Urban Landscape Vegetation and Rainfall Canopy Interception:Through an Eco-Hydrological Lens

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Abstract

Urban eco-hydrology is a critical research field for sustainable urban development. Rapid urbanization has led to a significant expansion of impervious surfaces, profoundly altering urban hydrological processes. Vegetation canopy interception plays a key role in stormwater regulation and microclimate mitigation. Current research relies mainly on direct measurements, which face limitations in spatial scalability and high costs. Although models are widely used in natural ecosystems, like the revised Gash model, but their urban applications—especially in northern cities - remain limited, representing only 5.7% of relevant studies. To address these gaps, this study developed a multi-scale interception model based on the revised Gash model, incorporating planting configuration parameters for typical species in Beijing. The results demonstrate that interception capacity is significantly influenced by species traits, planting configuration, and rainfall intensity. Coniferous species consistently outperformed broadleaved species across all scenarios, with *Juniperus chinensis L.* exhibiting the highest interception (up to 18.46 mm under high rainfall intensity in 5-plant clusters). Interception increased with planting density, following the order: clump planting (5 plants) > clump planting (4 plants) > opposite planting > solitary planting. In mixed-species configurations, combinations involving high-interception species—such as *Cedrus deodara.* with *Juniperus chinensis L.*—achieved the highest interception (17.78 mm), significantly exceeding low-interception combinations such as *Prunus persica 'Duplex'.* with *Prunus triloba.* (8.13 mm). Sensitivity analysis revealed that evaporation rate (E) and canopy cover (C) were the most influential parameters under solitary planting, while canopy storage capacity (S) became increasingly important in dense planting configurations.This work enhances understanding of micro-scale hydrology and provides practical strategies for nature-based urban resilience, aiding vegetation optimization in green infrastructure (GI).

Keywords: Canopy interception, the Revised Gash model, Urban vegetation, Plant configuration

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1. Introduction

Research on the coupling mechanisms between urban water and carbon cycles represents a critical scientific direction for addressing global climate change and promoting sustainable urban development. Against the backdrop of accelerating global urbanization, China's built-up urban areas expanded from 22,400 square kilometers in 2000 to 63,700 square kilometers by 2020. The phenomenon of "imperviousization" resulting from rapid urbanization has significantly altered urban water cycle processes. Vegetation constitutes a vital component of urban ecosystems, providing essential ecological services (Sun et al.2019; Märit Jansson et al.2013; J. Lindén et al.2023). Among these, vegetation canopy interception serves as a vital component in precipitation redistribution (Zeng et al. 2000), playing a crucial role in urban water circulation systems, regulating urban stormwater runoff, and improving microclimate conditions.

Current research on canopy interception primarily employs two methods: direct measurement and model simulation. Direct measurement techniques include weighing methods (Fan et al.2015), wiping methods (Wang K et al.2025;Jenny L et al.2023;Jin et al. 2021), and spray methods (Ma et al.2015). While these methods can accurately capture interception rates at the individual plant level, they are spatially limited and involve high equipment maintenance costs. Model simulation methods offer significant advantages in spatio-temporal scalability and scenario prediction, while dynamically reflecting rainfall redistribution processes. Common models are broadly categorized into three types (Zhang et al.2000): the exponential model based on Horton's theory, Rutter's microclimatology model (Rutter et al.1972), and analytical models including the Gash model (Gash et al.1979) and the Revised Gash model (Gash et al. 1995; Valente et al. 1997; Carlyle et al.1999). Among these, the modified Gash model, incorporating canopy closure correction factors and precipitation redistribution coefficients, has been extensively studied and applied by researchers. It demonstrates good applicability in natural ecosystems such as temperate oak forests (Carlyle-Moses et al. 2018) , tropical rainforests (Fan et al. 2015), and other natural ecosystems. The Revised Gash model has demonstrated good performance in simulating canopy interception across diverse global climatic zones, including arid and semi-arid forests (Sadeghi et al.2015), temperate forests (Shi et al.2010), seasonally temperate rainforests (Link et al.2004), and tropical rainforests (Cuartas et al.2007). However, existing Gash model-based studies predominantly focus on single forest types in field settings. Current research on rainwater interception by urban horticultural plant communities primarily employs direct measurement methods, leaving significant gaps in modeling studies. This deficiency is particularly pronounced in northern cities, where regional characteristics—such as short vegetation growing seasons and unique canopy structures (e.g., mixed broadleaf deciduous and evergreen coniferous forests)—further limit relevant studies, which constitute only 5.7% of comparable research. Furthermore, current urban vegetation retention studies have not fully addressed the "nature-society" synergy emphasized in the dual water cycle theory (Wang et al.2016). Urban vegetation retention models must simultaneously integrate natural precipitation processes with the runoff regulation objectives of the social water cycle.

Urban vegetation, particularly the canopy layer of trees, serves as the primary green sponge in urban ecosystems. Through processes such as retention, absorption, and evaporation of precipitation, it actively regulates water volume during the initial stages of rainfall. How to effectively utilize plants through rational configuration to regulate urban hydrological processes and enhance water resource utilization efficiency is a crucial aspect of sponge city research (Li et al. 2022). This study focuses on typical landscape plants and plant configurations in Beijing. Based on the modified Gash model, it constructs a diversified, multi-scale interception simulation framework implemented via Python algorithms. Innovatively incorporating plant community configuration parameters into model refinement, it systematically analyzes interception efficiency differences under various plant configuration patterns. The findings provide quantitative design guidelines for plant landscape configurations in northern sponge city construction, advancing urban green spaces from a "landscape-function-dominated" paradigm toward "hydrological regulation-carbon sequestration synergy." By establishing a comprehensive research framework encompassing "mechanism study-model optimization-application transformation," this work aims to offer novel research approaches and solutions for stormwater management and carbon neutrality goals in high-density cities. Research on urban canopy retention not only explores micro-level components of the hydrological cycle but also holds practical significance for optimizing green space layout and structural design. It clarifies the retention effects of various green space parameters—including tree species, configuration methods, and mixed patterns—guiding the selection of high-retention native tree species and the establishment of multi-layered vegetation communities and sponge cities. This helps propel cities toward resilience-based adaptation rather than flood resistance, prioritizing nature over engineering dependency, and from single-function approaches to integrated systems. This research provides a crucial theoretical foundation and practical guide for building sustainable, livable, and resilient future cities, holding profound strategic significance. It further advances the synergistic development of Green Infrastructure (GI) and Low Impact Development (LID) systems.

2. Methodology

2.1 Study area

Beijing, as a typical northern megacity, features a temperate monsoon climate. The municipality administers 16 districts, and with urbanization, its built-up land area has significantly expanded (Jia et al. 2014; Li et al. 2015; Wu et al. 2006). The average annual precipitation over the past decade has been 555.99 mm, characterized by rainy summers and dry winters. Over 70% of precipitation occurs during summer, while winter accounts for only about 2%, predominantly as snowfall. Due to climatic influences, Beijing rarely experiences consecutive days of rainfall. Beijing's vegetation primarily consists of deciduous broadleaf forests and mixed coniferous-broadleaf forests. Through long-term urban development and ecological practices, the city's landscape plantings have evolved into a unique configuration system that integrates ecological functions, cultural significance, and aesthetic qualities. Regarding ecological suitability principles, the selection and arrangement of greenery plants must fully consider local natural conditions, including climate, soil, and hydrology. Beijing's landscape plants are dominated by drought-resistant, cold-tolerant, and dust-trapping native tree species, such as *Juniperus* *chinensis L.*, *Styphnolobium japonicum (L.) Schott.*, among others. These are complemented by shrubs like *Forsythia suspensa (Thunb.) Vahl.* and *Berberis thunbergii 'Atropurpurea'.*, as well as groundcover plants such as *Ophiopogon japonicus (L. f.) Ker Gawl.* and *Iris tectorum Maxim.* to establish a "tree-shrub-herb" multi-layered mixed planting pattern. "Tree-herb" and "shrub-herb" planting patterns also exist. This vertically integrated structure not only adheres to aesthetic principles in landscape design—creating beautiful, comfortable, and distinctive spatial environments through horticultural plants—but also significantly enhances the water retention capacity per unit area through canopy interlocking effects, thereby boosting the hydrological benefits of garden landscapes. Observation data indicates that canopy interception rates in multi-layered stands can reach 1.3–1.8 times those of single-layer pure stands (Zhang et al. 2021).

Additionally, in the process of landscaping plant arrangements in Beijing, beyond considering the rational combination of trees, shrubs, and grasses, the characteristics of seasonal changes and growth cycles are also taken into account. Flexible use of mixed plantings featuring flowering, foliage, and bark-accentuating tree species creates distinct seasonal landscapes, ensuring sustainable visual appeal. While enhancing the ornamental value of gardens, emphasis is placed on improving the stability of greenery communities. Plant landscape configurations highly respond to the heterogeneity of urban microenvironments. This differentiated configuration strategy enables Beijing's landscape plants to meet urban spatial constraints while maximizing hydrological benefits through canopy parameter regulation.

2.2 Construction of the Revised Gash Model and Algorithm Framework

The Gash model, proposed by Gash in 1979 based on Rutter's microclimatology model, is a classic analytical model frequently used in ecological hydrology research to calculate vegetation canopy rainfall interception. This model describes the temporal variation of canopy interception based on the law of mass conservation and water balance equations, finding extensive application in simulating hydrological processes within ecosystems. The Revised Gash model was developed in 1995 by Gash et al. by incorporating canopy closure as an additional factor into the original model. This modification enables more accurate simulation of forest canopy characteristics and broadens the model's applicability. The core framework of the Revised Gash modelremains grounded in the fundamental principles of the original model. Within the model, each rainfall event is treated as a rainfall redistribution process, as illustrated in figure1Crown interception is determined by calculating the relationship between rainfall penetration, stemflow, and interception. The Revised Gash model divides each rainfall event into three stages: the wetting stage when rainfall intensity is insufficient to saturate the entire canopy, the saturation stage when the entire canopy reaches saturation, and the drying stage after rainfall ceases. It assumes the canopy is fully dry before each rainfall event. The specific expression is given by Equation (1):

$$\sum_{j=1}^{m+n} I_j = c\sum_{j=1}^{m} P_{Gj} + \sum_{j=1}^{n}\left(\frac{c\overline{E}_e}{\overline{R}}\right)\left(P_G - P'_G\right) + c\sum_{j=1}^{n} P'_G + qcS_t + cP_t\left(1-\frac{E_G}{R}\right)\sum_{j=1}^{n-q}\left(P_{Gj} - P'_c\right) \qquad (1)$$

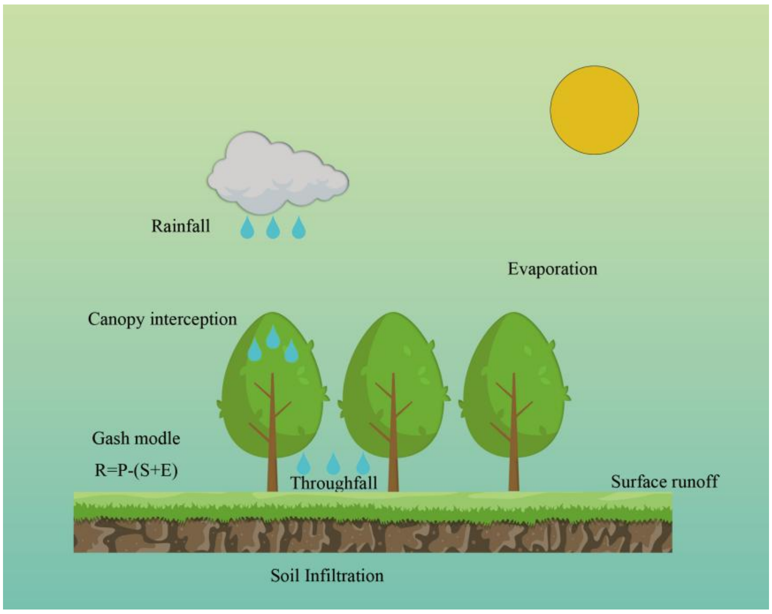

Fig. 1 Rainfall Redistribution Process of the Gash Model

This study builds upon the original formula algorithm of the Gash model and the planting characteristics of Beijing's landscape plants. Using Python programming software, a modified Gash model more suited to urban greening was constructed as the foundational model for this research. The model primarily consists of three components: the core computational module, the parameter generator, and the main program runtime. The core computational module is the most critical part, formed by implementing the fundamental algorithms and formulas of the Gash model, defining and configuring various parameters, and incorporating a dynamic parameter generator. Dynamic parameters include: "S" (water storage capacity), "C" (canopy closure, range 0–1), "St" (stemflow capacity), "p" (penetrating rainfall proportion, range 0–1), "pt" (stemflow proportion, range 0–1), "P" (total precipitation), "R" (rainfall intensity), and "E" (evaporation rate). Strictly controlling 'R' (rainfall intensity) ensures it remains greater than "E" (evaporation rate). Compared to the original Gash model, this model enables simulation calculations for water interception across different tree species by modifying dynamic parameters. It can simultaneously calculate interception volumes for various landscape plant configurations, including solitary, paired, and clustered plantings. Based on the fundamental algorithmic formula and simulation conditions of the Revised Gash modelconstructed, the additional overlay algorithms for canopy closure and total water storage capacity incorporated into this model are calculated as follows:

$$C_t = \begin{cases} C_{single} \\ 1-(1-C_{single})^n \end{cases} \tag{2}$$

$$S_t = S_{single} \cdot (1+\alpha \cdot (n-1)) \tag{3}$$

Here, Ct is the total canopy closure, Csingle is the canopy closure of a single plant, and n is the number of simulated plants ($n \geq 3$; when $n \leq 2$, Ct = Csingle); St is the total water storage capacity, Ssingle is the water storage capacity of a single plant, and α is the synergy coefficient.

In the first stage of the model (wetting stage), the calculation formula for P′ (rainfall during the wetting stage) is:

$$P' = \frac{S \cdot C}{1 - \mathrm{p}} \tag{4}$$

$$t = \frac{P}{R} \tag{5}$$

Here, P′is the rainfall during the wetting stage, S is the canopy water storage capacity, C is the canopy closure, p is the throughfall ratio, t is the rainfall duration, P is the total rainfall, and R is the rainfall intensity.

The interception calculation formula for the canopy during the first stage of the wet period is:

$$I' = (1 - p)P + E \cdot t \tag{6}$$

The canopy water storage capacity S is a critical parameter in the model. It is typically estimated using regression analysis, scale extrapolation, and remote sensing methods. This study references the interception research by Chinese scholars Liu et al. on South Asian evergreen broadleaf forests and Chen et al. on Pinus massoniana forests (Liu 2016; Chen 2022), employing Leyton's method (Liu et al. 1998). The relationship between stemflow capacity St and atmospheric precipitation is determined using Llorens' relationship equation (Llorens et al. 1997). The overall operational logic of the model code is as follows: When the code begins execution, it first determines the model's current stage by calculating the magnitude relationship between P′ and P. When P′ ≤ P, the canopy water storage capacity has not yet reached its maximum, indicating the moist stage within the original Gash model. At this point, the interception amount is calculated using formula (6). When P′ > P, the interception amount is determined as the entire canopy reaches the saturated stage. and the interception calculation formula becomes the fully modified Gash model formula incorporating parameters such as stemflow.

Based on the aforementioned base model, a second interception model—the "Clump Planting Mixed Interception Model." —was constructed in Python. This model specifically simulates the interception of rainfall for two plant species planted in a five-plant cluster configuration within landscape plant arrangements. The key difference from the previous model lies in its focus: while the original model calculated interception rates for the same plant species under varying rainfall intensities and different arrangement combinations, the new model compares interception rates for different plant species combinations under identical landscape plant arrangements across varying rainfall intensities. This model was developed by modifying the existing Gash model for landscape plants to calculate rainfall interception in mixed-species groupings. In addition to the aforementioned calculation methods and formulas, it incorporates the following formula (where k and m represent the number of broadleaf trees and coniferous trees, respectively, with k+m=5):

$$S_{\text{total}} = \left(\mathrm{k}^{0.7} \cdot S_{\mathrm{b}} + \mathrm{m}^{0.7} \cdot S_{\mathrm{c}}\right)\alpha_{\text{factor}} \qquad (7)$$

Here, Stotal is the total canopy water storage capacity, Sb is the canopy water storage capacity of broad-leaved forests, Sc is the canopy water storage capacity of coniferous forests, and α factor is the actual adjacent plant influence coefficient, derived from the adjacent plant influence coefficient.

$$\alpha_{\text{factor}} = 1 + \alpha(\mathrm{n}-1)^{0.8} \qquad (8)$$

Here, α is the adjacent plant influence coefficient, and n is the number of planted plants (generally set to 5 in this model).

$$C_{\text{total}} = 1 - 0.9\left(1-\mathrm{C_b}\right)^{\mathrm{k}} \times \left(1-\mathrm{C_c}\right)^{\mathrm{m}} \qquad (9)$$

Here, Ctotal is the total canopy closure, Cb is the canopy closure of broad-leaved forests, and Cc is the canopy closure of coniferous forests.

$$\mathrm{p}_{\text{total}} = \frac{\mathrm{k}^{1.2} \cdot \mathrm{pb} + \mathrm{m}^{1.2} \cdot \mathrm{pc}}{\mathrm{k}^{1.2} + \mathrm{m}^{1.2}} \qquad (10)$$

Here, ptotal is the total throughfall, pb is the throughfall of broad-leaved forests, and pc is the throughfall of coniferous forests.

This study primarily constructs a calculation model for urban landscape plant configuration interception and a mixed clump planting interception model based on the modified Gash model. The simulated study area is Beijing, a central city in northern China. Appropriate tree species for simulation were selected based on Beijing's landscaping characteristics, considering both the Beijing Municipal Bureau of Landscape and Forestry's "Catalogue of Major Native Tree Species in Beijing (2021 Edition)" and plants commonly used in Beijing's greening configurations. The selected plants are as follows: *Juniperus chinensis L., Cedrus deodara (Roxb.) G. Don., Pinus tabuliformis Carrière., Styphnolobium japonicum (L.) Schott., Ginkgo biloba L., Populus tomentosa Carrière., Prunus persica 'Duplex'.* and *Prunus triloba Lindl.*.

Based on the selected plants and an investigation of clump planting configurations in Beijing's greening projects, common plant combinations were chosen for simulation using the "Clump Planting Mixed Interception Model." The selected mixed planting types include: *Prunus persica 'Duplex'.* and *Pinus tabuliformis Carrière., Prunus persica 'Duplex'.* and *Ginkgo biloba L., Prunus persica 'Duplex'.* and *Prunus triloba Lindl., Cedrus deodara (Roxb.) G. Don.* and *Pinus tabuliformis Carrière., Cedrus deodara (Roxb.) G. Don.* and *Juniperus chinensis L., Cedrus deodara (Roxb.) G. Don.* and *Styphnolobium japonicum (L.) Schott., Prunus triloba Lindl.* and *Ginkgo biloba L., Prunus triloba Lindl.* and *Populus tomentosa Carrière., Prunus triloba Lindl. a*nd *Pinus tabuliformis Carrière., Ginkgo biloba L.* and *Populus tomentosa Carrière., Ginkgo biloba L.* and *Styphnolobium japonicum (L.) Schott., Ginkgo biloba L.* and *Cedrus deodara (Roxb.) G. Don.*totaling 12 types. Simulation calculations were performed based on the selected study tree species and mixed planting types. Rainfall scenarios were simulated using precipitation data from Beijing's hydrological yearbook. Three rainfall intensity gradients were selected in the model: low intensity (P=10mm, R=2mm/h), medium intensity (P=25mm, R=4.5mm/h), and high intensity (P=60mm, R=10mm/h). Parameter values were determined through field measurements, empirical formulas, and literature references. The model simulation results were then analyzed to investigate differences in interception capacity among plant species, sensitivity analysis of parameters, and simulation outcomes of various plant groupings. Conclusions were ultimately drawn.

Considering the diversity of plant combinations in mixed plantings, the model simulation for retention capacity was conducted using only two plant species with five plants each. Four configuration scenarios are set as shown in table 1 below.

Table 1 Table of Configuration Quantities of Plant A and Plant B Under the "Clump Planting Mixed Interception Model"

	Number of plant species A	Number of plant species B

Scenario 1	1	4
Scenario 2	2	3
Scenario 3	3	2
Scenario 4	4	1

3. Research Results

3.1 Interception Capacity and Sensitivity Analysis of the Same Tree Species Under Different Planting Modes

Based on the Revised Gash model algorithm constructed by the above-mentioned Python software code, the interception capacity of several common arbor and shrub species in Beijing was calculated under different rainfall intensities. The calculation results are shown in Figures 2 to 4 (here *Juniperus chinensis L.* is J.chi、*Cedrus deodara (Roxb.) G. Don.* is C.deo、*Pinus tabuliformis Carrière.* is P.tab、*Styphnolobium japonicum (L.) Schott.* is S.jap、*Ginkgo biloba L.* is G. b、*Populus tomentosa Carrière.* is P.tom、*Prunus persica 'Duplex'.* is P. per、*Prunus triloba Lindl.* is P.tri), which respectively represent the canopy interception capacities of the 8 selected plant species under different gradient rainfall conditions.

In Figure 2 (low-intensity rainfall scenario), for the configurations of single planting, paired planting, and cluster planting of 3 plants, the species with the highest interception capacity was *Juniperus chinensis L.*, with interception values of 4.86 mm and 6.99 mm. For the configurations of cluster planting of 4 plants and 5 plants, the species with the highest interception capacity was *Cedrus deodara (Roxb.) G. Don.*, with both interception values reaching 10 mm. The lowest interception capacity was observed in the single-planted *Prunus triloba Lindl.*, with an interception value of only 2.98 mm. Affected by rainfall intensity, most plant species with strong interception capacity reached their maximum interception capacity under the cluster planting configuration in this scenario.

In Figure 3 (moderate-intensity rainfall scenario), *Juniperus chinensis L.* had the highest interception capacity under all configurations: the interception value for single planting was 5.94 mm, and the maximum interception value (16.22 mm) was achieved under cluster planting of 5 plants. The lowest interception capacity under all configurations was observed in *Prunus triloba Lindl.*: the interception value for single planting was only 3.25 mm, and that for cluster planting of 5 plants was only 7.02 mm.

In Figure 4 (high-intensity rainfall scenario), the situation was similar to that of moderate-intensity rainfall: *Juniperus chinensis L.* still had the highest interception capacity, with an interception value of 6.39 mm for single planting and 18.46 mm for cluster planting of 5 plants.

Under low rainfall intensity, plant species with high interception capacity—such as *Cedrus deodara (Roxb.) G. Don.*, *Pinus tabuliformis Carrière.*, *Juniperus chinensis L.*, *Styphnolobium japonicum (L.) Schott*., and *Populus tomentosa Carrière.*—were more likely to reach canopy saturation under cluster planting.

Across the three rainfall scenarios, the interception capacities of all plant species, when ranked from highest to lowest, were as follows: J*uniperus chinensis L. > Cedrus deodara (Roxb.) G. Don. > Pinus tabuliformis Carrière. > Styphnolobium japonicum (L.) Schott. > Populus tomentosa Carrière. > Ginkgo biloba L. > Prunus persica 'Duplex' > Prunus triloba Lindl. Specifically*, under low rainfall intensity, the interception capacity of single-planted *Cedrus deodara (Roxb.) G. Don.* was lower than that of single-planted *Pinus tabuliformis Carrière.*; under moderate rainfall intensity, the two species had equal interception capacity; under high rainfall intensity, the interception capacity of single-planted *Cedrus deodara (Roxb.) G. Don.* was higher than that of single-planted *Pinus tabuliformis Carrière.* However, under high rainfall intensity, the interception capacity of *Pinus tabuliformis Carrière.* was higher than that of *Cedrus deodara (Roxb.) G. Don.* under all three cluster planting configurations. Under low rainfall intensity, plant species with high interception capacity reached their maximum saturation interception capacity when cluster-planted in groups of 4 or 5. For all tree species, the interception capacity was the lowest under single planting and increased with the number of configured plants; the maximum interception capacity of all plants was achieved under cluster planting of 5 plants. Among them, *Cedrus deodara (Roxb.) G. Don.* exhibited the best interception effect under cluster planting (surpassing other plants) under low rainfall intensity, while

Juniperus chinensis L. showed the best interception effect under moderate and high rainfall intensities.

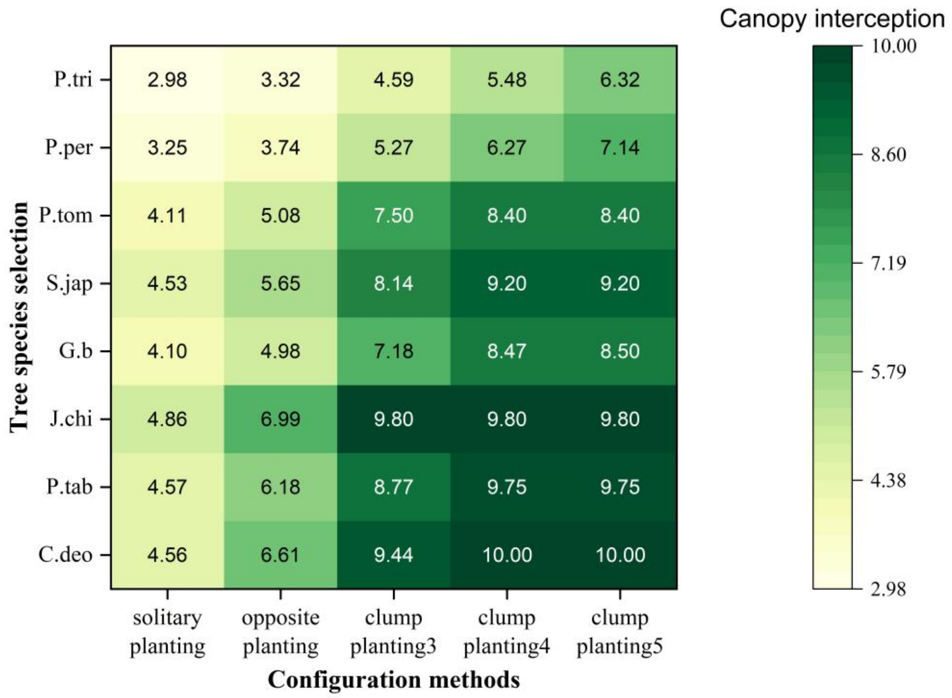

Fig. 2 Interception Results Under Low Rainfall Intensity

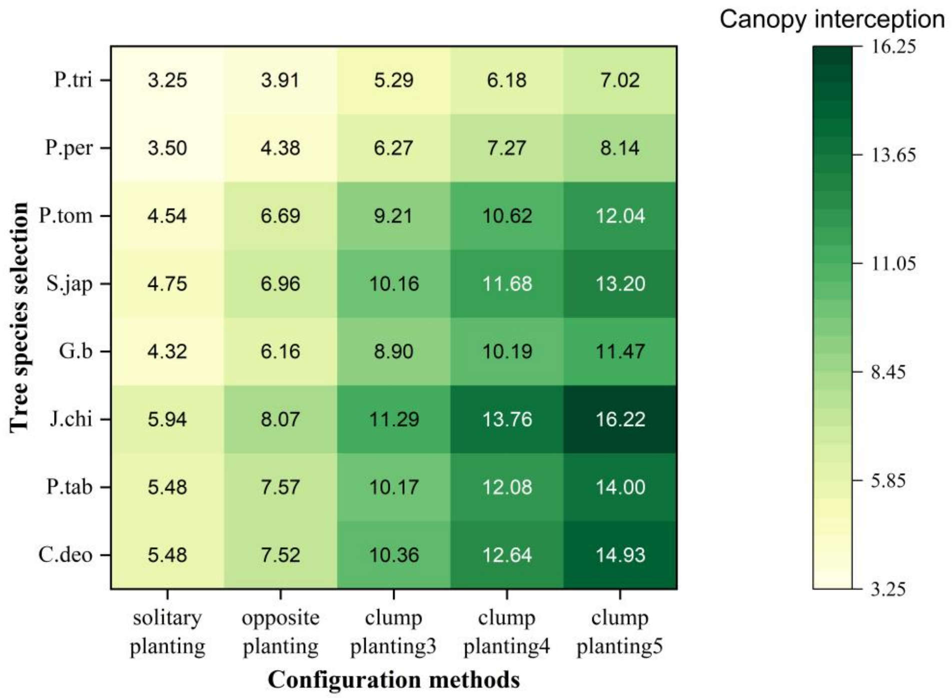

Fig. 3 Interception Results Under Moderate Rainfall Intensity

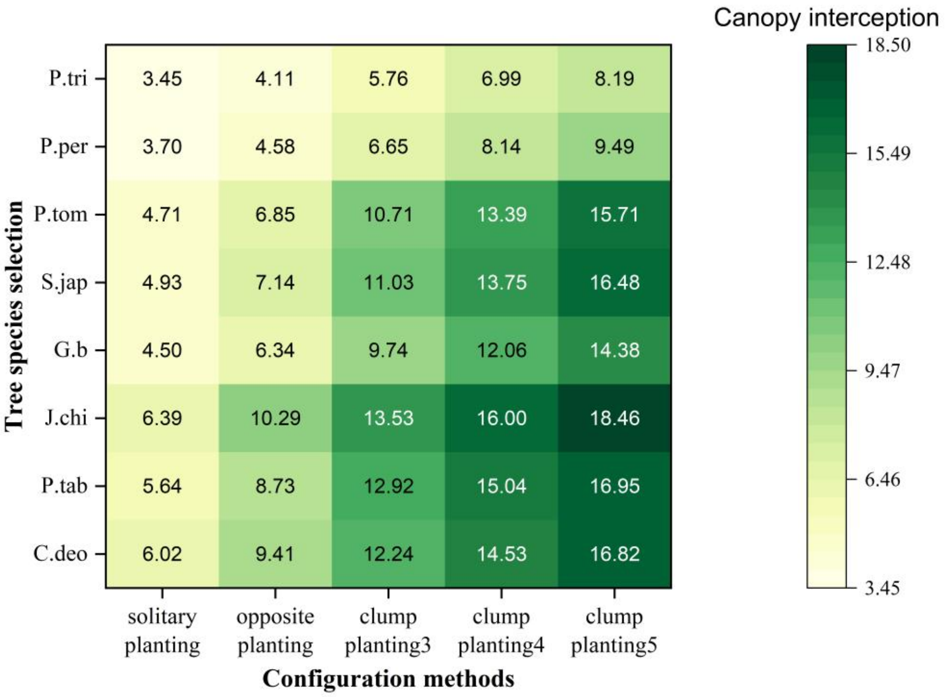

Fig. 4 Interception Results Under Intense Rainfall Intensity

An analysis of the variation trend in interception capacity of the 8 selected plant species (the research objects) under different rainfall intensities is shown in Figure 5, where panels a to h represent the variation trends of "*Cedrus deodara (Roxb.) G. Don., Pinus tabuliformis Carrière., Juniperus chinensis L., Ginkgo biloba L., Styphnolobium japonicum (L.) Schott., Populus tomentosa Carrière., Prunus persica 'Duplex'., and Prunus triloba Lindl.*," respectively. As shown in the figure, the absolute values of interception capacity differ among different tree species, but the influencing rule of planting methods is consistent: cluster planting > paired planting > single planting. Moreover, the interception effect increases with the number of plants. For all plant species, the interception capacity is the highest when 5 plants are cluster-planted and the lowest when planted singly. By comparing the variation trends under different rainfall intensities, it can be found that the interception capacity of all plants increases with the increase of rainfall intensity. Under low, moderate, and high rainfall intensities, the interception capacity of all tree species shows an upward trend (all curves extend to the upper right), indicating that the higher the rainfall intensity, the better the interception effect. Among different planting methods, the interception capacity of single-planted plants increases relatively slowly, showing the worst growth effect; paired planting ranks second; and the most significant growth is observed in cluster planting—especially when 5 plants are cluster-planted, the interception capacity of plants shows a distinct upward trend with the increase of rainfall intensity. For *Cedrus deodara (Roxb.) G. Don.*, *Pinus tabuliformis Carrière., Juniperus chinensis L., Ginkgo biloba L., Styphnolobium japonicum (L.) Schott., and Populus tomentosa Carrière*., the interception capacity values under cluster planting of 4 plants and 5 plants are close under low rainfall intensity, with obvious differences only appearing under moderate and high rainfall intensities. In contrast, *Prunus persica 'Duplex'.* and *Prunus triloba Lindl.* show significant differences in interception capacity among various planting methods under low, moderate, and high rainfall intensities. Among the 8 plant species, *Juniperus chinensis L.* has the fastest growth rate of interception capacity—especially when 5 *Juniperus chinensis L.* plants are cluster-planted, its interception capacity increases significantly with the rise of rainfall intensity. This indicates that *Juniperus chinensis L*. has the strongest canopy water-holding capacity. For *Pinus tabuliformis Carrière.*, the increase in interception capacity is not obvious when rainfall intensity changes from moderate to high.

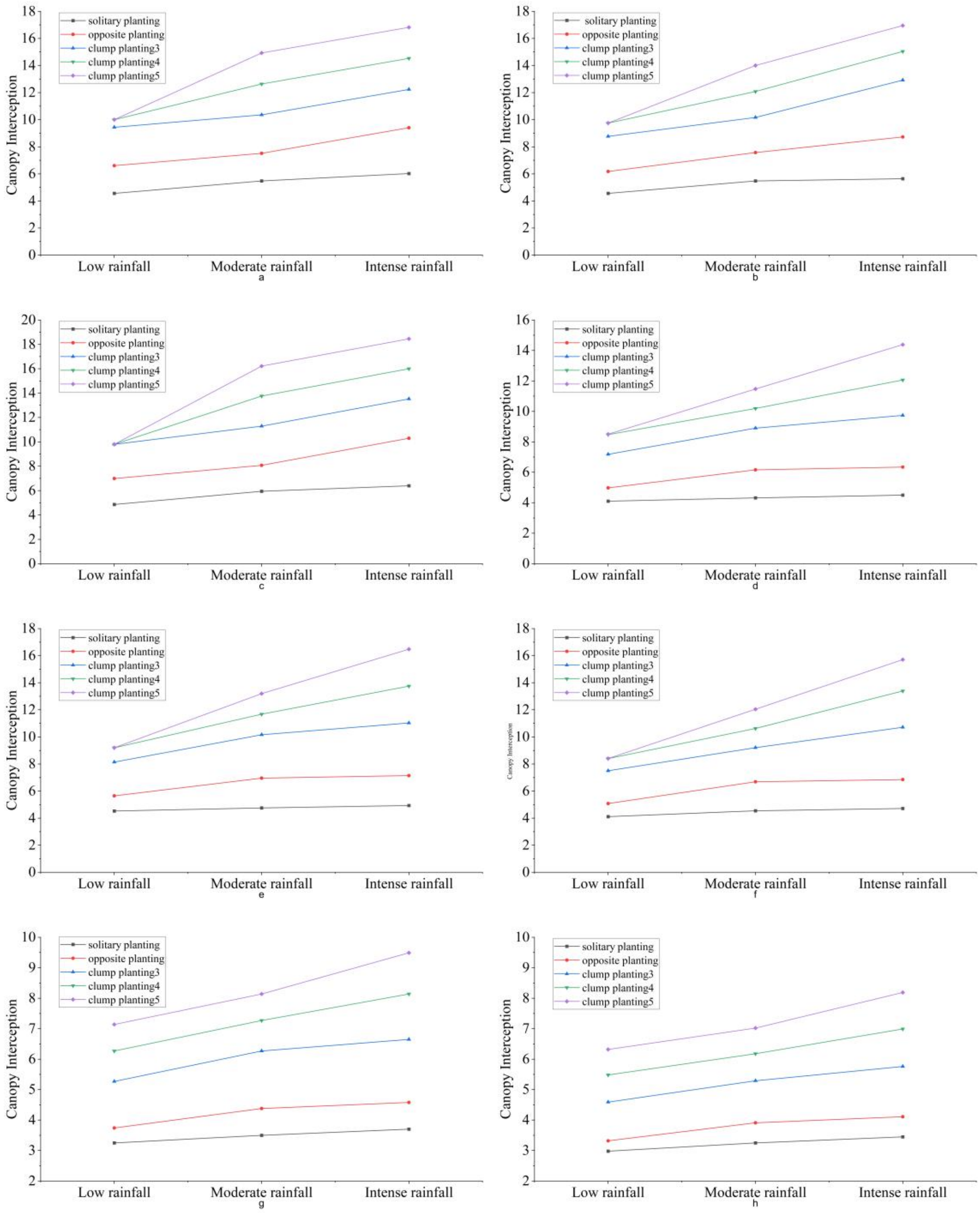

Fig. 5 Trends of Different Urban Vegetation Under Different Rainfall Intensities

According to the research results, the sensitivity analysis of the parameters in the model is shown in Figure 6. In the figure, the evaporation rate (E) of single-planted plants is the most sensitive, followed by the canopy closure (c). Both parameters have strong sensitivity. The sensitivity of the canopy water-holding capacity (S) is relatively weaker than the previous two parameters, while the sensitivities of the stem water-holding capacity (St) and the runoff ratio (Pt) are low, which have little impact on canopy interception. The sensitivity changes with the increase in the number of configured plants. The sensitivity of parameter E gradually decreases, reaching the lowest in the case of 5-plant cluster planting. The sensitivities of parameter S and parameter c gradually increase, reaching the maximum in the case of 5-plant cluster planting.

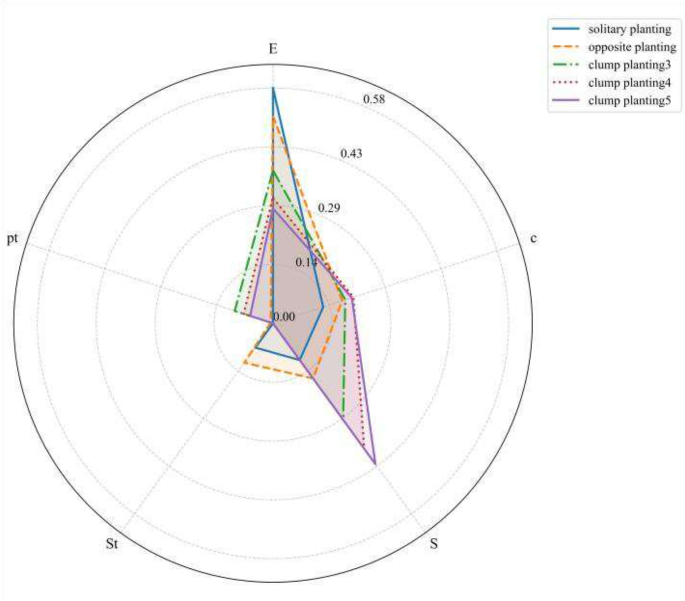

Fig. 6 Chart of Sensitivity Analysis

3.2 Results of Interception Capacity Under Different Plant Combination Scenarios

Based on the aforementioned selected tree species and 12 mixed plant combination scenarios, interception simulations were conducted for all cases of 5-plant cluster planting under 3 different rainfall intensities, resulting in a total of 144 sets of data. A comparative analysis was performed to determine the interception capacity of different combinations under the 5-plant cluster planting condition. Among these, the single-plant planting scenario of each species was used as a reference to verify consistency with the calculation results of the previous model. After calculation, the single-plant interception capacity of each plant in the mixed interception model for all combination types of cluster planting was consistent with the simulation results of the previous model, confirming the rationality of the model calculation. According to the results, under all combination types, the area of the purple region (representing high rainfall intensity) was the largest, followed by the green area (representing moderate rainfall intensity), and the orange area (representing low rainfall intensity) was the smallest. This indicates that interception capacity increases significantly with the increase in rainfall intensity.

Figure 7 shows the interception capacity of *Prunus persica 'Duplex'* combined with different plants, where panels a to c represent combinations with *Ginkgo biloba L*., *Pinus tabuliformis Carrière*., and *Prunus triloba Lindl.*, respectively. Among these combinations, the one with the highest interception capacity was the combination of 1 *Prunus persica 'Duplex'* plant and 4 *Pinus tabuliformis Carrière*. plants (panel b), which reached 15.34 mm under high rainfall intensity. The lowest interception capacity was observed in the combination of 2 *Prunus persica 'Duplex'* plants and 3 *Prunus triloba Lindl.* plants (panel c), with only 6.14 mm under low rainfall intensity.

Figure 8 presents the interception capacity of *Cedrus deodara (Roxb.) G. Don.* combined with different plants, where panels a to c represent combinations with *Pinus tabuliformis Carrière.*, *Juniperus chinensis L*., and *Styphnolobium japonicum (L.) Schott.*, respectively. The combination with the highest interception capacity was the pairing of 1 *Cedrus deodara (Roxb.) G. Don.* plant and 4 *Juniperus chinensis L.* plants (panel b), achieving 17.78 mm under high rainfall intensity. The combination with the lowest interception capacity was 1 *Cedrus deodara (Roxb.) G. Don.* plant and 4 *Styphnolobium japonicum (L.) Schott.* plants (panel c), with 9.4 mm under low rainfall intensity. In the mixed planting scenario of *Cedrus deodara (Roxb.) G. Don.* and *Styphnolobium japonicum (L.) Schott.*, the combination of 1 *Cedrus deodara (Roxb.) G. Don.* plant and 4 *Styphnolobium japonicum (L.) Schott.* plants had the highest interception capacity (16.95 mm), which was 0.13 mm higher than that of the pure 5-plant *Cedrus deodara (Roxb.) G. Don.* planting and 0.47 mm higher than that of the pure 5-plant *Styphnolobium japonicum (L.) Schott.* planting.

Figure 9 displays the interception capacity of *Ginkgo biloba L.* combined with different plants, where panels a to c represent combinations with *Populus tomentosa Carrière., Styphnolobium japonicum (L.) Schott.,* and *Cedrus deodara (Roxb.) G. Don.*, respectively. The combination with the highest interception capacity was 1 *Ginkgo biloba L.* plant and 4 *Cedrus deodara (Roxb.) G. Don.* plants (panel c), with 15.9 mm under high rainfall intensity. The lowest interception capacity was found in the combination of 1 *Ginkgo biloba L.* plant and 4 *Populus tomentosa Carrière.* plants (panel a), with only 8.4 mm.

Figure 10 shows the interception capacity of *Prunus triloba Lindl.* combined with different plants, where panels a to c represent combinations with *Ginkgo biloba L.*, *Populus tomentosa Carrière.*, and *Pinus tabuliformis Carrière.*, respectively. The combination with the highest interception capacity was 1 *Prunus triloba Lindl.* plant and 4 *Pinus tabuliformis Carrière.* plants (panel c), with 14.69 mm. The lowest interception capacity was observed in the combination of 4 *Prunus triloba Lindl.* plants and 1 *Ginkgo biloba L.* plant, with 6.95 mm under low rainfall intensity.

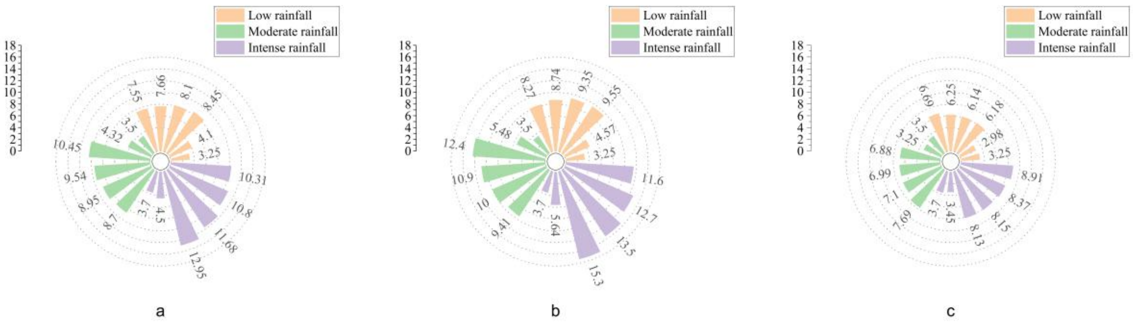

Fig. 7 interception of *Prunus persica 'Duplex'.* in Combination with Different Plants

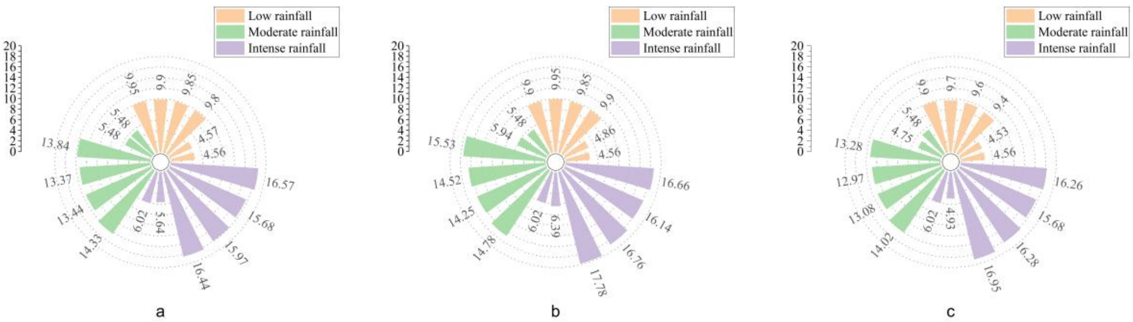

Fig. 8 interception of *Cedrus deodara(Roxb.)G.Don.* in Combination with Different Plants

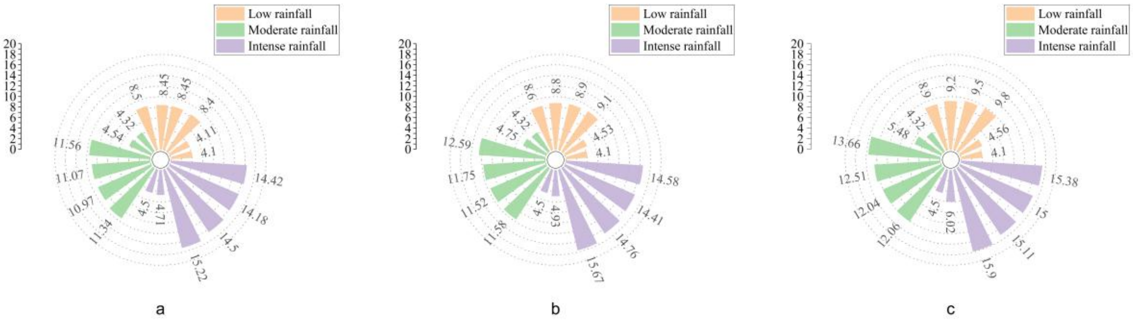

Fig. 9 interception of *Ginkgo biloba L.*in Combination with Different Plants

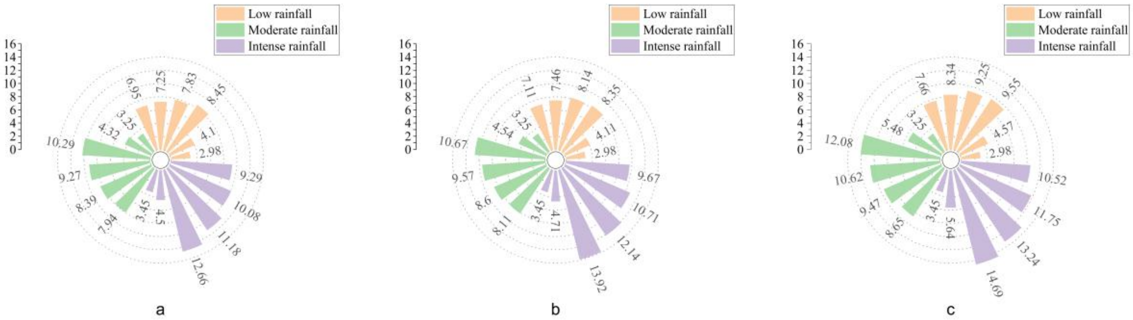

Fig. 10 interception of *Prunus triloba Lindl.*in Combination with Different Plants

4. Discussion and Conclusions

This study employed a modified Gash model to simulate rainfall interception by various garden plants under three distinct rainfall intensity scenarios. Based on the obtained interception data, the results were analyzed in descending order of interception rates: *Juniperus chinensis L., Cedrus deodara (Roxb.) G. Don., Pinus tabuliformis Carrière.* are High-canopy interception urban vegetation, *Styphnolobium japonicum (L.) Schott., Populus tomentosa Carrière., Ginkgo biloba L.* are Mid-canopy interception urban vegetation, *Prunus persica 'Duplex'. and Prunus triloba Lindl.* are Low-canopy interception urban vegetation. Through sorting, it can be observed that the three tree species with the highest retention rates are all conifers, while the species with the lowest retention rate is a broadleaf dwarf shrub. The study suggests that in terms of tree species classification, coniferous forests exhibit higher retention rates than broadleaf forests. Regarding tree morphology, tall trees demonstrate greater retention capacity than small shrubs. The narrow needles of conifers (such as *Juniperus chinensis L. and Cedrus deodara (Roxb.) G. Don.*) significantly increase their maximum canopy water storage capacity by substantially enlarging their specific surface area through clustered arrangements of narrow needles. Combined with dense canopy shapes or layered canopy structures, this prolongs rainfall retention time while hindering water penetration through the canopy, thereby increasing overall canopy interception (Holder et al.2017). Inverted conical canopy types are generally considered more conducive to enhancing plant canopy interception (Xu et al. 2005). Concurrently, the evergreen nature of coniferous species extends the annual retention period in northern regions by over 120 days compared to deciduous broadleaf trees, significantly enhancing winter snow retention effects (Lundberg A et al. 2010; Xiao et al.2017; Liu et al. 2015) suggest that plant size significantly influences canopy retention capacity. For instance, small trees or low shrubs (such as *Prunus persica 'Duplex'.* and *Prunus triloba Lindl.)* exhibit the weakest retention due to sparse canopies and slender branches. In urban ecohydrology, coniferous species perform best in single-tree plantings, followed by broadleaf species. Low-growing tree types are unsuitable for single-tree planting. Among them, *Cedrus deodara (Roxb.) G. Don.* and *Pinus tabuliformis Carrière.* exhibit similar levels of rainfall interception. Under heavy rainfall conditions, single-tree *Cedrus deodara (Roxb.) G. Don.* outperforms *Pinus tabuliformis Carrière.* under heavy rainfall. Conversely, *Pinus tabuliformis Carrière.* demonstrates greater canopy interception than *Cedrus deodara (Roxb.) G. Don.* during low rainfall events and when planted in clusters. Therefore, in cities with abundant rainfall, high annual precipitation, and a high likelihood of heavy rain or rainstorm events, *Cedrus deodara (Roxb.) G. Don.* and *Juniperus chinensis L.* can be preferred for single-plant landscaping. In cases of cluster planting or multi-plant planting, *Pinus tabuliformis Carrière.* can be used as a replacement for *Cedrus deodara (Roxb.) G. Don*., which will result in a better interception effect. Studies on different tree species configuration methods and mixed tree species planting have shown that the canopy interception capacity of landscape plants increases with the rise in rainfall intensity and rainfall amount. Some scholars (Hao et al., 2025) have suggested that the magnitude of rainfall directly determines the amount of canopy interception.

Wang Sisi et al. reported that the plant canopy interception capacity of Beijing No. 21 Middle School follows the order: Juniperus chinensis L. > Cedrus deodara (Roxb.) G. Don. > Pinus tabuliformis Carrière. > Populus tomentosa Carrière. > Ginkgo biloba L. > Prunus persica 'Duplex' > Prunus triloba Lindl.which is consistent with the findings of this study(Sisi Wang et al., 2020,Jianing Dinget al.2024) .Besides the direct impact of rainfall intensity on plant canopy interception(Ma M et al.2025).

In the mixed planting mode, when the plant combination consists of one low-interception plant and one high-interception plant, the canopy interception capacity shows a significant linear increase as the proportion of the high-interception plant in the combination rises. A typical example is the combination of *Prunus persica 'Duplex'.* and *Pinus tabuliformis Carrière.* Generally, the interception capacity of a group formed by two plant species increases with the proportion of the plant with higher interception capacity in the two. However, the opposite situation occurs when both plants in the combination are high-interception species. For instance, in the mixed mode of *Cedrus deodara (Roxb.) G. Don.* and *Styphnolobium japonicum (L.) Schott.*, the interception capacity of some combination ratios is even higher than that of the pure *Cedrus deodara (Roxb.) G. Don.* forest.Some scholars argue that in ecosystems, numerous studies (Yoda, 1963; White, 1984) have shown that there is an upper limit to plant population density. Excessively high-density planting will not infinitely increase the total leaf area index (LAI) of the forest stand; instead, it will induce changes in individual plant morphology through competition and may trigger self-thinning. Eventually, the LAI stabilizes around the peak determined by environmental carrying capacity, or even decreases (Wang et al.2024; Brauman A K et al.2010). Therefore, a higher canopy density does not necessarily mean better functionality; instead, there exists an "optimal density". Beyond this density, the group functionality will decline due to resource competition and structural deterioration (Purves D W et al., 2007; Stegen J C et al., 2009). Combining the "optimization theory" and the "overcrowding" phenomenon in ecology, when using combinations of high-interception plants, it is more important to carry out reasonable dense planting and use a larger green space area. This is conducive to increasing the unit LAI, thereby improving the vegetation canopy interception capacity.

The model developed based on the Revised Gash model yields relatively accurate simulation results for the interception capacity of urban landscape plants. Using this modified Gash model, the code quantitatively reveals the differences in rainwater interception among different gardens and under various configuration methods, while clarifying the sensitivity of key parameters. The results provide a scientific basis for the construction of sponge cities and research on urban eco-hydrology. The results of the parameter sensitivity analysis in the model show the order E>c>S>St>Pt, which is consistent with the conclusions of (Guo Bo et al. 2023) in their Gash model simulation of typical Pinus tabuliformis Carrière forests in the Taihang Mountains. Japanese scholars, who used the Revised Gash model to study the impact of canopy structure on interception, also identified the E value as the most sensitive parameter in the model (Deguchi A et al.2006). Additionally, the low sensitivity of the two parameters (St and Pt) aligns with the research findings of Su (Su et al.2022), Fan (Fang et al.2014), and other researchers. As the number of configured plants increases, the importance of canopy water storage capacity becomes more prominent.

In future studies, the scope of model simulation can be expanded by applying the scale to the complete urban ecosystem to explore the relationship between the Leaf Area Index (LAI) value and vegetation canopy interception under mixed planting conditions. Some scholars argue that LAI directly affects vegetation canopy closure. For study areas without high-resolution canopy closure images, Zhang et al. (Zhang et al.2017; Liu et al.2014; Zhao et al.2020) suggest that LAI products can be directly used to estimate forest stand canopy closure. Based on this, in subsequent research on rainfall interception at the large-scale urban ecosystem level, urban LAI can be used to estimate canopy closure, and then combined with the Revised Gash model to calculate the overall urban rainfall interception.

Based on the study on canopy interception of 8 common landscape tree species in Beijing and their common mixed planting patterns, this research draws the following main conclusions:

(1) **Tree species characteristics dominate the basic interception capacity:** Coniferous tree species exhibit significantly superior canopy interception capacity compared to deciduous broad-leaved species, and tall arbors outperform low shrubs. Among the 8 tested tree species, *Juniperus chinensis L.*, *Cedrus deodara (Roxb.) G. Don.*, and *Pinus tabuliformis Carrière.* are high-interception species. Notably, *Juniperus chinensis L.*, with its inverted conical crown structure, demonstrates the most prominent interception advantage under moderate to high rainfall intensities (reaching up to 18.46 mm when planted in clusters of 5). In contrast, *Prunus persica 'Duplex'* and *Prunus triloba Lindl.* are low-interception species, with the lowest interception capacity of only 3.25mm and 2.98 mm for single-plant cultivation under low rainfall intensity. This difference stems from the larger specific surface area formed by the clustered narrow leaves of conifers, their dense canopy structure, and the stronger canopy water storage capacity of tall arbors.

(2)**Planting patterns significantly regulate interception efficiency:** The interception capacity of all tree species follows the order: "cluster planting (5 plants) > cluster planting (4 plants) > cluster planting (3 plants) > paired planting > single planting". With the increase in the number of planted individuals, the interception capacity shows a stepwise rise, peaking at 5 plants per cluster. Under low rainfall intensity, high-interception tree species (such as Cedrus deodara) can achieve saturated canopy interception when planted in clusters of 4 or more. Under moderate to high rainfall intensities, *Juniperus chinensis L.* exhibits the fastest interception growth rate, with the interception capacity of 5-plant clusters increasing by approximately 189.7% compared to single-plant cultivation. This highlights the role of clustered planting in enhancing interception benefits through canopy interlocking and overlapping.

(3)**Mixed configurations exhibit synergistic effects:** The interception capacity of mixed planting patterns depends on the proportion of high-interception tree species and their combination characteristics: ① When low-interception species are mixed with high-interception species, the interception capacity shows a significant linear increase with the increasing proportion of high-interception species. For example, the combination of 1 *Prunus persica 'Duplex'* and 4 *Pinus tabuliformis.* achieves an interception capacity of 15.34 mm under high rainfall intensity, a 67.3% increase compared to pure *Prunus persica 'Duplex'* clusters. ② Mixed planting of high-interception species can achieve superposition effects. Among them, the combination of 1 *Cedrus deodara.* and 4 *Juniperus chinensis.* demonstrates the best interception performance, reaching 17.78 mm under high rainfall intensity, which is significantly higher than that of all single-species plantations and other combinations (the lowest value is 8.13 mm for the *Prunus persica 'Duplex'* + *Prunus triloba.* combination). ③ The mixed configuration of *Cedrus deodara.* and *Styphnolobium japonicum (L.) Schott.* (1:4 ratio) achieves an interception capacity of 16.95 mm, which is higher than that of pure plantations of either species, verifying the complementary advantages of combining different functional tree species.

(4) **Adaptability between rainfall intensity and tree species/configuration is critical:** Among single-species plantations, Cedrus deodara is more suitable for single-plant cultivation under high-intensity rainfall (with a single-plant interception capacity of 6.02 mm, higher than 5.64 mm of Pinus tabuliformis). In contrast, Pinus tabuliformis performs better under low rainfall intensity and clustered planting scenarios (the interception capacity of 5-plant clusters reaches 16.95 mm under high rainfall intensity, slightly higher than 16.82 mm of Cedrus deodara). Therefore, in rain-prone areas or regions with frequent rainstorms, Cedrus deodara and Juniperus chinensis L. can be prioritized for single-plant cultivation. For clustered planting or areas with low rainfall frequency, the combination of Pinus tabuliformis and Juniperus chinensis L. can better exert interception efficiency.

(5) **Universal law of interception capacity:** It is a universal phenomenon that the interception capacity of landscape plants increases with the increase of rainfall intensity and rainfall duration.

(6) **Optimization path for practical application: Urban greening configurations should balance the goals of "hydrological regulation - carbon sequestration synergy":** ① In regions prone to extreme rainfall, prioritize clustered planting (5 plants) of coniferous trees such as Juniperus chinensis L., Cedrus deodara, and Pinus tabuliformis, or mixed configurations of high-interception species. ② For daily light rainfall scenarios, moderately incorporate high-interception species (with a proportion not less than 60%) into low-interception species combinations to balance ornamental value and interception function. ③ In the construction of sponge cities in northern China, recommend the establishment of a multi-layered mixed structure of "coniferous trees + broad-leaved arbors + shrubs" to enhance interception benefits by increasing the leaf area index (LAI) per unit area, promoting the transformation of green spaces from "ornament-dominated" to "function-integrated".

The innovative value of this study lies in extending the Revised Gash model from natural ecosystems to urban landscape vegetation, quantifying for the first time the impact of planting configuration parameters (number of plants, proportion, species combination) on interception, and filling the gap in canopy interception model research in northern cities. It is worth emphasizing that the canopy rainfall interception capacity of landscape plants is jointly determined by the tree species themselves and artificial configuration methods, with a significant synergistic effect between the two—providing a scientific basis for rational plant selection in landscape greening based on actual conditions. Consequently, this research not only offers guiding significance for model-based studies on landscape plant canopy interception but also provides novel eco-hydrological insights for sponge city construction and new ideas for vegetation optimization in urban ecosystems. However, the model still has limitations: it does not fully consider the influence of vegetation phenology (e.g., the leafless period of deciduous broad-leaved trees in winter) and is restricted to typical tree species in a single region, necessitating further research on interception capacity differences among tree species across diverse regions. In the future, the spatio-temporal applicability of the model can be expanded by integrating remotely sensed urban leaf area index (LAI) to achieve regional-scale interception estimation, while incorporating phenological dynamics, soil moisture, and other factors to further enhance the model's accuracy and promotion value.

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CRediT authorship contribution statement

Rongkang Yu: Writing-review & editing, Writing-original draft, Visualization, Validation, Methodology, Investigation, Data curation, Conceptualiza-tion.Weiwei Shao: Writing-review & editing, Supervision, Resources. Methodology, Funding acquisition. Haimei Li: Writing-review &editing, Supervision, Funding acquisition. Jiaqi Li: Writing - review &editing, Visualization, Methodology, Data curation. Guang Han: Writing-review & editing, Validation.Methodology. Haibing Wu: Writing-review & editing, Validation.

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