Agricultural Groundwater Footprint of Major Cropping Patterns in the North China Plain: A Case Study of Wuqiao County, Hebei Province (Postprint)

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Abstract

This study employs the groundwater footprint analysis method, taking Wuqiao County in Hebei Province, a traditional winter wheat-summer maize double-cropping region in the North China Plain, as a case study to investigate agricultural groundwater resource consumption in the winter wheat-summer maize double-cropping system. Based on this, the impact of different crop groundwater footprints on groundwater resources was analyzed, aiming to provide a theoretical basis for planting structure adjustment in groundwater over-exploitation areas of the North China Plain. The results show that since 1949, the groundwater footprint of winter wheat in Wuqiao County has been consistently higher than that of summer maize, with multi-year average values of 89.02 km2 and 29.84 km2 for winter wheat and summer maize, respectively. In terms of trends, the groundwater footprints of both winter wheat and summer maize in Wuqiao County show a fluctuating upward trend. Regarding the crop groundwater footprint stress index (GF/Aaq), winter wheat is basically at a moderate stress level (0.1

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Full Text

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Agricultural Groundwater Footprint of the Major Cropping System in the North China Plain: A Case Study of Wuqiao County, Hebei Province*

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Abstract: This study employs groundwater footprint analysis to investigate agricultural groundwater resource consumption in the winter wheat-summer maize double-cropping system, using Wuqiao County in Hebei Province—a traditional wheat-maize rotation area in the North China Plain—as a case study. The impact of different crops' groundwater footprints on groundwater resources was analyzed to provide a theoretical basis for adjusting cropping structures in groundwater over-exploitation zones in the North China Plain. The results show that since 1949, the groundwater footprint of winter wheat in Wuqiao County has consistently exceeded that of summer maize, with mean annual values of 89.02 km^2 and 29.84 km^2, respectively. Both crops exhibited fluctuating upward trends in groundwater footprint. In terms of the crop groundwater footprint stress index (GF/Aaq), winter wheat generally fell within the moderate stress category ($0.1 < \text{GF/Aaq} < 1$), while summer maize remained in the light stress category ($0.01 < \text{GF/Aaq} < 0.1$) for most years, though both indices have increased in recent years. Calculations for other crops in the region revealed that summer peanut and potato had the lowest per-unit-area groundwater footprints at 2.08×10 km^2 and 1.94×10 km^2, respectively, with correspondingly lowest stress indices of 3.57×10^{1} and 3.34×10^{1} among the compared crops. Based on these comparisons, introducing peanut and potato as alternative crops into the local cropping structure through agricultural system adjustments could reduce groundwater resource consumption and alleviate regional groundwater pressure. Therefore, to improve agricultural groundwater utilization in the North China Plain, adjusting crop planting structures and increasing the area of multi-crop rotation between low water-consumption crops and staple grains could effectively control groundwater exploitation and achieve sustainable agricultural development.

Keywords: Winter wheat–summer maize rotation; Groundwater footprint; Groundwater footprint stress index; Plantation structure; North China Plain

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Introduction

With China’ s socio-economic development and population growth, water resource scarcity has become a critical bottleneck affecting sustainable development. Agricultural water consumption accounts for over half of national water use, with irrigation water comprising a high proportion. The North China Plain suffers from severe surface water shortages, relying extensively on groundwater for agricultural irrigation and drinking water, with agricultural groundwater extraction exceeding 70% of total groundwater withdrawal. This has led to serious groundwater over-exploitation and ecological environmental degradation in some areas, limiting agricultural sustainability in the region.

Water footprint research has been a hot topic in water resource studies both domestically and internationally. Since the water footprint concept was introduced in 2002, it has transformed traditional water resource evaluation methods and prompted new perspectives on water resource management. In this context, Gleeson et al. (2012) proposed the groundwater footprint concept as an indicator for evaluating groundwater resources and a complement to established water footprint methods. This approach links specific crops to local groundwater utilization, enabling better assessment of regional groundwater security. Han et al. used water footprint methods to evaluate water resource security in Hebei Province, concluding that approximately 80% of irrigation water in most agricultural areas is extracted from groundwater, with per capita and per unit area water resources being only 14% and 13% of national averages, respectively, making agricultural activity a dominant factor in groundwater over-exploitation. Chen et al. analyzed crop yield, economic benefit, and water use efficiency under different multi-cropping systems in the North China Plain drylands, suggesting that adjusting agricultural planting structures could control excessive water resource exploitation while ensuring regional food security. Other scholars have studied the impacts of different cropping patterns on regional groundwater balance and water use economic efficiency in the Hebei low plain, recommending a cotton (*Gossypium hirsutum*)-winter wheat (*Triticum aestivum*)-summer maize (*Zea mays*) biennial three-crop system from the perspective of sustainable agricultural water resource development. However, most of these studies relied on experimental and statistical data using water footprint methods, with few employing the novel groundwater footprint evaluation approach. Therefore, applying groundwater footprint methodology to study the impact of crop planting structures on groundwater resource utilization in China' s major groundwater consumption regions can guide sustainable groundwater use. This study examines crop planting conditions in Wuqiao County, Hebei Province, using groundwater footprint methods to calculate crop groundwater footprints for locally common crops (winter wheat and summer maize), and evaluates agricultural groundwater resource utilization through estimating crop groundwater footprint stress indices. The aim is to provide a theoretical basis for sustainable groundwater resource utilization and planting pattern adjustments in groundwater over-exploitation zones of the North China Plain.

1.1 Concept of Groundwater Footprint

Groundwater resources refer to the amount of renewable fresh groundwater that can be supplied for human use within a certain period. The groundwater footprint is defined as the area of aquifer required to maintain groundwater use and support groundwater-dependent ecosystem functions in a region. It can evaluate changes in natural storage and flow groundwater consumption and complements established water footprint methods. The concept is expressed by the following formula:

$$\mathrm{GF} = \frac{(C - R + E) \times A}{R - E}$$

where GF is groundwater footprint (km^2), C is the regional average annual groundwater extraction, R is recharge rate, E is groundwater contribution to environmental flow (m^3 · a ^{1}), and A is the aquifer area under study for C, R, and E (km^2).

Groundwater footprint essentially represents a water balance between aquifer inflow (R) and outflow (C, E), as illustrated in [Figure 1: see original paper], with data derived from observations and model outputs. Although actual groundwater extraction is difficult to obtain, C can be directly replaced by regional groundwater use. R represents the sum of long-term natural recharge and irrigation recharge inflow, while E refers to groundwater allocated to surface runoff to support ecosystem services, particularly important during low-flow periods. Recharge rate R is the primary source of uncertainty in groundwater footprint calculations and can be estimated through model outputs, chemical tracers, or field surveys.

1.2.1 Calculation Method for Crop Groundwater Footprint

Based on the formula proposed by Esnault et al. (2014) for specific crop water consumption, this study estimates crop groundwater footprint for Wuqiao County, Hebei Province:

$$\mathrm{GF}_{i,aq} = \frac{(B_{i,co}/e_{i,co} \times A_{i,co} \times p_i)}{(R_{aq} - E_{aq})}$$

where i represents a given crop type (in this study, focusing on Wuqiao County’ s traditional winter wheat-summer maize system, the calculated crops are winter wheat and summer maize); *co* denotes county-scale data; *aq* denotes aquifer-scale data. GF*i,aq* is the groundwater footprint for a specific crop and aquifer region; Bi,co* is the crop’ s net blue water requirement (i.e., net irrigation requirement); ei,co* is total irrigation efficiency (ei,co* = ec,co* × $e$ai* × em*, where* e*c,co* is water conveyance system efficiency, $e$ai* is irrigation water use efficiency, and em* is a management factor); Ai,co* is the irrigated crop area; pi* is the proportion of crop area irrigated with groundwater; Raq* is the groundwater recharge rate for the specific aquifer region; and Eaq* is environmental flow.

1.2.2 Evaluation of Crop Groundwater Footprint

After calculating crop groundwater footprint, the ratio of GF*i,aq* to regional area Aaq* yields the crop groundwater footprint stress index. A higher index indicates greater groundwater footprint occupation by the crop and higher groundwater resource consumption. To facilitate evaluation of winter wheat and summer maize stress levels in Wuqiao County, we adapted the classification method from Esnault et al. (2014), dividing GF/Aaq results into five categories:

- $GF/Aaq < 0.01$: Slight stress
- $0.01 < GF/Aaq < 0.1$: Light stress
- $0.1 < GF/Aaq < 1$: Moderate stress
- $1 < GF/Aaq < 10$: Heavy stress
- $GF/Aaq > 10$: Severe stress

1.3 Study Area and Data Sources

The North China Plain is located between 112°30 E–119°30 E and 34°46 N-40°25 N, extending from the Yan Mountains in the north to the Yellow River in the south, bordering the Bohai Sea to the east and bounded by the Taihang Mountains to the west [Figure 2: see original paper]. Administratively, it includes all plains under the jurisdiction of Beijing, Tianjin, and Hebei Province, as well as the northern Henan and western Shandong plains north of the Yellow River, covering an area of 139,200 km^2 with a total population of 133 million. Wuqiao County in Hebei Province lies in the center of the North China Plain, with average annual precipitation of 562 mm (mainly distributed in June–August), mean annual temperature of 12.9°C, accumulated temperature (0°C) of 4,826°C, frost-free period of 201 days, and annual sunshine duration of 2,724 hours. Over the past decade, average annual precipitation and temperature were 544 mm and 13.1°C, respectively.

Major crops in Wuqiao County include winter wheat, summer maize, cotton, peanut (*Arachis hypogaea*), and potato (*Solanum tuberosum*), with winter wheat, summer maize, cotton, and peanut being traditional staple crops. Liu et al. studied irrigation water requirements for China’ s major crops, providing data for some of these crops used in groundwater footprint calculations. Potato irrigation parameters were derived from studies by Wang et al., while peanut irrigation parameters came from Wan et al. Although numerous domestic studies address crop irrigation water use efficiency, few focus on regional crop-specific irrigation efficiency (e_{ai}); *therefore, we referenced values from Esnault et al. for estimation. For the management factor* (e_m), we adopted a value of 0.95 based on Rohwer et al. In Wuqiao County, farmers primarily use the “small white dragon” hose irrigation method to extract groundwater for flood irrigation, which causes 2-3% irrigation water loss according to Fu et al.; we used the minimum loss value, setting conveyance system efficiency ($e_{c,co}$) *at 0.98. Irrigated crop area* ($A_{i,co}$) data were obtained from Wuqiao County yearbooks, including winter wheat and summer maize planting areas since 1949. The proportion of crop area irrigated by groundwater (p_i) *represents the fraction of cultivated area using groundwater irrigation. Wuqiao County belongs to the Cangzhou region with scarce surface water, relying entirely on groundwater for agricultural irrigation, so* $p_i = 1$. The groundwater recharge rate (R) for Wuqiao County is $0.839 \times 10\ \mathrm{m}^3 \cdot \mathrm{a}^{\ 1}$.

This study estimates local crop groundwater footprint using the method E = 0. Relevant parameters are detailed in .

2.1 Calculation of Groundwater Footprint for Wheat and Maize in Wuqiao County

Using the crop groundwater footprint calculation method and obtained parameters for Wuqiao County, we calculated the crop groundwater footprints for winter wheat and summer maize from 1949 to 2015 [Figure 3: see original paper].

Since 1949, Wuqiao County' s winter wheat groundwater footprint has consistently exceeded that of summer maize by approximately twofold, with mean annual values of 89.02 km² and 29.84 km², respectively. Both crops show fluctuating upward trends. The peak winter wheat groundwater footprint occurred in 2015 at 165.74 km², representing a ~30% increase from 2014, with substantial overall fluctuations. Summer maize is planted in mid-to-late June when rainfall is relatively abundant, requiring less irrigation groundwater and consequently generating a smaller groundwater footprint. The figure shows that summer maize groundwater footprint has also increased steadily year by year. Without reasonable cultivation measures to control this trend, Wuqiao County's groundwater resources will face increasing pressure, and groundwater footprints for both crops will continue growing, potentially disrupting groundwater cycle balance and exacerbating regional ecological environmental problems.

2.2 Groundwater Stress Index for Winter Wheat and Summer Maize in Wuqiao County

Based on Wuqiao County' s aquifer area, we calculated the crop groundwater stress indices for winter wheat and summer maize from 1949 to 2015 . Since the aquifer area was treated as constant, the stress index trends mirror those of groundwater footprints. According to the five-tier classification system, neither crop reached the slight, heavy, or severe stress categories. Winter wheat experienced light stress in four years (1951–1953 and 1955) and moderate stress in the remaining 63 years. Summer maize showed light stress in all years except 2015, when it reached moderate stress.

Analysis of annual data reveals that winter wheat groundwater footprint stress index in Wuqiao County generally falls in the moderate category, with a rising trend in recent years. Summer maize stress index remained predominantly in the light category, showing a slow, steady increase, but jumped from 0.095 in 2014 to 0.123 in 2015, entering the moderate stress range and potentially impacting groundwater cycling.

2.3 Composition of Groundwater Footprint for Major Crops in Wuqiao County

Based on major crops mentioned in the 2013 Wuqiao County Annals, we calculated groundwater footprints, stress indices, and their proportions . Oil crop peanut had the smallest groundwater footprint at only 1.05 km^2, with a corresponding stress index of 0.002 (below 0.01), classifying it as slight stress and accounting for less than 1% of the four crops' total groundwater footprint. Summer maize had a higher footprint than peanut but lower than cotton at 55.31 km^2, with a stress index of 0.095 (light stress), comprising 23% of the total. Cotton' s groundwater footprint was slightly higher than summer maize at 61.66 km^2, with a stress index of 0.106 (moderate stress), accounting for 25% of the total—similar to maize. Winter wheat showed the highest groundwater footprint at 127.49 km^2, approximately double that of cotton, with a stress index of 0.219 and the highest proportion at 52%. Thus, in 2013, approximately 52% of Wuqiao County' s major crop groundwater footprint originated from winter wheat, ~25% from cotton, and ~23% from summer maize.

2.4 Impact Estimation for Different Crops

Per-unit-area groundwater footprints and stress indices for different crops in Wuqiao County are shown in . Winter wheat generated the highest groundwater footprint at 5.46×10   km^2·m ^{2}, while potato produced the lowest at 1.94×10   km^2·m ^{2}, reducing groundwater footprint by ~65% compared to winter wheat. Cotton generated a similar footprint to winter wheat at 5.15×10   km^2·m ^{2}, though cotton cultivation in Wuqiao has gradually decreased. Spring maize requires more irrigation than conventional summer maize, producing approximately double the groundwater footprint. Summer peanut and potato showed the lowest stress indices. If peanuts were cultivated in Wuqiao County, per-unit-area groundwater footprint would range from 2.08×10   to 3.52×10   km^2, 36–62% lower than winter wheat. Therefore, from a groundwater conservation perspective, introducing peanut and potato as alternative crops during agricultural system adjustments could reduce crop groundwater footprint and alleviate local groundwater pressure, promoting effective groundwater resource recovery.

3 Discussion and Conclusion

Water footprint studies for water resource security evaluation typically employ the virtual water methodology, calculating virtual water consumption based on production, transportation, and import/export processes. Due to lack of calculation methods and data, actual groundwater consumption by specific crops in particular regions is often estimated. This study estimated groundwater footprints for different crops in Wuqiao County, Hebei Province, and proposed suitable cropping systems from a groundwater conservation perspective. Compared with previous studies recommending cotton–winter wheat–summer maize systems based on experimental and statistical data, this research provides refinement and supplementation to planting structure adjustment strategies.

This study primarily applied the groundwater footprint method from Gleeson et al., which used relatively low-precision data for global aquifer assessments. However, Esnault et al. improved the calculation formula by integrating regional hydrological, crop, and management data, enabling more targeted accounting of groundwater resources used during crop growth periods. The crop groundwater footprint method incorporates factors such as planting area and water consumption, and after calculating the footprint value, compares it with the regional aquifer area to derive a stress index for intuitive evaluation of cropping systems' groundwater resource utilization. This methodology can provide theoretical basis and reference indicators for adjusting regional planting patterns, representing one of its application prospects.

Numerous studies have addressed groundwater level decline in the North China Plain, achieving results through water-saving irrigation, agronomic measures, and cropping pattern changes. Despite severe groundwater exploitation, certain groundwater reserves—especially deep groundwater—must still be consumed to ensure stable agricultural production and people' s livelihoods. Local governments have implemented comprehensive management measures, including groundwater extraction reduction, promotion of water-saving technologies, and agricultural planting structure adjustments, to alleviate groundwater resource issues. However, Wang et al. demonstrated that planting structure changes cause substantial variations in irrigation quotas, with crop type and dry-season precipitation being major factors affecting groundwater extraction.

Based on our groundwater footprint results, the North China Plain' s groundwater resource problems could be mitigated through crop planting structure adjustments. Calculations for Wuqiao County' s existing winter wheat–summer maize system show that each planting cycle generates approximately 7.83×10 km^2 of groundwater footprint per square meter, with a relatively high stress index. From a water conservation perspective, this study introduces low groundwater footprint crops (summer peanut and potato) and estimates their potential impact:

1. **Potato-Summer Maize System:** Plant potatoes in early March, harvest in mid-June, then plant summer maize. This system generates 4.31×10 km^2 of groundwater footprint per square meter, reducing the footprint by ~45% compared to the current winter wheat–summer maize system. If all 3.03×10 km^2 of Wuqiao County' s winter wheat–summer maize area in 2015 were converted, annual groundwater footprint could be reduced by 106.66 km^2; a 50% conversion would reduce it by 53.33 km^2.

2. **Winter Wheat-Summer Peanut System:** Replace summer maize with summer peanut during the traditional planting period. This system generates 7.54×10 km^2 of groundwater footprint per square meter, reducing the footprint by only ~4% compared to the current system. Full conversion of the 2015 planting area would reduce annual groundwater footprint by 8.79 km^2; 50% conversion would reduce it by 4.39 km^2. This

approach shows limited water-saving effects compared to the traditional system.

This study has several limitations in estimating crop groundwater footprints. The calculations considered only groundwater quantity changes (extraction, irrigation losses, utilization, and recharge) without accounting for groundwater quality, which also affects agricultural, industrial, and domestic applications. Additionally, since groundwater footprint methodology has not been widely studied or applied domestically, available data are limited. This study used county-level units, with some data and parameters derived from secondary literature sources, introducing potential biases. Future research should excavate more precise regional hydrological, geological, and agricultural data, expand research perspectives, and innovate methodologies to enhance the targeting and scientific rigor of groundwater footprint evaluation for water resource security assessment.

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