Water Conservation Capacity of Major Forest Ecosystems in the Taihang Mountains: A Postprint

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Abstract

The water conservation function of forest ecosystems is a process in which the canopy layer, litter layer, and soil layer redistribute atmospheric precipitation. This study collected and compiled data through literature review on canopy interception capacity for single rainfall events, litter layer water holding capacity, and soil layer water storage capacity of forest vegetation in the Taihang Mountain region, analyzed the interception and storage capacities of major forest vegetation types in this region for precipitation, and evaluated the comprehensive water conservation capacity of forest vegetation using the comprehensive water storage capacity method, aiming to provide a basis for rational management and administration of forest ecosystems. The results indicate: 1) Soil non-capillary porosity is positively correlated with ecosystem comprehensive water holding capacity, and the maximum water holding capacity accounts for over 90% of the comprehensive water holding capacity of the entire forest ecosystem, demonstrating that the soil layer, as the most important layer for hydrological effects in forest ecosystems, serves as the primary storage reservoir and regulator of the water cycle in the entire forest system; 2) In coniferous forests, the canopy interception capacity for single rainfall events of Pinus tabuliformis and Platycladus orientalis is significantly higher than that of other forest types, with their canopy structure being better adapted to the meteorological conditions of this region, and the precipitation redistribution capacity of their canopy layer also superior to other forest types; 3) Mixed forests have low canopy density, which is conducive to the growth of understory shrubs and grasses, and their litter standing crop is higher than that of pure forests and plantation forests; although their canopy interception capacity for single rainfall events is low, the rich litter layer under the forest facilitates water conservation; 4) The comprehensive water storage capacity of natural forests is overall higher than that of plantation forests, with Platycladus orientalis plantations and Pinus

tabuliformis plantations ranking second only to natural forests of Robinia pseudoacacia, Platycladus orientalis, and Pinus tabuliformis. In summary, rational utilization of forest resources to prevent soil and water loss, long-term enclosure of natural forests for protection, rational control of dominant tree species density, and increasing vegetation coverage are of significant importance for vegetation restoration and ecological construction in the Taihang Mountain region. To enhance the comprehensive water conservation capacity of this region, the planting area of native tree species plantations such as Pinus tabuliformis and Platycladus orientalis can be increased.

Full Text

Preamble

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Water Conservation Capacity of Forest Ecosystems in Taihang Mountain*

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Abstract

Water conservation in forest ecosystems represents a comprehensive water resource regulatory function achieved through various hydrological processes, including canopy interception, litter containment, and soil retention. As a typical northern rocky mountain region, Taihang Mountain is characterized by low rainfall with uneven seasonal distribution, shallow soil layers, low water-holding capacity, and fragile environmental conditions. Nevertheless, it serves as a critical ecological security shelter and water source protection zone for the North China Plain. Water availability has become one of the key limiting factors for vegetation protection and restoration in this region. Therefore, comparative analysis of water conservation capacities across major forest vegetation types is essential for developing feasible measures to enhance water conservation and ensure sustainable water security.

This study compiled 196 records of canopy interception, litter characteristics, and soil water-holding capacity from natural deciduous broad-leaved forests, artificial deciduous broad-leaved forests, mixed forests, natural coniferous forests, coniferous plantations, and shrublands in the Taihang Mountain region. We integrated water storage capacity with canopy rainfall interception, litter water-holding capacity, and soil water retention to analyze the water conservation capabilities of major forest vegetation types. Forest integrated water conservation capacity was calculated using a comprehensive water conservation function approach.

The results showed that: (1) Soil non-capillary porosity was positively correlated with integrated water-holding capacity of the ecosystem, and maximum soil water-holding capacity accounted for over 90% of the total water capacity of forest ecosystems in the region. This reveals that the soil layer, as the main water reservoir, constitutes the most important layer for hydrological processes in these forests. (2) Coniferous forests such as *Pinus tabuliformis* and *Platycladus orientalis* were particularly well-suited to regional meteorological conditions, with precipitation redistribution capacity significantly higher than other forest types. (3) Mixed forests exhibited lower canopy density, which facilitated understory shrub and herb growth, resulting in higher litter biomass compared to pure and artificial stands. Although canopy interception was lower, the abundant litter layer enhanced water conservation capacity. (4) Natural forests demonstrated higher overall water storage capacity than plantation forests, though *P. orientalis* and *P. tabuliformis* plantations ranked just below natural stands of *Robinia pseudoacacia*, *P. orientalis*, and *P. tabuliformis*.

In summary, rational utilization of forest resources to prevent soil erosion, long-term enclosure of natural forests, appropriate control of dominant species density, and increased vegetation coverage are crucial for vegetation restoration and ecological construction in the Taihang Mountain region. To enhance comprehensive water conservation capacity, we recommend expanding plantation areas of native species such as *P. tabuliformis* and *P. orientalis*.

Keywords: Taihang Mountain; Forest vegetation type; Water conservation; Comprehensive water retention capacity

Introduction

The interaction between forests and water has long been a focal issue in forestry and ecology, with water conservation capacity representing a crucial ecological service function of forest ecosystems—the process and ability of ecosystems to retain water within a certain spatial and temporal range. Since the late 20th and early 21st centuries, numerous scholars have investigated forest-water relationships. Growing population pressure, water scarcity, and deteriorating water quality have heightened interest in forest water conservation functions, prompting in-depth research on hydrological processes and mechanisms across different regions and scales. Studies on water conservation functions in the upper Yangtze River, Qilian Mountains, Daxing' anling, Loess Plateau, subtropical zones, major terrestrial ecosystems in China, and nationwide have provided important insights for soil and water conservation, hydrological regulation, resource utilization, ecological security barrier construction, and ecosystem management.

Multiple factors influence forest water conservation capacity, primarily including meteorological conditions, elevation, vegetation type, topography, surface litter layers, and soil characteristics, though vegetation type and soil water-holding capacity are the dominant controls. Given this complexity and dynamic nature, various accounting methods have been developed, including canopy interception remainder method, comprehensive water storage capacity method, soil water storage capacity method, precipitation storage method, and water balance method, each with distinct advantages and limitations. Among these, the comprehensive water storage capacity method is relatively ideal and most commonly used for integrated assessment. This approach evaluates water conservation through three layers: canopy interception, litter layer water absorption and retention, and soil non-capillary porosity water storage, thereby reflecting the potential capacity of the entire ecosystem to conserve and store water.

As a typical northern rocky mountain region, Taihang Mountain faces ecological disadvantages of low precipitation with uneven seasonal distribution, shallow soil layers, and low water-holding capacity, resulting in a fragile environment. Nevertheless, it serves as an important ecological barrier and water source guarantee for the North China Plain. Water has become a key limiting factor for vegetation protection and restoration, making comparative analysis of water conservation capacities among major forest vegetation types essential for developing practical recommendations to enhance water conservation and ensure water resource security in North China. While numerous case studies on forest water conservation exist for the Taihang Mountain region, most have been limited to small watersheds or individual forest communities, lacking comprehensive comparative analysis across vegetation types.

To address this gap, we compiled literature data on natural deciduous broad-leaved forests, artificial deciduous broad-leaved forests, mixed forests, natural coniferous forests, coniferous plantations, and shrublands in the Taihang Mountain region. Using the comprehensive water storage capacity method, we systematically compared canopy rainfall interception, litter water storage, and soil water-holding capacity among major forest vegetation types to analyze differences in water conservation functions. This study provides a basis for evaluating vegetation water conservation capacity, rationally managing forest resources, and implementing scientific water resource management, while also contributing to environmental protection and disaster prevention in the Taihang Mountain region.

1.1 Study Area Overview

Taihang Mountain extends from 110°14 -114°33 E, 34°34 -40°43 N, with fault structures on its eastern side creating relative elevation differences of 1,500–2,000 m. The highest peak reaches 2,882 m. Stretching over 400 km across Hebei, Beijing, Shanxi, and Henan provinces, it lies on the eastern margin of China' s second topographic step and forms the eastern boundary of the Loess Plateau. The region features a warm temperate semi-humid continental monsoon climate with distinct seasons, concurrent rainfall and heat, but longer winters and shorter summers. The mean annual temperature is approximately 10°C, with annual precipitation around 530 mm. July receives the most precipitation (approximately 130 mm), while December receives the least (less than 10 mm). The zonal soil type is primarily cinnamon soil. As an important geographical boundary in eastern China, Taihang Mountain exhibits clear differences in vegetation vertical belts between its eastern and western slopes: the eastern side belongs to the warm temperate deciduous broad-leaved forest zone with rich species diversity, while the western side falls within forest-steppe and dry steppe zones.

1.2 Data Collection and Analysis

This study utilized SRTM (Shuttle Radar Topography Mission) 90 m × 90 m DEM data to extract boundary information for the Taihang Mountain region [Figure 1: see original paper], delineating the study area and identifying major forest vegetation types. We collected data since the 1990s on precipitation, forest type, canopy density, canopy interception, litter biomass, and soil non-capillary porosity to estimate water retention capacity across canopy, litter, and soil layers. Referencing the China Vegetation Distribution Map (1:1,000,000), we established a water conservation indicator database for typical vegetation types in Taihang Mountain, obtaining 196 valid data records at the forest stand scale representing major forest and shrub vegetation types. We calculated mean values and ranges of water conservation indicators for major forest vegetation types (Table 1 shows representative vegetation data). Temporally, the dataset included 24 records from 8 papers in the 1990s, 50 records from 15 papers in the 2010s, and 122 records from the 2000s, with 86.5% of data from 2003–2013. Thus, this study primarily reflects vegetation water conservation capacity during the 2000s–2010s.

Vegetation was classified according to the Chinese vegetation classification system. Considering mountain climate zones and plant life forms in Taihang Mountain and referencing sample sizes in the literature, we categorized vegetation into four types and seven forest stands. The four vegetation types were coniferous forest, coniferous-broadleaf mixed forest, deciduous broad-leaved forest, and shrubland. Forest stands were grouped by dominant species into six representative tree communities and one shrub type: deciduous broad-leaved trees including *Tilia*, *Quercus*, *Populus*, and *Robinia*; coniferous trees including *Pinus*, *Platycladus*, and *Larix*. Referencing provincial and municipal soil survey data and county soil records from Taihang Mountain, we determined the effective depth for soil water storage evaluation as 0.4 m. For missing canopy interception data in the literature, we used the indicator database to interpolate based on relationships between adjacent similar vegetation types and NDVI values.

We compared mean water conservation capacities among major forest and shrub vegetation types using stand-level averages to represent capacity and standard deviations to reflect regional heterogeneity.

1.3 Canopy Interception Rate

Forest regulation of precipitation first manifests through canopy interception, a complex process representing the initial water distribution as rainfall reaches the ground. This process not only affects precipitation redistribution but also creates retention effects and influences nutrient input, playing a crucial role in forest ecosystem hydrological cycles. Previous research indicates that canopy interception rate (I, %) is influenced by precipitation amount (p, mm), rainfall intensity (i, $\mathrm{mm} \cdot \mathrm{h}^{1}$), wind speed ($v$, $\mathrm{m} \cdot \mathrm{s}^{1}$), and canopy density ($n$, %) [1,25]:

$I \quad f(p,\ i,\ v,\ n)$

Canopy density correlates with vegetation type and growth condition when ignoring morphological differences among individual plants (spherical, ellipsoidal, conical). Tree growth condition can be estimated through integration of field measurements and remote sensing imagery. After ignoring dynamic effects of rainfall intensity and wind speed, Formula 1 can be simplified for specific forest types based on stand type and NDVI values [25]. Therefore, we collected 30 MODIS Level 4 16-day data products (h2705, h2605, h0604) from August-September 2011-2016 (2 periods per year). After projection transformation and mosaic processing, we determined forest types through literature study areas and field surveys, selecting NDVI values within 3 km radius as canopy density sample points. We calculated multi-year average NDVI for August-September with weighting to obtain NDVI_stand for estimating precipitation interception rates across different stands.

1.4 Quantification of Forest Water Conservation Function

Forest water conservation capacity strongly correlates with climatic factors. Due to interannual temperature and precipitation variability and precipitation concentration, forest water storage capacity is dynamic. However, short-term field precipitation experiments face uncertainties due to equipment and condition limitations. Considering relatively small soil texture differences and high precipitation synchrony across the Taihang Mountain region, we used forest water conservation capacity as a comprehensive indicator integrating canopy interception, litter water-holding capacity, and soil water storage to calculate water conservation capacity across forest types (Formulas 2–5) [2,6].

Canopy interception capacity refers to interception during a single precipitation event, calculated from canopy interception and open precipitation (Formula 3). Litter water-holding capacity is calculated from litter biomass and maximum water-holding rate (Formula 4). Soil water storage is calculated from soil non-capillary porosity and soil thickness (Formula 5). This method comprehensively considers water interception across three forest layers, enabling comparison of water interception functions among different layers, though it requires extensive measured data and complex calculations.

Comprehensive water conservation capacity of forests:

$$TW_i = CI_i + LC_i + S_i \quad (2)$$

where TW_i, CI_i, LC_i, and S_i represent comprehensive water conservation capacity, single-event canopy interception, litter layer water-holding capacity per unit area, and soil layer water storage per unit area for vegetation type i, respectively (all in mm).

Single-event canopy interception:

$$CI_i = X_i - (A_i \times X_i^{B_i}) \quad (3)$$

where X_i is open precipitation for forest type i; A_i and B_i are constants in the power function equation relating canopy interception to open precipitation. Canopy interception data were directly extracted from literature. When literature provided power function equations rather than direct interception values, we adopted the original data and formulas.

Litter water-holding capacity:

$$LC_i = L_i \times W_i \quad (4)$$

where L_i is litter accumulation (t · hm ²) and W_i is maximum water-holding rate (%) for forest type i.

Soil water storage:

$$S_i = P_i \times D_i \quad (5)$$

where P_i is soil non-capillary porosity (%) and D_i is soil depth (set at 0.4 m) for forest type i.

2.1 Canopy Interception of Major Forest Vegetation Types in Taihang Mountain

Statistical analysis revealed that weighted NDVI_stand (canopy density × NDVI) for different forest growth conditions correlated with documented interception rates [Figure 2: see original paper]. Logistic regression showed that at low growth conditions (NDVI_stand < 0.4), deciduous broad-leaved forests had the highest precipitation interception rates, followed by coniferous-broadleaf mixed forests, with coniferous forests lowest. At better growth conditions (NDVI_stand > 0.6), coniferous forests showed the highest interception rates, followed by mixed forests, with broad-leaved forests lowest. We used these regression relationships to calculate missing single-event interception values in the forest water conservation indicator database.

Mean single-event canopy interception differed among forest vegetation types in Taihang Mountain . Coniferous forests dominated by *Pinus tabuliformis* and *Larix gmelinii* showed significantly higher canopy interception than deciduous broad-leaved forests dominated by *Robinia pseudoacacia*, *Populus*, *Quercus*, and *Tilia*, as well as coniferous-broadleaf mixed forests ($P < 0.05$). Coniferous forest interception reached 2.18 mm, while deciduous broad-leaved forests averaged 1.93 mm—the lowest among the three forest types, though not significantly different from mixed forests. The ranking of canopy interception capacity was: *Platycladus orientalis* > *Pinus tabuliformis* > *Quercus*/*Tilia* > *Robinia* > *Betula*/*Populus* > *Larix* > shrubland. Maximum interception was 2.53 mm for *P. orientalis* stands, while *Larix* stands had only 1.20 mm, still higher than shrubland.

2.2 Litter Water-Holding Capacity of Major Forest Vegetation Types

The litter layer represents another major water conservation stratum, performing important functions in intercepting precipitation and regulating surface runoff. Litter biomass is crucial for evaluating forest hydrological functions and is influenced by climate, forest type, stand age, soil fauna, and decomposition rates.

Mean litter biomass across Taihang Mountain stands was 14.75 t · hm ^{2}, ranging from 9.97 to 19.47 t · hm ^{2} . Mixed forests had the maximum biomass, while shrublands had the minimum. Mean maximum water-holding rate was 232.54%, ranging from 210.37% to 260.01%, with the ranking: shrubland > deciduous broad-leaved forest > mixed forest > coniferous forest. Mean maximum water-holding capacity was 3.41 mm, ranging from 1.80 to 4.27 mm, with mixed forests highest and shrublands lowest.

Litter layer water storage differed among forest types [Figure 3: see original paper], with the overall ranking: *Quercus*/*Tilia*/*Betula*/*Populus* broad-leaved forests > *Pinus*/*Larix*/*Platycladus* coniferous forests > shrublands. Maximum litter storage was 4.92 mm for *Quercus*/*Tilia* stands, while shrublands stored only 1.80 mm.

2.3 Soil Water Storage of Major Forest Vegetation Types

The soil layer serves as the primary water storage reservoir and regulator in forest ecosystems, with critical and irreplaceable water conservation capacity. Soil water storage capacity is closely related to soil texture, thickness, and porosity. After precipitation infiltration, water primarily exists in non-capillary pores. During forest growth, root turnover and litter decomposition improve soil structure, increase non-capillary porosity, enhance infiltration, and strengthen water storage functions.

Soil non-capillary porosity varied little among stands in Taihang Mountain , ranging from 10.45% to 15.62%, with deciduous broad-leaved forests highest and mixed forests lowest. Mean soil thickness was 40 cm. Mean maximum water-holding capacity of non-capillary pores in this soil depth was 52.22 mm, ranging from 43.06 to 60.27 mm, with deciduous broad-leaved forests highest and shrublands lowest.

Soil layer water-holding capacity also differed among vegetation types [Figure 3: see original paper], with the ranking: *Quercus*/*Tilia*/*Betula*/*Populus* broad-leaved forests > *Platycladus*/*Pinus*/*Larix* coniferous forests > shrublands. Maximum soil water storage was 71.32 mm for *Quercus*/*Tilia* stands, while shrublands stored only 38.82 mm.

2.4 Comprehensive Water Storage Capacity of Major Forest Vegetation Types

Total water-holding capacity comprises contributions from canopy, litter, and soil layers. Higher total capacity indicates stronger water conservation ability. Mean comprehensive water conservation capacity across Taihang Mountain forest vegetation was 64.66 mm. The ranking was: coniferous forest (*P. orientalis*, *P. tabuliformis*) > deciduous broad-leaved forest (*Quercus*, *Tilia*, *R. pseudoacacia*, *Betula*, *Populus*) > mixed forest > shrubland. The strongest capacity was 78.77 mm for *Quercus*/*Tilia* broad-leaved forests, while shrublands were weakest at 41.52 mm [Figure 3: see original paper].

Mean canopy interception ranked: natural forest (2.02 mm) > plantation (1.99 mm), with no significant difference; natural pure stand (2.10 mm) > plantation (1.99 mm), with no significant difference; natural pure stand (2.10 mm) >

natural mixed stand (1.86 mm) ($P < 0.05$).

Mean litter water-holding capacity ranked: natural forest (3.69 mm) > plantation (3.54 mm), with no significant difference; natural mixed stand (4.38 mm) > natural pure stand (3.56 mm) ($P < 0.05$); natural mixed stand (4.38 mm) > plantation (3.54 mm) ($P < 0.05$).

Mean soil water-holding capacity ranked: natural forest (61.32 mm) > plantation (57.88 mm), with no significant difference; natural pure stand (64.60 mm) > plantation (57.88 mm) ($P < 0.05$); natural pure stand (64.60 mm) > natural mixed stand (51.56 mm) ($P < 0.05$).

Mean comprehensive water storage capacity ranked: natural forest (66.68 mm) > plantation (58.63 mm), with no significant difference; natural pure stand (69.95 mm) > plantation (58.63 mm) ($P < 0.05$); natural pure stand > natural mixed stand (56.97 mm) ($P < 0.05$), with no significant difference between plantations and natural mixed stands. Water interception and storage capacities across the three layers for different vegetation types are shown in .

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3 Discussion and Conclusion

Forest water conservation function refers to the process by which forest ecosystems intercept and store precipitation through three layers—canopy, litter, and soil—thereby altering precipitation distribution, moderating surface runoff, replenishing groundwater, and effectively regulating water storage. By establishing quantitative relationships between precipitation interception rates and forest growth conditions in Taihang Mountain [Figure 2: see original paper] and employing the comprehensive water storage capacity method that emphasizes ecological processes, this study quantified water conservation across ecosystem layers, providing more realistic assessments. As a vital ecosystem service function, water conservation research guides forest management, vegetation construction, land use planning, environmental protection, and water-soil resource optimization.

Based on extensive literature analysis, we found:

1) Soil non-capillary porosity positively correlated with ecosystem integrated water-holding capacity [Figure 4a: see original paper], with maximum soil water-holding capacity accounting for over 90% of total forest ecosystem capacity [Figure 3: see original paper]. This confirms that the soil layer is the most important stratum for hydrological effects and the primary water storage reservoir and regulator in forest water cycling. Similar findings by Liu et al. [20,58] showed soil layer contributions exceeding 70% of water conservation in the Qiongjiang and Pan River basins. Therefore, soil quality improvement should be prioritized in water conservation areas. Given that soil change and restoration are slow processes, land use plan-

ning and vegetation construction schemes should first consider impacts on soil layers, and forest management should avoid exceeding soil thresholds.

2) Coniferous forests in this region showed significantly higher precipitation interception rates than broad-leaved and mixed forests, with coniferous canopy interception being highest, followed by mixed forests, and deciduous broad-leaved forests lowest . Among coniferous species, *P. tabuliformis* and *P. orientalis* showed significantly higher interception rates. This results from concentrated precipitation (July–September) with high intensity and strong winds, which favors water collection by coniferous needle clusters. The leaf morphology of *P. tabuliformis* and *P. orientalis* is particularly adapted to this climate. Their superior canopy redistribution concentrates water in root zones, benefiting overall water conservation. Additionally, these species have strong drought resistance and adaptability to harsh environments, making them suitable for vegetation construction in barren areas of Taihang Mountain.

3) Pure stands showed higher canopy interception than plantations and mixed stands. Among forest types, *P. orientalis*, *P. tabuliformis*, and *Quercus*/*Tilia* stands had higher interception due to dense foliage and large crowns. However, pure stands had lower litter water-holding capacity than mixed stands. Mixed forests' lower canopy density facilitates understory growth, resulting in higher litter biomass and maximum water-holding capacity [Figure 4b: see original paper]. This indicates that while mixed forests have weaker canopy redistribution, their litter layers are more effective for water conservation. Han et al. [60] similarly found that litter effective water storage in northern rocky mountain areas followed the pattern: coniferous-broadleaf mixed forest > broad-leaved forest > coniferous forest.

4) Natural and plantation forests showed no significant difference in canopy redistribution capacity, but natural forests had slightly higher litter water-holding capacity and significantly higher soil water-holding capacity. Consequently, natural forests demonstrated higher overall water storage capacity than plantations. Among forest types, natural *R. pseudoacacia* stands showed optimal comprehensive water storage capacity, followed by natural *P. orientalis*, natural *P. tabuliformis*, *P. orientalis* plantation, *P. tabuliformis* plantation, and natural *Quercus*/*Tilia* stands.

Forest vegetation in Taihang Mountain plays a crucial ecological regulation role throughout North China, but long-term human exploitation has resulted in low biomass production and water conservation functions, with relatively low water-holding capacity in canopy and litter layers. To improve regional water conservation capacity, we must protect natural forests while expanding plantation areas, using artificial planting of high-capacity species like *P. tabuliformis* and *P. orientalis* to replace *Larix* and shrublands. However, biodiversity' s importance for ecosystem resilience and stability must be considered, avoiding large-scale monocultures. Additionally, recent research indicates that vegetation reconstruction on the Loess Plateau is approaching sustainable water resource limits [61]. Therefore, Taihang Mountain vegetation restoration should consider actual water resources, optimize water-soil resource allocation, and aim to contribute to water supply deficits in the North China Plain and Beijing-Tianjin-Hebei region while ensuring ecological security.

In the long term, while planting water-conserving species, we must reduce human impacts and implement long-term local enclosure of natural forests. As enclosure duration increases, stand age and canopy structure develop, litter biomass increases, and soil humus from litter decomposition improves soil structure, thereby enhancing precipitation interception and storage and improving overall forest ecosystem water conservation functions.

This study analyzed and compared water conservation capacities of major forest vegetation types in Taihang Mountain based on extensive literature, providing guidance for rational forest resource management and vegetation construction. However, we did not consider understory vegetation interception, soil types, stand age, elevation, or slope differences, limiting detail and potentially causing deviations from actual conditions. Future work should integrate soil databases and GIS technology with field surveys for more systematic and visual evaluation of water conservation capacity and its contributions to the North China Plain. Additionally, as vegetation is dynamic, future research should consider temporal dynamics, investigate limiting factors for water conservation capacity across periods, and conduct more in-depth studies.

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