framework.

The research objectives are as follows:

(1) Explore the water–soil matching of grain production in the NCP from the physical water–water footprint perspective.

(2) Calculate the reasonable range of the water–soil matching coefficient of grain in the NCP.

(3) Assess the impact of the elastic range of the water–soil matching coefficient on the optimization and adjustment of the crop-planting structure.

2. Materials and Methods

2.1. Study Area

The North China Plain (NCP) (112°30′ E~119°30′ E, 34°46′ N~40°25′ N) is the second largest plain in China, bordered by the Taihang Mountains to the west, the Yanshan Mountains to the north, the Bohai Sea to the east, and the Yellow River to the south [24]. The administrative region includes most cities of Beijing, Tianjin, and Hebei, as well as parts of Shandong and Henan north of the Yellow River, for a total area of approximately 1.4×10^5 km^2 [22], and the geographical distribution is shown in Figure 2. This area is a resource-based water-scarce area, where local precipitation is insufficient to meet the water demands of crop growth. Irrigation is therefore crucial to achieving high and stable crop yields. Agricultural water consumption in the region accounts for about 70% of the total water use, with 75% of this being based on groundwater [25]. The prolonged overexploitation of groundwater has led to the formation of multiple groundwater funnel areas, severely threatening the sustainable development of agriculture in the irrigation zones. Due to the rigid water constraint, the extent of the irrigated planting area is primarily determined by water availability, with the NCP producing approximately one-fifth of China's total grain on just one-sixth of its cultivated land [26]. Wheat and corn are the dominant crops, together accounting for more than 91% of the total grain output. Notably, the water requirements of winter wheat during its growing season are poorly aligned with the available water resources, necessitating additional irrigation to sustain wheat production. As such, irrigation has become essential to the continued agricultural development of the region [19].

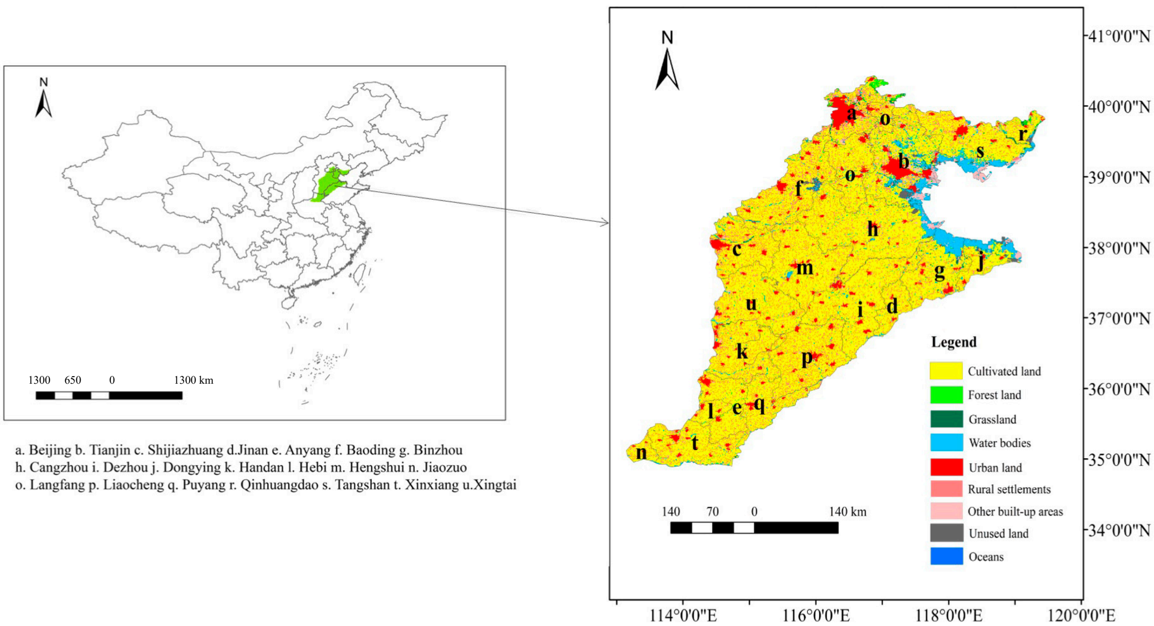

Figure 2. Geographical location of and land use types in the NCP under the current scenario (2020).

2.2. Data Sources

(1) Production conditions of the main grain in the NCP: The yields and planting areas of five grain crops (rice, wheat, corn, soybean, and potato) from 1949 to 2022 were derived from the provincial Statistical Yearbooks (1950–2023). The data referenced in this study regarding crop growth cycles, planting time, and water consumption were sourced from [27–30].

(2) Water resources and irrigation data: The agricultural water data were obtained from the provincial Water Resources Bulletin. It is generally believed that agricultural irrigation in China accounts for 90% to 95% of the total agricultural water use [11]. In this study, we thus selected a conservative value, using 90% of total agricultural water use as the irrigation volume for calculations. Meteorological data (precipitation, relative humidity, average wind speed, and sunshine hours) were sourced from the National Meteorological Science Data Center (https://data.cma.cn/ (accessed on 12 September 2024)).

(3) Spatial data: The cultivated land data and base map data of the NCP were derived from the Third National Land Survey and standard base map service website of the National Bureau of Surveying, Mapping, and Geoinformation (http://211.159.153.75/index.html (accessed on 16 September 2024)), respectively. The boundary of the base map was extracted based on the boundary of the NCP, and the corresponding NCP shapefile was obtained. The China Multi-Period Land Use Remote Sensing Monitoring Data Set (CNLUCC) data from 2020 were obtained from the Resource and Environmental Science Data Registration and Publishing System (https://www.resdc.cn/ (accessed on 12 September 2024)). The groundwater depth and groundwater level contour in the NCP were derived from Yang's study [31].

(4) Trial data: By referring to Zhang's study on the typical regional farmland in the NCP [32], the field experimental area was located at the Luancheng Agroecosystem Experimental Station of the Chinese Academy of Sciences, where conducted long-term locational irrigation trials were conducted from 1980 to 2017. To ensure the data's scientific accuracy, we also compared the studies performed by Zhao [29] in the same study area between 1986 and 2015. Additionally, soybean field experimental data were obtained from the Wuqiao Experimental Station of China Agricultural University [33], which used three phases of data, with each plot being 60 m^2 and soybean receiving 75 mm of irrigation water after sowing.

2.3. Methodology

2.3.1. Water Footprint Model Method for Grain Crop Production

Blue and green water footprints are the primary water resources consumed during crop production [13]. They refer to the water extracted from surface water and groundwater during crop growth and the water stored in soil aquifers following precipitation or absorbed by plant roots via evapotranspiration, respectively. The method proposed by the United States Department of Agriculture Soil Conservation Service (USDA-SCS) is predominantly used to calculate these footprints, whereby effective precipitation is calculated and coupled with the Penman–Monteith equation to estimate evapotranspiration. The blue and green water footprints are then simulated with the CROPWAT model. Since the gray water footprint does not directly reflect actual water consumption in crop production, we did not calculate or analyze it in this study, as it pertains to the environmental impact of water usage rather than actual consumption. The specific formula is as follows:

$$WF_{green} = (CWU_{green}/Y) \times P_c = (10 \times ET_{green}/Y) \times P_c \quad (1)$$

$$WF_{blue} = (CWU_{blue}/Y) \times P_c = (10 \times ET_{blue}/Y) \times P_c \quad (2)$$

$$ET_{green} = \min\left(ET_c, P_e\right) \quad (3)$$

$$ET_{blue} = \max\left(0, ET_c - P_e\right) \quad (4)$$

$$P_e = \begin{cases} P \times (125 - 0.6 \times P)/125, \ P \leq 250/3 \\ \frac{125}{3} + 0.1 \times P, \ P > 250/3 \end{cases} \quad (5)$$

In the formula, WF_{green} is the green water footprint of grain crop production, m^3; WF_{blue} is the blue water footprint of grain crop production, m^3; CWU_{green} and CWU_{blue} are, respectively, the amounts of green and blue water consumed by crops per unit area, m^3/hm^2; P_c is the total yield of crop c, kg; Y is the crop yield per unit area, kg/hm^3; P_e is the effective precipitation, m^3; ET_c is the crop evapotranspiration, calculated as per CROPWAT8.0; ET_{green} is equal to the smaller value in ET_c and P_e; ET_{blue} is equal to the difference between ET_c and P_e, but when P_e exceeds ET_c, its value is 0; and P is the ten-day precipitation, mm.

2.3.2. Quantification of Water and Land Footprints of Grain

From the perspective of producers, the water footprint of grain production represents the actual water consumption for producing a product and depends on the status of the production area and the efficiency of water utilization. The water resource consumed during the growth of all crops in the region constitutes the production water footprint. The specific formula is as follows:

$$WF_{n,c} = \sum_{i=1}^{n} WF_{n,c(blue,green)} \tag{6}$$

$$W_n = \sum_{c=1}^{n} WF_{n,c} \tag{7}$$

where W_n represents the water footprint of grain in the region n, 10^8 m^3, and $WF_{n,c}$ is the water footprint of crop c production in region n, m^3.

As early as the 1960s, some scholars proposed the concept of "ghost acreage" to describe the invisible land resource consumption behind agricultural trade [34]. Since then, the concepts of ecological footprint, land footprint, virtual land, and hidden land have been proposed to describe the impact on land resources caused by human behavior. The "shadow area" proposed by Borgstrom in 1966 marks the beginning of the study of land area trade in agricultural trade [35]. Based on the perspective of producers, the land footprint is the amount of land resources needed to produce a certain food crop.

The calculation of the land footprint per unit grain is performed as follows:

$$LF_{n,c} = A_{n,c}/P_{n,c} \tag{8}$$

where $LF_{n,c}$ refers to the land footprint of grain c in region n, hm^2/kg; $A_{n,c}$ refers to the planting area of grain c in region n, 10^3 hm^2; and $P_{n,c}$ refers to the total yield of crop c in region n, kg.

2.3.3. Agricultural Water–Soil Matching Coefficient from a Water Footprint Perspective

The water–soil matching coefficient of grain refers to the water footprint of grain per unit area of cultivated land, which defines the spatial and temporal relationship between water and soil consumed in grain production. A smaller water–soil matching coefficient indicates lower water consumption per unit area of cultivated land, reflecting a higher degree of resource matching and more sustainable use of water–soil in agricultural production. Conversely, a larger matching coefficient signifies higher water consumption in grain production, suggesting a lower level of resource matching.

$$R_n = \frac{W_n}{L_n} \tag{9}$$

In this formula, R_n represents the water–soil matching coefficient of the region n, 10^4 m^3/hm^2, and L_n represents the area of cultivated land in region n, 10^4 hm^2.

In this study, we departed from traditional methods, which reflects the spatial coordination between soil and water resources based solely on irrigation volume per unit of cultivated land [18]. Instead, we integrated physical water availability with the water footprint approach, providing a more comprehensive evaluation of the matching relationship between these resources. Given the time frame of the field trial data, the water–soil matching coefficient was calculated for selected time points—1984, 1998, 2003, and 2022—chosen to represent different phases of agricultural development and water resource availability in the NCP. When the value exceeds the upper limit of the acceptable range, it indicates excessive irrigation water use, reflecting poor resource matching and negatively impacting the sustainability of agricultural production. Conversely, if the value falls below the lower limit of the regional range, it suggests insufficient irrigation water for agricultural production, indicating a low degree of alignment between water and soil sources.

3. Results

3.1. Physical Water Perspective: Characteristics of Natural Water and Soil Change

Physical soil–water matching is fundamental to agricultural production, directly reflecting the strengths and limitations of regional agricultural conditions. Overall, there was a noticeable intra-regional variation in grain yield, with a general upward trend (Figure 3a). In the study period, the contributions of the major grain crops to the total grain yield were as follows (in descending order): wheat (44.78%), corn (39.12%), potato (8.61%), rice (4.87%), and soybean (2.62%). Wheat and corn yields exhibited a pattern of increase, followed by a decline, and then another increase. In contrast, soybean and potato yields exhibited a fluctuating downward trend, while rice yields remained relatively stable. The total planting area of grain showed an overall fluctuating growth trend from 1949 to 2022 (Figure 3b). During this period, the grain planting area increased, marking a cumulative growth rate of 44.45%. Specifically, the trends of the planting areas of rice, wheat, and corn fluctuated upward, with average annual growth rates of 2.29%, 0.51%, and 1.77%, respectively. In contrast, the planting areas of soybean and potato decreased.

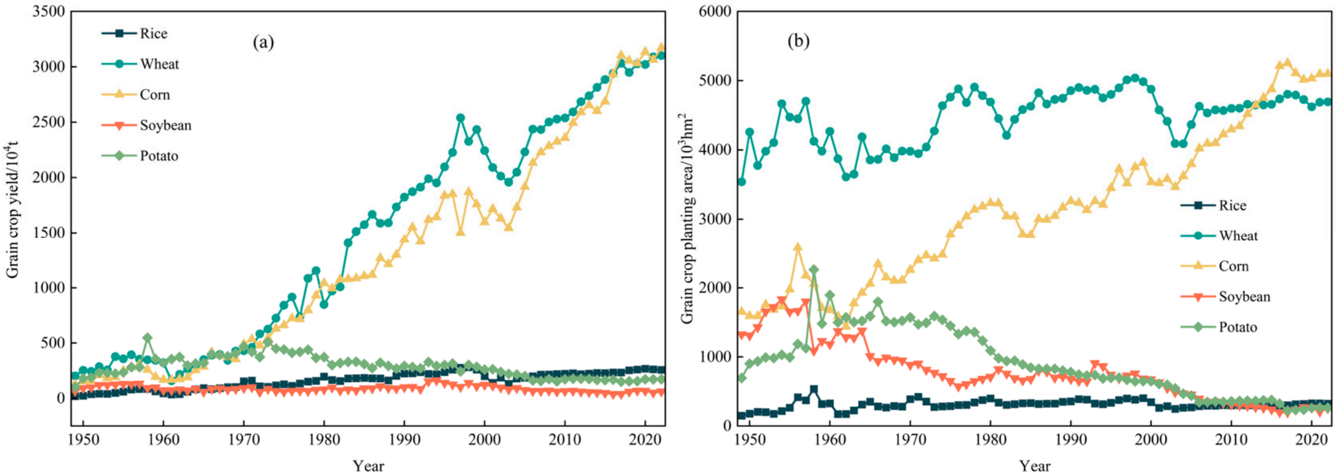

Figure 3. Overview of rain planting in the NCP from 1949 to 2022: grain crop yield (**a**); grain crop planting area (**b**).

The spatial matching of natural water–soil shows a trend of spatial mismatch, primarily evident in the distribution of precipitation, cultivated land, and irrigation water (Figure 4). Precipitation shows a spatial pattern of “higher values in the east and north and lower values in the central and southern regions”. Specifically, it is mostly concentrated in areas such as Tianjin, Jinan, Binzhou, and Dongying in Shandong Province and Xinxiang in Henan Province. In contrast, the main agricultural production areas, including Hengshui, Xingtai, Handan, and Cangzhou, experience lower precipitation (Figure 4a). The spatial distributions of cultivated land and irrigation water in the NCP generally exhibit a state of spatial overlap (Figure 4b,c), displaying a distribution pattern distinguished by "higher values in the central areas and lower values in the northern parts". They are particularly concentrated in the central region of the NCP, specifically in cities such as Hengshui, Xingtai, Handan, and Cangzhou.

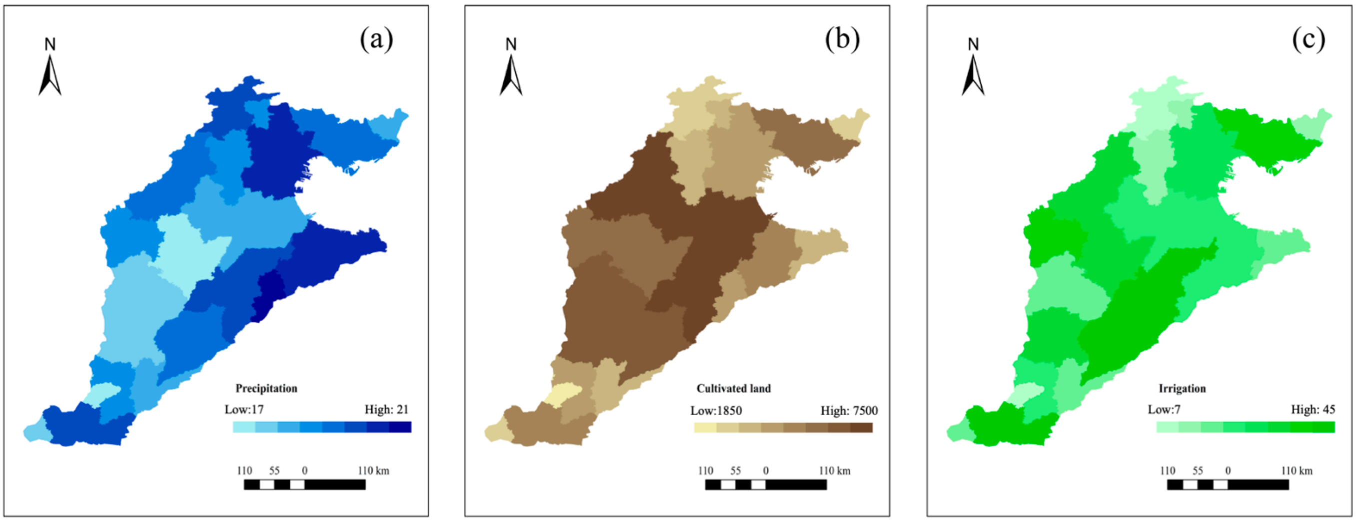

Figure 4. Physical water and soil matching in the NCP over the last ten years: precipitation (**a**); cultivated land (**b**); irrigation (**c**).

3.2. Water Footprint Perspective: Water–Soil Matching Characteristics of Grain

Water and land footprints serve as barometers of agricultural production, indirectly reflecting changes in the regional agricultural planting structure and crop water consumption. During the period of 1949–2022, the average water footprint of the five major grains was 328.49×10^8 m^3, where the blue and green water footprints accounted for 57.85% and 38.38% of the total, respectively (Figure 5a), and the total water footprint of the five grains showed a fluctuating upward trend. The blue water footprint was the dominant component of the total water footprint, and the blue and green water footprints of the considered crops exhibited a cyclical trend, alternating between increases and decreases. Wheat and corn were the primary grains in the NCP, with their total water footprints increasing at average annual rates of 4.85% and 5.21%, respectively. The average water footprints of these two crops together accounted for 80.28% of the total, followed by those of potato (12.76%), soybean (9.16%), and rice (6.67%). Notably, the total blue water footprint exceeded the total green water footprint of most crops. The blue water footprint of wheat in the NCP was 94.4×10^8 m^3 higher than its green water footprint, indicating a heavy reliance on irrigation. In contrast, the green water footprint of corn was 42.42% higher than its blue water footprint, suggesting a lower dependency on irrigation.

Figure 6 illustrates the spatial layout of the water and land footprints of grain in the NCP. Both exhibit significant north–south variations and spatial clustering patterns. Specifically, regions with high water footprints of grain are concentrated in Baoding, Shijiazhuang, Cangzhou, Dezhou, and surrounding areas. When combined with the spatial distribution of irrigation water (Figure 4c), it is evident that the central and southern parts of the NCP, where irrigation water availability is high, also have a substantial proportion of wheat cultivation. As an irrigated crop, wheat is highly dependent on agricultural irrigation, which poses potential challenges for the sustainable development of agricultural production. The spatial distribution of the land footprint generally mirrors that of the water footprint, with a pattern of "high values in the central and southern regions and low values in the northern regions" (Figure 6b). Over the past decade, the land footprint has been concentrated in the central and southern parts, particularly in Baoding, Cangzhou, Dezhou, Hengshui, Xingtai, Liaocheng, and Xinxiang.

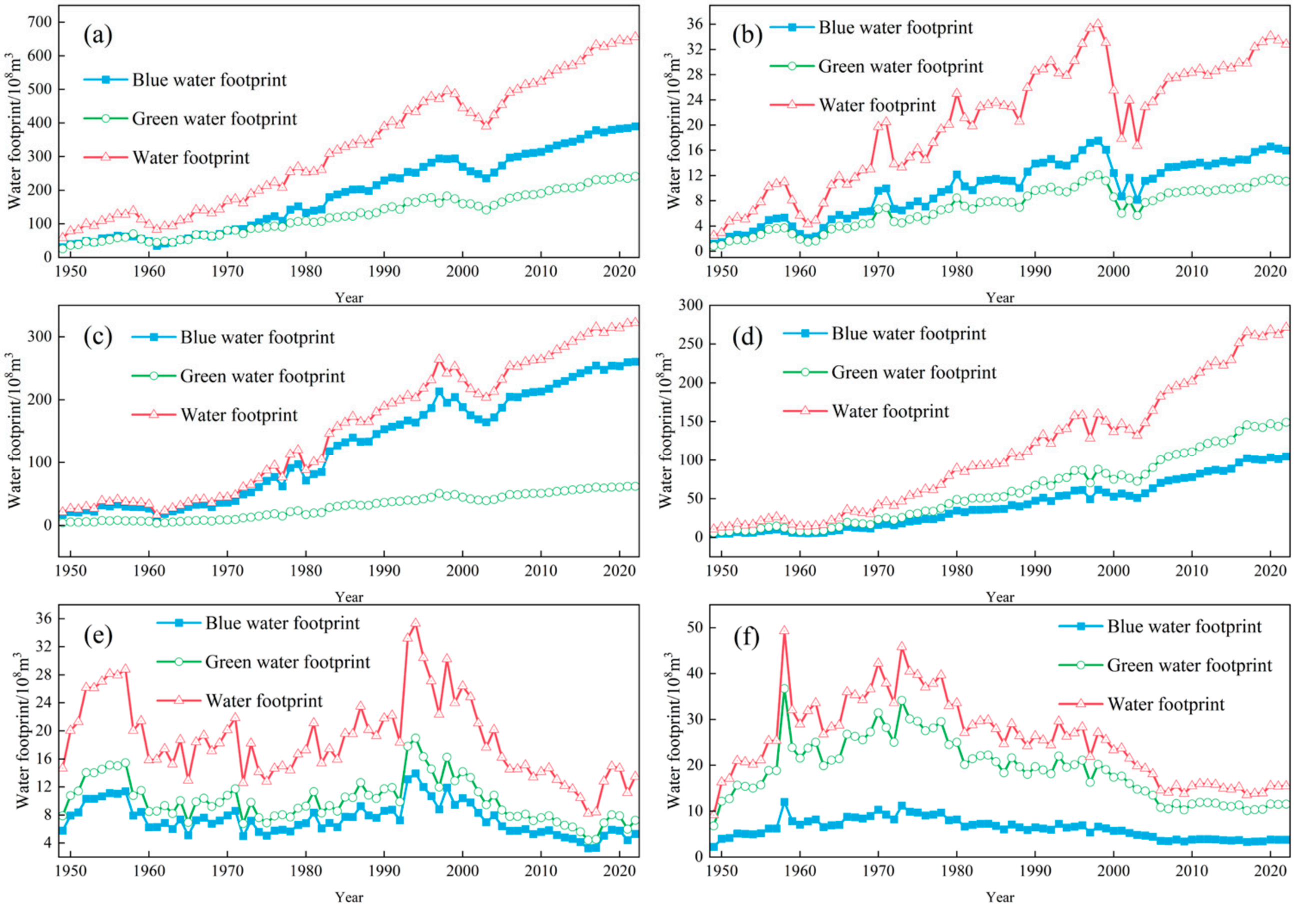

Figure 5. Variations in water footprints of grain crop production in the NCP from 1949 to 2022: total water footprint (**a**); rice (**b**); wheat (**c**); corn (**d**); soybean (**e**); potato (**f**).

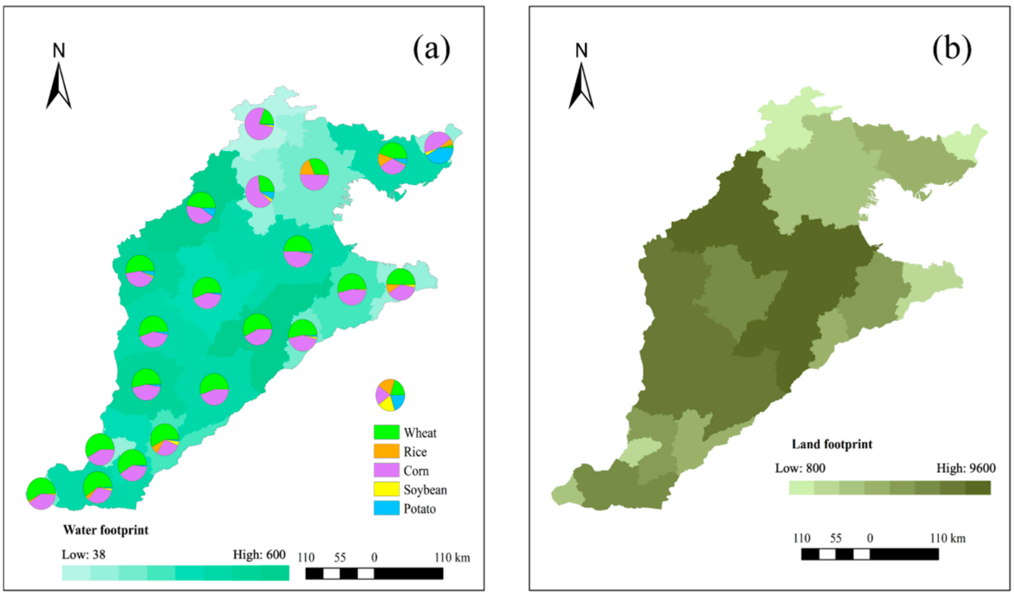

Figure 6. Water and land footprint matching in the NCP over the last ten years: water footprint (**a**); land footprint (**b**).

3.3. Physical Water–Water Footprint Combination: Water–Soil Matching Pattern for Grain

Considering the time frame of the trial data from the "physical water–soil perspective" and the inflection points observed in the line graph (Figure 3), 1984, 1998, 2003, and 2022 were selected as specific time nodes (Figure 7). The water–soil matching coefficient of the NCP showed an overall increase, with significant spatial variation. From 1984 to 2022, regional differences in the degree of matching were evident. The pattern of water–soil matching showed spatial clustering, with areas of higher matching being concentrated in the southern and western regions, while areas with lower matching were found in the north and in Beijing and Tianjin. The high-value areas were predominantly located in traditional agricultural cities, such as Shijiazhuang, Liaocheng, and Puyang, while the low-value areas were concentrated in Beijing and Tianjin. Specifically, the high proportion of wheat and rice in the high-value areas indicates that the structure of crop cultivation affects the soil–water matching coefficient in the NCP. On the contrary, the grain crop proportion structure was relatively appropriate in the low-value areas. From 1984 to 2022, the soil–water matching coefficient increased, with most cities having matching coefficients of between 0.724 and 1.90, significantly above the upper limit of the suitable range. In addition, in terms of crop structure change, the matching coefficients of wheat and rice were relatively high overall, especially in the area with high matching coefficients of soil–water, which indicates that these two crops have a greater demand for irrigation water. In addition, from the perspective of time series, the soil–water matching coefficients of wheat, rice, corn, soybean, and potato also showed an increasing trend, where wheat and potato increased significantly, followed by corn, soybean, and finally rice.

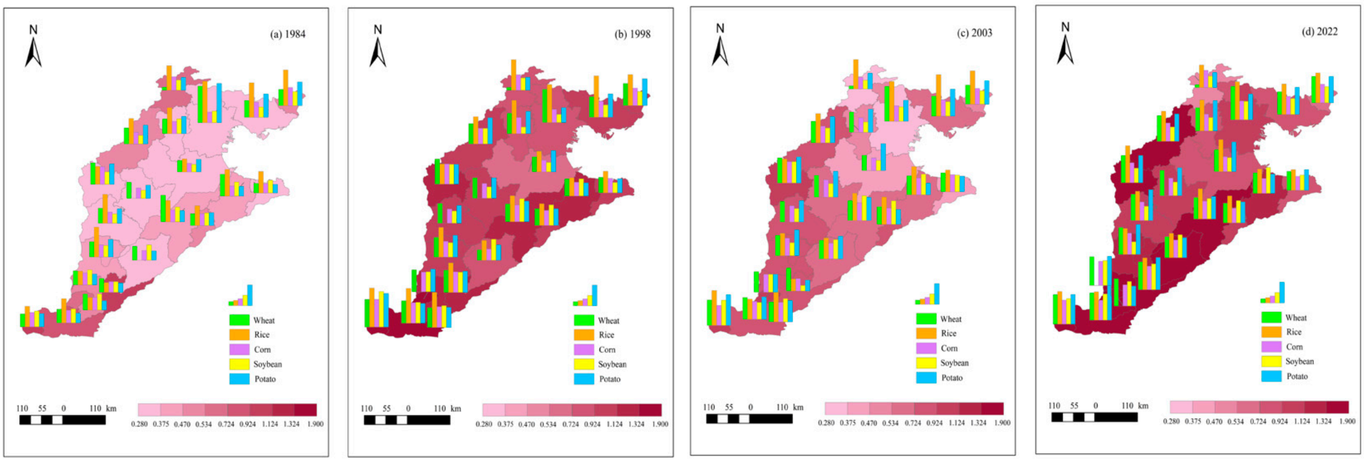

Figure 7. Water–soil matching coefficient of grain crops in the NCP.

Shallow groundwater differs from deep groundwater mainly in three aspects: annual thermal stability, sensitivity to land use change and surface pollution, and output pathways [36]. The natural surface temperature of shallow groundwater fluctuates markedly and tends to weaken rapidly with increasing depth, while there is low annual thermal variability in deep groundwater. Second, shallow groundwater is more sensitive to land use changes and surface pollution than deep groundwater. Finally, shallow groundwater can be directly depleted by transpiration and irrigation withdrawals and is more affected by seasonal groundwater levels during dry periods, but discharge from deep groundwater sources is more stable.

The shallow groundwater depth in the NCP ranges from 10 to 70 m, and the elevation of the groundwater level ranges from −30 to 45 m. The deep groundwater head depth ranges from 50 to 120 m, and the elevation of the head is about −90 to 40 m [31]. The high-value area of water–soil matching coefficients in the NCP coincides with the boundary of the groundwater funnel area (Figure 8). The latter is primarily distributed across the central and eastern regions, such as Hengshui and Cangzhou, as well as the alluvial fan margin of "Baoding–Shijiazhuang–Xingtai" in front of the Taihang Mountains. This forms a composite shallow and deep groundwater funnel area represented by Baoding, Shijiazhuang, Xingtai, and Handan. The groundwater funnel area tends to expand, influencing both the agricultural water–soil matching coefficient and the boundary of the groundwater funnel. The matching coefficients of overlapping areas, such as Shijiazhuang, Xingtai, Handan, and Langfang, were all greater than 0.534. Most of the high-value areas of water–soil matching was distributed in the range of the groundwater funnel, demonstrating a spatial connection between the two (Figure 8).

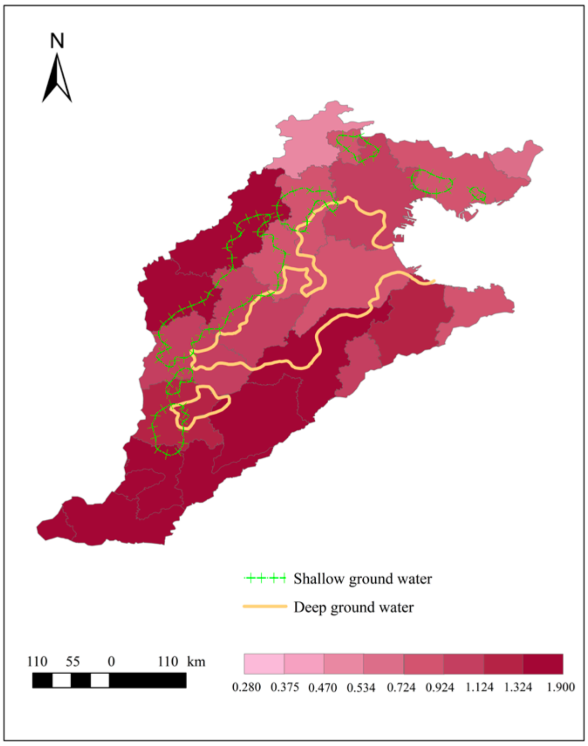

Figure 8. Water–soil matching coefficient of grain and the boundary of the groundwater funnel area in the NCP.

4. Discussion

4.1. Precipitation and Cultivated Land Area Affect Regional Agricultural Production

Agricultural production is directly influenced by climate variables such as precipitation, and reduced precipitation and water deficits negatively affect food production. In China, where precipitation is unevenly distributed, changes in precipitation (Figure 4) can significantly alter crop production patterns. For example, a shortage of rainfall exacerbates food insecurity in local regions [1], while another key consequence of changes in precipitation is the increased reliance on groundwater for irrigation, accelerating the depletion of regional groundwater resources [1,37]. As natural precipitation cannot fully meet the water requirements of grain crops, irrigation compensates for it. However, irrigation represents the highest energy-intensive boundary through water intake, water delivery, and water use in the grain crop production system, with an average energy consumption of 11.4 ± 1.1 GJ ha^{-1}. Consequently, water scarcity is a critical factor limiting agricultural water–soil matching in the NCP [4,38]. Changes in precipitation are expected to reshape water demand and availability between rainfed and irrigated agriculture, such as wheat [7], further modifying the regional water–soil matching dynamics.

Land use transformation also affects food production. The per capita cultivated land in China has gradually decreased but has begun to stabilize, while the planting area has also increased. For every additional 1000 hm^2 of planting, grain production increases by an average of 1390.95×10^4 t (Figure 3). The trend of farmland spatial transformation is significant, contributing to a gradual increase in grain yield in the NCP [3]. Rapid economic development and accelerated urbanization have significantly altered land use patterns, changing underlying surface conditions. Consequently, surface water availability in the NCP has decreased by approximately 52.7% [38]. Given the limited water resources, further expansion of both cultivated land and effective irrigated areas is no longer feasible [19]. Land use transformation should therefore not be equated with the continuous expansion of cultivated areas. Globally, much agricultural land operates below its potential. Improving irrigation and soil fertility to enhance crop yields offers a more environmentally sustainable pathway for agricultural intensification, ensuring long-term agricultural security [39].

4.2. Crop Evapotranspiration Affects Agricultural Planting Structure

The water–soil matching pattern of grain crops is shaped by both regional physical water availability and the crop-planting structure. Changes in the agricultural water footprint reflect adjustments in the regional crop-planting structure, which are influenced by evapotranspiration and yield [13]. Crop evapotranspiration is primarily driven by climatic conditions and their variations. Precipitation forecasts for the NCP indicate a declining trend over the next 27 years, which will impact crop evapotranspiration and water consumption [40]. In addition to precipitation, rising temperatures will also affect crop evapotranspiration, and by the end of the 21st century, the temperature is expected to increase by 1.3 °C to 5.0 °C, with the NCP being expected to experience high-impact effects [40]. These climatic changes will directly influence the water footprint of crops, which in turn will indirectly affect the crop-planting structures. The divergent trends in crop water footprints in the NCP (Figure 5) reflect the changes in the region's agricultural structure.

Simultaneously, the dynamic changes in agricultural land use show a clear transition from double-cropping systems (mainly wheat–corn) to single-cropping systems (mainly corn). The area planted with corn has increased (Figure 3b), and economic forests have transitioned from monoculture to diversified systems. These structural changes led to an 11% reduction in grain crop area between 2013 and 2022, yet the water consumption for these crops rose by 11% [41]. Despite the decline in the grain crop-planting area, the water footprint continues to increase (Figures 5 and 6), suggesting that the yield per unit area has risen, reflecting improved agricultural productivity [38]. Studies have shown that in major agricultural countries, improving crop yields is a key strategy for reducing crop water footprints and decreasing water usage in production [42,43]. Additionally, attention must also be paid to irrigation efficiency and other irrigation management factors related to the blue water footprint, as these directly influence the water footprint of non-crop production. This further confirms the dominant role of green water in agricultural production. The effective management of regional agricultural water footprints is crucial to maintaining agricultural productivity and ensuring the sustainable use of water [44].

4.3. The Water–Soil Matching Pattern Indirectly Indicates the Overexploitation of Groundwater

Agricultural production in the NCP primarily relies on groundwater and river irrigation. Continuous irrigation for winter wheat and summer corn has steadily increased, resulting in frequent overexploitation of groundwater, with levels declining at a rate of 1 m per year [45,46]. In response, the government has implemented policies to limit groundwater extraction, such as the winter wheat return-to-field program in areas with severe groundwater overexploitation. In the NCP, the boundary between the high values of water–soil matching coefficients and the groundwater funnel areas closely overlaps (Figure 8), indicating a spatial correlation [21]. Moreover, studies have shown that the groundwater funnel area has a tendency to expand, with no alternative water source available for agricultural irrigation, and reliance on the over-extraction of groundwater is a key factor causing the continuous decline in groundwater levels [31]. Yang [46] proposed that replacing the traditional rotation system with annual shallow-rooted crop rotation could partially reduce groundwater depletion in the NCP. Furthermore, the field experimental data of their study mainly include ET data from grain crops under two irrigation regimes: high water consumption (two crops per year) and low water consumption (one crop per year). Relying solely on water-saving irrigation to achieve sustainable water use in the NCP is not feasible [19,29]. To alleviate water stress, enhancing water use efficiency and optimizing irrigation schedules are essential. Future management should prioritize water demand management over water supply-oriented strategies [47,48].

In response to the water scarcity problem, the government has proposed projects like the "South-to-North Water Diversion," aimed at replacing deep groundwater extraction and replenishing river ecosystems [49]. These initiatives have helped lessen water shortages, with an annual water supply of 95×10^8 m^3 to Henan, Hebei, Beijing, and Tianjin, improving the region's population capacity. However, these initiatives have certain drawbacks. The sustainability of local resources and ecosystems has not been fully considered, leading to the over-exploitation of soil and water in exchange for higher grain yields. This exacerbates issues such as groundwater funnel formation and environmental pollution [16,50], while also leading to potentially negative impacts on import–export river ecosystems and large capital costs (USD 60 billion) [48]. To optimize physical water–soil matching and improve agricultural productivity, changes in irrigation patterns are necessary, as climate change may further reduce yields, particularly for wheat and corn in northern China [51].

5. Conclusions

In this study, we systematically investigate the roles of physical water and water footprint in agricultural water–soil matching research in the NCP, employing geospatial analysis techniques and the water–soil matching coefficient model. From the perspectives of physical water and water footprint, we assess the water–soil matching of grain crops in the NCP, providing empirical evidence for ensuring food security. The following conclusions can be drawn:

(1) The natural water–soil matching in the NCP exhibited spatial misalignment. From 1949 to 2022, grain production and planting area showed an increasing trend, with average annual growth rates of 3.96% and 0.6%, respectively. Wheat yields were the highest, followed by those of corn, potato, and rice, and soybean yields were the lowest.

(2) The water footprint of grain in the NCP still has room for further optimization, with the total water footprint increasing at an average annual growth rate of 3.74%. The annual proportion of the total blue water footprint (57.85%) consistently exceeded that of the green water footprint (38.38%). Spatially, the water footprints displayed overlapping patterns, with higher values in the central and southern regions and lower values in the northern areas. Regions with high water footprints had a larger proportion of wheat cultivation.

(3) By using field trial data, the critical range of the water–soil matching coefficient under irrigation water constraints in the NCP was calculated to be between 0.534 and 0.724. Currently, regional water–soil matching coefficients far exceed this critical range, indicating that the land distribution is concentrated, agricultural water resources are scarce, and groundwater extraction intensity is high. The proportion of wheat and

rice matching coefficients in the area with a high soil–water matching coefficients was also higher. The overlap between major grain-producing areas and the groundwater depletion zones was evident.

The water–soil matching coefficient is a key metric for evaluating the suitability of water–soil resources for regional agriculture. In this study, we examine the spatio-temporal variation characteristics of major food crop and cultivated land water footprints in China, as well as their matching relationships. In terms of resource efficiency, improving water–soil matching should focus on two aspects: reducing the planting area of water-intensive crops such as wheat and rice, and promoting water-saving irrigation technologies like drip irrigation. In the short term, the government should discourage planting high-value crops in high-value areas through subsidies or ecological compensation measures, and establish corresponding water–soil matching monitoring mechanisms based on the growth cycles of different crops to adjust the crop planting structure according to local conditions. In the long term, relevant government departments should establish different levels of regulation areas based on the matching coefficient. In addition, the bottom line for crop water use should be set, and farmers should be encouraged to adopt water-retaining agricultural technologies to enhance the soil's water retention capacity.

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