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Effect of Green Infrastructure with Different Woody Plant Root Systems on the Reduction of Runoff Nitrogen

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Abstract: Rainfall-runoff nitrogen (N) pollution has emerged as the primary source of water contamination due to rapid urbanization. Green infrastructure (GI), as the representative measure, is widely used in controlling N pollution in runoff. However, there is limited research on the impact of woody plants on N reduction in GIs. Therefore, this study aimed to investigate the influence and relationship of *Sophora japonica* (with tap root) and *Malus baccata* (with fibrous root) on N removal in GIs. Utilizing the advanced root analysis software WinRHIZO (version 4.0b), a meticulous examination of the morphological traits of plant roots was conducted. The findings unveiled a striking contrast between the root systems of two species: *S. japonica* primarily boasts a vertically oriented root configuration, whereas *M. baccata's* root system is characterized by an extensively lateral, or horizontal, growth pattern. Specifically, in comparison to *S. japonica*, the horizontal roots of *M. baccata* demonstrated a substantial superiority, with their total root length measuring 10.95 times longer, the surface area spanning 6.25 times wider, and the cumulative volume being 3.93 times greater. For comparing the load reduction rates on runoff NH_3-N, NO_3-N, and TN of the different root morphologies' GIs, *S. japonica* GI had the highest purification effect on the three pollutants, and the average load reduction rates of three pollutants reached 67.74%, 33.83%, and 38.96%, respectively, which were 11.42%, 27.46%, and 6.16% higher than those of the control. The variance contribution rate of vertical root and horizontal root characteristics on runoff nitrogen load reduction accounted for 86.47% of the total root contribution rate. The volume of vertical roots emerged as the most crucial characteristic factor affecting the reduction of N load.

Keywords: root morphologies; woody plant; root directions; reduction rate; green infrastructure

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Citation: Zhang, B.; Chen, L.; Gao, T. Effect of Green Infrastructure with Different Woody Plant Root Systems on the Reduction of Runoff Nitrogen. *Water* **2024**, *16*, 1628. https://doi.org/10.3390/w16111628

Academic Editor: Jian Liu

Received: 5 May 2024
Revised: 30 May 2024
Accepted: 5 June 2024
Published: 6 June 2024

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1. Introduction

Currently, the development of urbanization has caused substantial amounts of nitrogen (N) to accumulate on the surface of roads, and this directly enters the soil through the rainwater scouring process, causing severe environmental N pollution [1,2]. Non-point source pollution caused by N pollution has seriously threatened the urban environment [3]. Green infrastructures (GIs) are kinds of green wastewater treatment systems that are widely used to deal with the polluted runoff caused by the development of urbanization [4]. GIs make full use of their function through the combined action of plants, microorganisms, and soil/fillers [5,6]. The numerous treatment mechanisms of GIs, including filtration, adsorption, and biological transformations, appear to be the main reason for the transformation of captured N pollutants [7].

As plants are critical in GIs, the quantitative relationship between plants and runoff regulation effect in green infrastructure has been examined [8,9]. The reductions in N pollutants in GIs with different plant species are quite complex [10]. For example, Fan et al. [11] concluded that the NO_3^--N removal rates from planting *Radermachera hainanensis Merr.* (79.59%) were significantly higher than those in the GIs system of planting *Ophiopogon japonicus*. (43.03%).

The root system of *Ophiopogon japonica.* was relatively sparse compared with *Radermachera hainanensis Merr*. Similarly, Barron et al. [12] reported that the deployment of plant species characterized by rapid growth rates and high root density led to a reduction in the effluent nitrogen concentrations within GIs. Specifically, they observed that under such conditions, the concentrations of Total Nitrogen (TN) in the outflow were diminished, ranging from 0.2 to 0.3 mg/L and 0.3 to 0.6 mg/L in different instances. These findings underscore the efficacy of selecting plants with these traits for mitigating N pollution in GIs.

The migration and transformation of N in GIs is primarily influenced by plants. Key factors include plant metabolism, rhizosphere microorganisms, and preferential flow generated by plant roots [13]. Owen and Jones [14] discovered that when N sources were introduced into the rhizosphere surrounding wheat plants, the plants absorbed an average of 6% of the added N sources, while rhizosphere microbes utilized the remaining sources. Although a growing body of literature is focused on the importance of N migration and transformation in GIs, the influence of plant root morphology traits on the nutrient-leaching potential in soil is usually neglected. Plants differ in their influences on the purification of N in different ways in the GIs system since they have different root system characteristics. Due to plant roots' ability to affect N migration and transformation in soil [15,16], analysis of the role of plants, especially deep-rooted woody plants, in the GIs system with regard to N purification is of great practical significance for strengthening environment risk control.

According to plant morphology, root systems are generally categorized as tap root systems or fibrous root systems [17]. The tap root system consists of a single, dominant primary root that grows vertically downward and gives rise to secondary and tertiary roots. This type of root system is common in dicotyledonous plants and provides strong anchorage and deep penetration to access water and nutrients from deeper soil layers [18]. On the other hand, fibrous root systems are characterized by a network of thin, highly branched roots that emerge from the stem base or various points along the stem. This type of root system is found in monocotyledonous plants and contributes to soil stabilization and the efficient absorption of water and nutrients from the upper soil layers [18]. Overall, the tap root system is typically more extensive and deeply penetrating, whereas the fibrous root system spreads out laterally and occupies a larger surface area. The structural characteristics of plant root systems (such as root length density, root diameter, root surface area density, and root volume ratio) can profoundly influence soil composition and impact the quantity and quality of water during seepage. The impact of deep-rooted woody plants on water volume and quality during seepage is particularly pronounced, and various root morphologies exert differing effects on the transport and transformation of nitrogen during seepage [19]. Therefore, conducting an in-depth analysis of the root system morphological traits of different woody plants is crucial for understanding how plant roots affect nitrogen transport and transformation in GI, ultimately aiming to mitigate the adverse effects of nitrogen runoff on the environment and ecological systems.

The aim of this study is to quantify the impact of different woody plant root morphological traits on GIs and to enhance the effectiveness of GIs in reducing urban nitrogen pollution loads. The objectives of this work were (i) to analyze the root morphology traits of different woody plants in GIs; (ii) to clarify the influence of morphology traits of different woody plants on the nitrogen purification effect in GIs; (iii) to investigate the relationship between the risk of nitrogen leaching and root system characteristics in GIs.

2. Materials and Methods

2.1. Column System

Based on the warm–temperate semi-humid monsoon climatic conditions and the list of suitable plants for sponge city construction in Tianjin, as outlined in the *Tianjin Sponge City Construction Technical Guidelines*, two plants were selected: the tap root system of *S. japonica* and the fibrous root system of *M. baccata*. The plants used in this study comply with the IUCN Endangered Species Research Policy Statement and the Convention on Trade in Endangered Species of Wild Fauna and Flora. These plants, which are well-suited for

growth in Tianjin and are commonly found there, exhibit resistance to flooding, water, and drought, along with strong adaptive abilities and a high survival rate. These two different 3-year-old plants, *S. japonica* and *M. baccata*, were planted in twelve pilot-scale GI columns at the Peiyang campus of Tianjin University, China. The tap root and lateral root of *S. japonica* has obvious differences. *S. japonica* species belongs to the Sophora Genus, in the Fabaceae Family, and it typically has a deep taproot system that helps anchor the tree and provide stability [20]. The taproot is accompanied by lateral roots that spread out in the soil to absorb water and nutrients efficiently. The *M. baccata* species belongs to the Malus Genus, in the Rosaceae Family, and it commonly has a fibrous root system consisting of many small lateral roots that spread out horizontally from the base of the tree [21]. This type of root system allows for the efficient absorption of water and nutrients from the soil [22]. There are 9 experimental devices in total, which are divided into 3 groups. Each group is provided with 3 parallel devices, namely, the non-plant control group, the tap root group, and the fibrous root group. Three groups of parallel trials can reduce random errors, while statistically, this can enhance the judgment of the significance of the experimental results and allow further calculation of the sample mean and standard deviation to improve the reliability and accuracy of the data. The experiment was conducted for 3 months, during which the plants were observed and studied. Prior to the commencement of the experiment, the plants were maintained inside the experimental columns for a period of 4 months. The specific structure profile of the GI was shown in Figure 1. The GI columns were composed of PVC tubes (50 cm in diameter) with a 10 mm thickness and 90 cm height. The column stratification, from bottom to top, was a 10 cm submerged layer (between soil surface and overflow), 75 cm soil layer, and 5 cm gravel drainage layer (5–10 mm particle size). Considering China's rainfall characteristics, domestic scholars recommend that the permeability coefficient K should be greater than 10^{-5} m/s and needs to be considered to decrease with the infiltration of runoff and pollutant loads [23,24]. Sandy soil is known for its high permeability and rapid drainage properties, which are advantageous for managing stormwater and controlling runoff in urban environments. By examining the properties of sandy soil and understanding its interaction with various root systems, valuable insights can be gained into its contribution to the overall effectiveness of green infrastructure solutions in mitigating runoff and pollutants. Therefore, we chose sandy soil for this study, and the properties of the sandy soil before the test were determined. The bulk weight was 1.4 g/cm^3, and the contents of total nitrogen, ammonia nitrogen, and nitrate nitrogen were 658 mg/kg, 7.05 mg/kg, and 0.42 mg/kg, respectively.

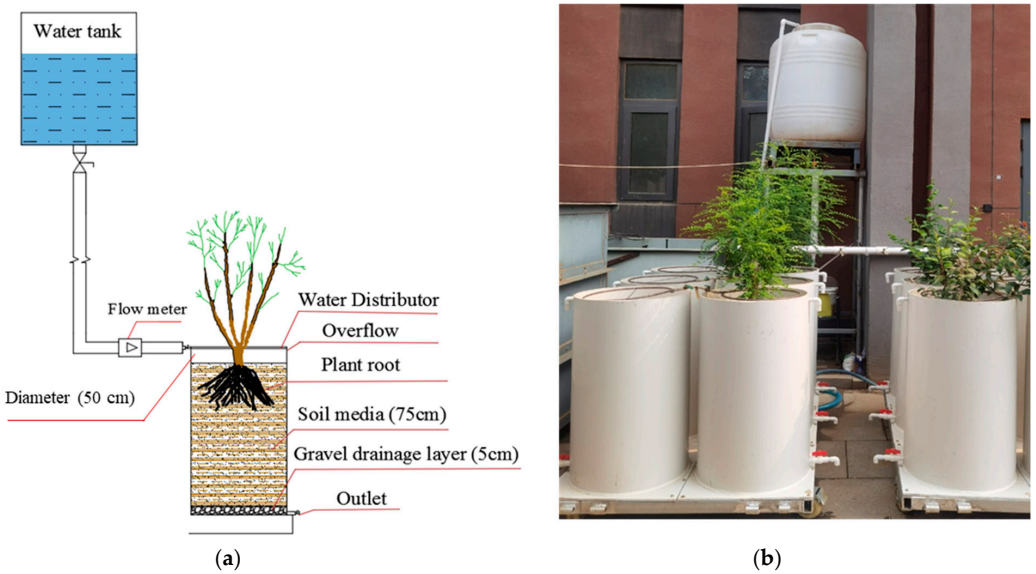


Figure 1. (**a**) Structure profile of the columns and (**b**) site photos of experimental devices.

2.2. Scheme Design

Artificial rainwater was utilized to simulate precipitation events, with copper pipes containing evenly distributed holes positioned beneath the plant canopy to prevent the interception of rainwater by the plants. The ratio of GI area to confluence area was 5:1, and the rainfall recurrence interval was 2 years. The guidelines outlined in the *Technical Guidelines for Sponge City Construction in Tianjin (2016)* were adopted for designing the runoff quantity.

NO_3-N and NH_3-N were chosen as the primary N pollutants, and artificial rainwater was prepared by using tap water and adding $NaNO_3$ and NH_4Cl (Fuchen Chemical Reagent Co. Ltd., Tianjin, China). The inflow concentrations were set based on the water quality of an urban road in Tianjin [20]. The specific test schemes are provided in Table 1. A pump was utilized to pressurize the tap water, which then flowed into the GI columns as described previously. Before the rainfall events, the soil was moistened and rinsed with clean tap water.

Table 1. Synthetic rainwater test scheme.

Date	Rainfall Intensity (L/s·hm^2)	Rainfall Duration (h)	Rainfall (mm)	Influent NO_3-N Concentration (mg/L)	Influent NH_3-N Concentration (mg/L)
13 August 2021	91.93	2	66.33	3.0	1.5
21 August 2021	70.72	3	76.52	3.0	1.5
29 August 2021	91.93	2	66.33	6.0	3.0
6 September 2021	70.72	3	76.52	6.0	3.0
14 September 2021	91.93	2	66.33	9.0	4.5
22 September 2021	70.72	3	76.52	9.0	4.5

2.3. Sampling and Analysis Method

2.3.1. Root Analysis

The difference between the root system architectures of plants lies in the direction and branch. After the experiment, the entire root system was dug out, and 3D scanning modeling (EPSON 1680, Rengent Instruments Inc., Québec, QC, Canada) was performed on the root system after cleaning. Simultaneously, the root analysis system (WinRHIZO, version4.0b, Rengent Instruments Inc., Québec, QC, Canada) was employed to analyze the morphological characteristics of plant roots.

2.3.2. Water Sample Collection and Analysis

During each rainfall event, water samples were collected after the column began producing water, and the timing of inflow, outflow, and overflow for each column was recorded. Outflow samples were collected every 30 min, with each water sample measuring 500 mL in volume. In each rainfall event, a total of 8 bottles of water were collected per column. Water sample analysis was conducted based on the standards outlined in *Monitoring and Analysis Methods of Water and Wastewater* (Fourth Edition). The load reduction rates were calculated using the following formula:

$$R_L = \frac{L_{in} - L_{out} - L_{over}}{L_{in}} \times 100\%$$

$$L_{in/out/over(water)} = \sum_{i=1}^{i} L_i = \sum_{i=1}^{i} C_i \cdot Q_i \cdot \Delta t_i$$

where R_L is load reduction rate, %; $L_{in/out/over}$ represents the inflow, outflow, and overflow water pollutant load, mg; C_i is the pollutant concentration; Q_i is the outflow volume in the time period; and Δt_i is the sample interval time.

2.3.3. Soil Sample Collection and Analysis

Soil water-stable aggregates were air-dried, weighed, and separated using the wet sieve method in accordance with the specification determinations of the composition of soil water-stable macroaggregates [25]. The soil total organic carbon (TOC) was analyzed using the potassium dichromate oxidation spectrophotometry method. This analysis was conducted to quantify the amount of TOC present in the soil, providing insights into the soil's fertility and its role in supporting plant growth. Ultraviolet spectrophotometry [26] was employed to analyze the soil nitrogen content.

3. Results and Discussion

3.1. Root Morphology Traits of Woody Plants

The root system models of the two plant species are depicted in Figure 2. Figure 3 presents the root morphology parameters of the taproot system in *S. japonica* and the fibrous root system in *M. baccata*.

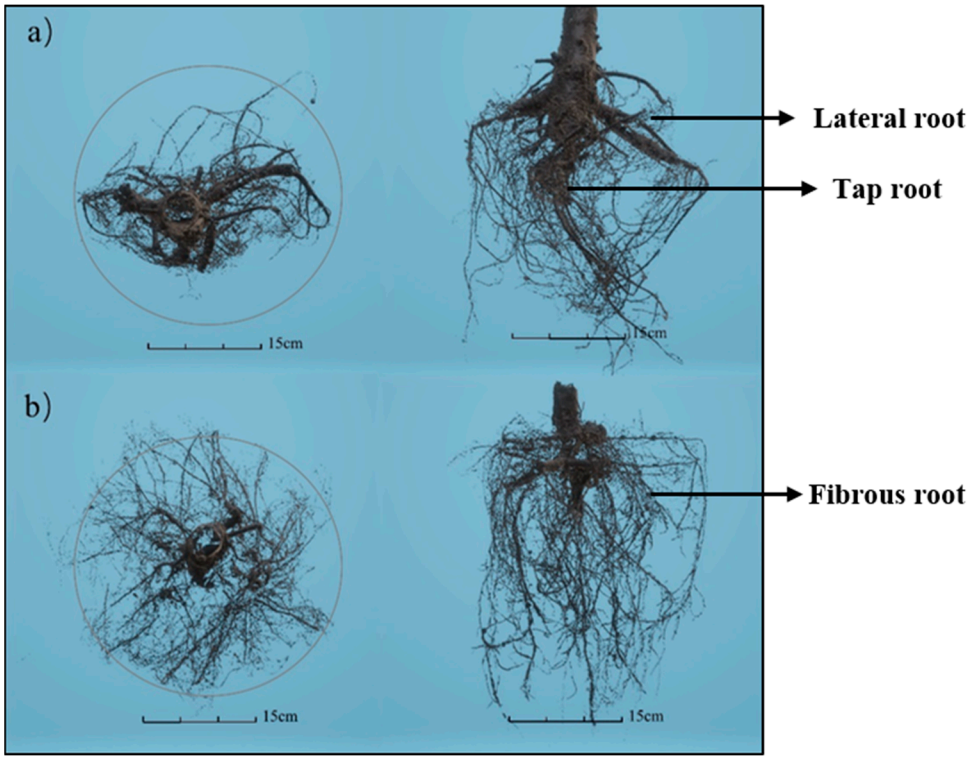


Figure 2. Example xy and xz view images from models of (**a**) *S. japonica* tap root and (**b**) *M. baccata* fibrous root.

According to Figure 2, it is evident that under the same planting age and conditions, *S. japonica* demonstrates a taproot system, displaying a clear distinction between the tap root and fibrous root structures. The taproot of *S. japonica* is thick, robust, and elongated, growing vertically downward. In contrast, *M. baccata* features a fibrous root system with an underdeveloped tap root and horizontally spreading roots without distinct tap or secondary roots. The majority of *M. baccata* roots grow horizontally (0–30°) and obliquely (0–60°), with only a few vertical roots present. In a study by Wang et al. [17], it was concluded that different root morphological characteristics have varying effects on soil infiltration properties. Scanning results indicated that the taproot system of *S. japonica* exhibited a higher number and volume of vertical and inclined roots in comparison to the fibrous root system of *M. baccata*. This distinction may impact soil infiltration properties, potentially leading to increased runoff infiltration rates and promoting the development of preferential flow pathways in the soil.

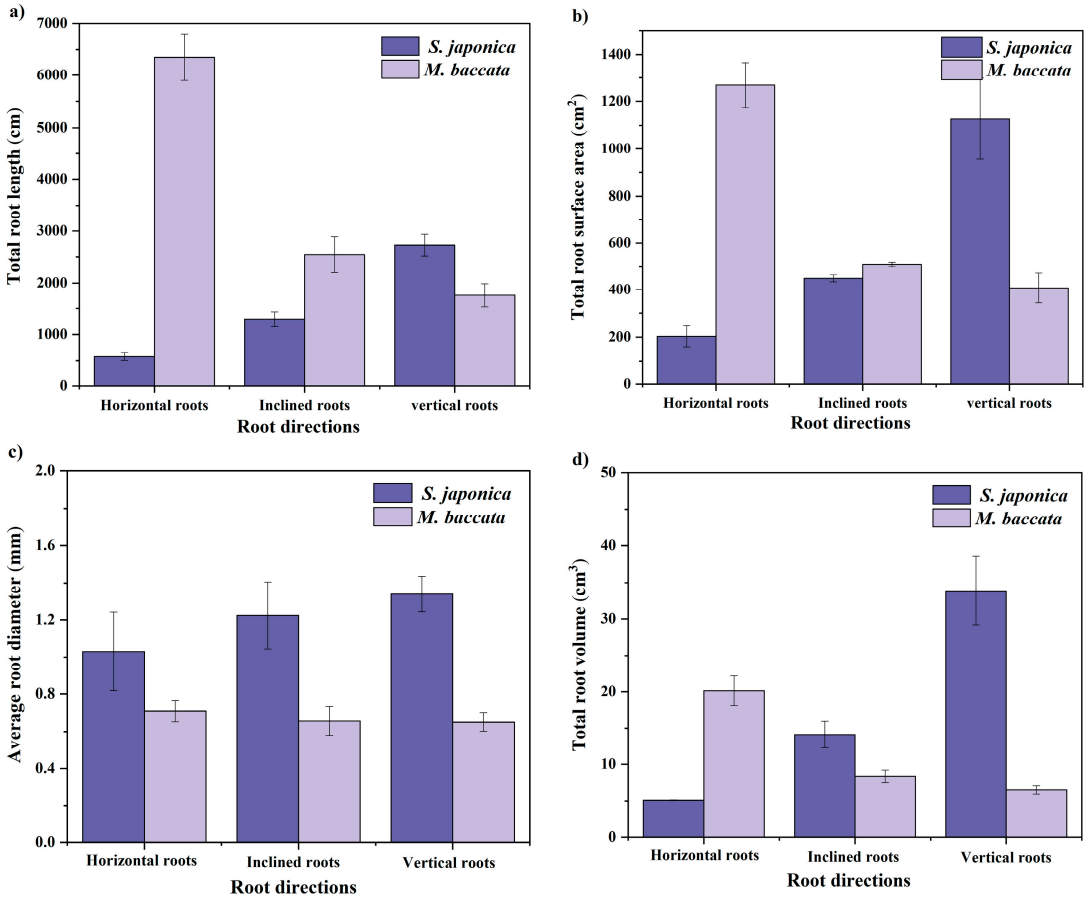


Figure 3. Total root surface area (**a**), root length (**b**), average root diameter (**c**), and total root volume (**d**) of different root directions for *S. japonica* and *M. baccata.* Note: the roots with angle 0–30° are the horizontal roots, those with 30–60° are the inclined roots, and those with 60–90° are the vertical roots.

The morphological characteristics of root systems have a significant impact on the regulation of water and nutrient uptake in plants [27]. A comparison of the root systems of *S. japonica* and *M. baccata* reveals distinct differences. *S. japonica* has relatively few fine roots (9% < 1 mm diameter) and a higher proportion of thick roots (35% > 3 mm diameter). Conversely, *M. baccata*'s root system exhibits a higher abundance of branches and fine roots (50% < 1 mm diameter) and a lower occurrence of thick roots (5% > 3 mm diameter). The distribution of the root systems is most active in the 0–40 cm soil layer, with the ability to develop lateral roots primarily influenced by the biological characteristics of the plants [28]. A greater number of lateral roots corresponds to a larger root volume and surface area, enhancing the roots' capacity for water and nutrient absorption [29]. Upon analyzing the root measurements, it becomes evident that *M. baccata's* fibrous root system demonstrates a notable ability to absorb nitrogen from runoff. The absorption capacities of woody plants with different root systems vary significantly. Research conducted by Yetgin [30] indicated that fibrous roots form a dense network of small, fine roots that extend near the soil surface, enabling the efficient uptake of water and nutrients from a wide soil area.

Root length, surface area, and volume are vital indicators for assessing the growth status of plant roots. These parameters directly influence the roots' absorption capacity and the friction force between roots and the soil [28]. Based on Figure 3, there were significant differences ($p < 0.05$) in the root morphological parameters between *S. japonica* and *M. baccata*. The total root length and surface area of *M. baccata* were 2.32 and 1.23 times greater than those of *S. japonica*. Conversely, *S. japonica* exhibited higher total root volume and average root diameter, 1.52 and 1.78 times larger than those of *M. baccata*. When classifying the root growth directions, the root morphological parameters of two woody

plants exhibited notable differences. The root system of *S. japonica* comprises mainly vertical and inclined roots, with the total root length, surface area, and volume of vertical roots accounting for 59.3%, 63.3%, and 63.8% of the total root, respectively. Meanwhile, the total root length, surface area, and volume of inclined roots accounted for 28.1%, 25.3%, and 26.6% of the total root, respectively. On the other hand, the fibrous root system of *M. baccata* consists mainly of horizontal roots, with the total root length, surface area, and volume of horizontal roots making up 59.6%, 58.1%, and 57.5% of the total root, respectively. The characteristics of the horizontal roots of *M. baccata* were approximately 10.95 times (total root length), 6.25 times (surface area), and 3.93 times (volume) larger than those of *S. japonica*, respectively. Research has indicated that the diverse distribution forms of plant roots contribute to their ability to adapt to various soil environments [31,32]. Typically, tap roots, such as those found in dandelions and oak trees, grow downward, allowing for effective water and nutrient uptake from deeper soil layers. Although their quantity is relatively small, tap roots tend to be thicker. Conversely, fibrous roots, as seen in plants like wheat and rice, extend horizontally, creating densely populated small root systems in the surface soil, thereby increasing the overall absorption area [33]. In uneven soil environments, both tap and fibrous roots may display some inclined growth, with tap roots tending to grow downward and fibrous roots favoring lateral expansion [34].

3.2. Reduction Rates of Runoff Nitrogen in Different GIs

Pollutant load could effectively characterize the regulation of GIs on the total amount of pollutants in rainwater runoff [31]. According to the water quality monitoring data during the experiment, water samples were collected from different woody plant GIs. The concentration and load reduction of NH_3-N, NO_3-N, and TN were calculated (Figure 4).

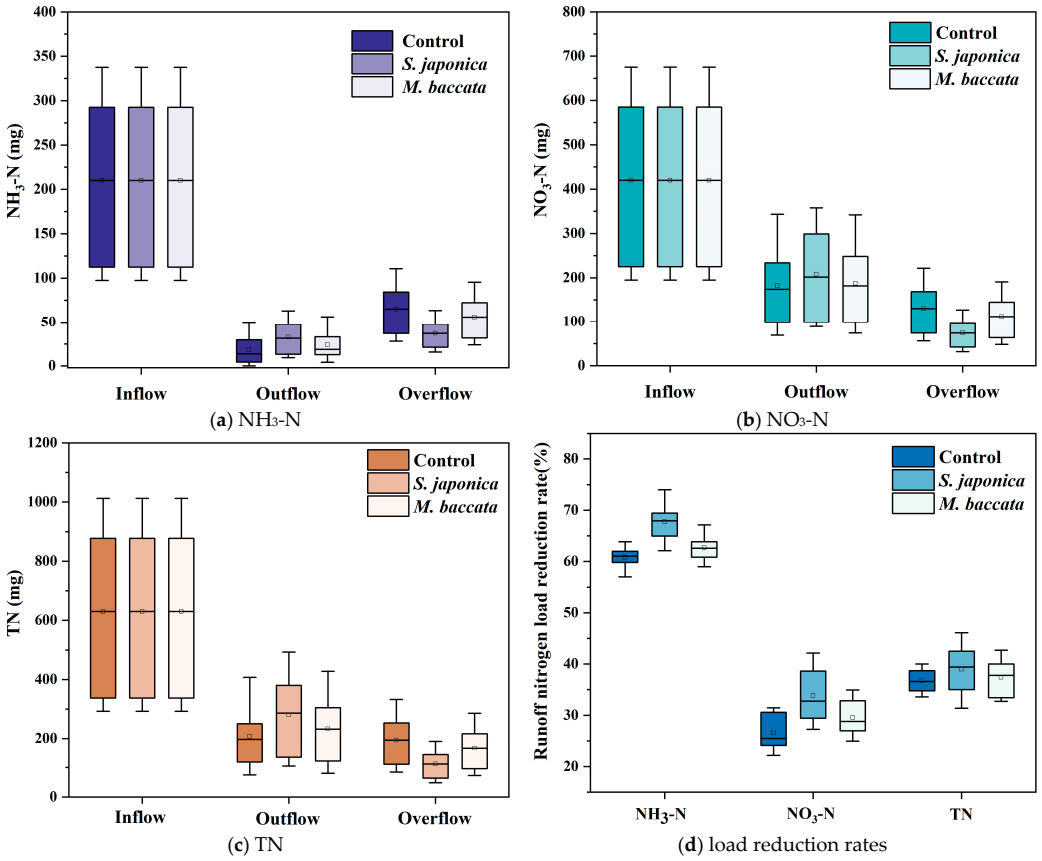


Figure 4. Inflow, outflow, and overflow load of (**a**) NH_3-N, (**b**) NO_3-N, (**c**)TN, and (**d**) load reduction rates in different GIs.

It can be seen from Figure 2a–c that under the condition of the same inflow, the order of outflow load of six simulation experiments is *S. japonica* GI > *M. baccatas* GI > Control, and the order of the average overflow load is reversed. This is because the presence of *S. japonica* and *M. baccatas* roots increases the soil infiltration rate and accelerates the preferential flow in soil, thereby accelerating nitrogen leaching [35]. Additionally, the NH_3-N outflow loads from the Control, *S. japonica*, and *M. baccata's* GIs (18.62 mg, 32.67 mg, and 23.96 mg) were notably lower compared to the outflow loads of NO_3-N (182.04 mg, 207.82 mg, and 187.62 mg). This difference can be attributed to the soil's propensity for easy adsorption of NH_4^+ and the ease of leaching of NO_3^- [36].

Figure 4d illustrates the load reduction rates of the Control, *S. japonica*, and *M. baccata's* GIs. The *S. japonica* GI exhibits the most effective purification capability for the three pollutants, with average load reduction rates of 67.74%, 33.83%, and 38.96%, respectively. These rates are 11.42%, 27.46%, and 6.16% higher than those of the Control. This disparity can be attributed to the more pronounced overflow phenomenon in the Control, leading to a greater amount of untreated runoff directly overflowing and thereby reducing its N removal efficiency [37]. Additionally, similar conclusions were drawn by Fan et al. [11], who found that the planting of *Radermachera hainanensis Merr.* resulted in improved NH_4^+-N and NO_3^--N removal efficiencies compared to those achieved with the herbaceous plant Ophiopogon japonicus in various GIs.

Studies have shown that the pollutant load reduction effect is closely related to the infiltration capacity and water holding capacity of the soil [3]. We tested the average stable infiltration rates of control, *S. japonica,* and *M. baccatas* GIs soil; the results were 3.44 cm/h, 7.26 cm/h, and 4.78 cm/h, respectively, and the average soil infiltration rates of the *S. japonica* and *M. baccatas* GIs were 1.78 and 1.39 times those of the control, respectively. The soil infiltration properties of initial infiltration rate (IIR), steady infiltration (SIR), and hydraulic conductivity (Ks) were significantly affected by plant communities [38], and Ks of shrub and grass communities with tap root systems were 1.90, 2.36, and 2.28 times greater than those with fibrous root systems. Soil aggregates are structural units with a diameter of 0.25~10 mm formed by various physical, chemical, and biological actions of soil particles, and their stability directly affects the soil surface structure [39]. Following rainfall infiltration, the water flow permeates through the soil aggregate gaps, facilitating the formation of preferential flow paths and subsequently increasing the solute transport rate within the soil. The measurement results of aggregates indicate that compared to the control, the roots of *S. japonica* and *M. baccata* increased the content of soil water-stable aggregates with diameters greater than 0.25 mm by 35.11% and 25.54%, respectively. This demonstrates that the roots of woody plants can enhance the content of soil aggregates with a diameter greater than 0.25 mm, highlighting the differing effects of various root morphologies. Similarly, Li et al. [40] discovered that planting purple alfalfa and switchgrass on the Loess Plateau under natural restoration conditions led to an increase in the content of soil water-stable aggregates by 19% and 11%, respectively. Moreover, purple alfalfa and switchgrass demonstrated even greater improvements, with an increase of 29% and 41%, respectively.

There are three main ways for plant roots to form soil macropores and accelerate nitrogen leaching: (i) creating cracks in the soil through mechanical actions, thereby increasing the number of large pores [41]; (ii) changing soil structure by increasing the content of soil organic matter and water-stable aggregates [42]; and (iii) through the seasonal death of the fine roots and the contraction of the coarse roots that cause large pore structures to form in the soil [43]. The GIs with *S. japonica* and *M. baccatas* had a higher reduction effect on runoff nitrogen than the control. This is because the control soil has a good water holding capacity, but its infiltration capacity is poor and the overflow phenomenon is more serious (the overflow of NH_3-N, NO_3-N, and TN is 1.75 and 1.26 times that of the GIs planted with *S. japonica* and *M. baccatas*). The majority of runoff overflows without treatment, leading to a reduction in its efficacy for reducing N load. Conversely, GIs planted with *S. japonica and M. baccatas* can absorb inorganic nitrogen such as NH_3-N and NO_3-N, and the abundant rhizosphere microorganisms can also enhance the reduction effect of runoff

N. Additionally, Berg et al. [44] conducted an assessment on the impacts of individual and combined cultivation of three tree species—poplar, willow, and alder—on microbial diversity in the rhizosphere and bulk soil through greenhouse experiments. The findings highlighted the significant influence of tree species on the index of microbial diversity in the rhizosphere soil, with these soil microbiotas playing a role in promoting the transformation of soil N. However, while the GI of growing plants reduces the risk of runoff contamination, root infiltration increases the risk of groundwater contamination when the regional groundwater table is low.

3.3. Analysis on Root Characteristic Factors of Runoff Nitrogen Load Reduction

The presence of plant roots in various woody plant GIs can significantly enhance soil pore connectivity and improve soil infiltration performance [45]. This improvement has dual implications: firstly, improved soil infiltration performance reduces surface runoff and associated pollution, benefiting soil and water conservation and mitigating surface runoff pollution. Secondly, enhanced soil infiltration performance leads to increased groundwater recharge by runoff, which in turn raises the risk of groundwater contamination [46]. Therefore, it is essential to study the relationship between the root characteristics of woody plants and the outflow nitrogen load of GIs, in order to provide a theoretical foundation for practical applications of GIs.

Correlation analysis was carried out on the root morphological indicators of *S. japonica* and *M. baccatas* (Table 2), and the results showed that these root characteristics were various, and there was a certain correlation and information overlap between various root characteristics. Therefore, quantitative equations between different factors and response values can be established by principal component analysis combined with linear regression analysis to determine the optimal solution in multivariate situations. In this study, the principal component analysis was performed by comparing the 12 measured traits of root surface area, root length, root volume, and root diameter with different root growth directions (horizontal, oblique, and vertical). Figure 5 is the scree plot of the variance contribution rate of each root component (root character). According to Figure 5, the eigenvalues after the second common factor change slowly, and the cumulative contribution rate of the first two principal components reached 97.552%, so could approximately replace all the information represented by the original factor. Therefore, it is more appropriate to select two common factors. Table 3 shows the scoring root morphology traits in different principal components.

Table 2. Correlation coefficients among root morphology traits in *S. japonica*, and *M. baccatas*.

Index	Total Root Length	Total Root Surface Area	Average Root Diameter	Total Root Volume
Total root length	1	0.831 *	−0.982 **	−0.753
Total root surface area	0.831 *	1	−0.889 *	−0.339
Average root diameter	−0.982 **	−0.889 *	1	0.683
Total root volume	−0.753	−0.339	0.683	1

Note: * and ** indicate significant correlation ($p < 0.05$) and extremely significant correlation ($p < 0.01$), respectively.

Table 3. Scoring root morphology traits in different principal components.

Root Growth Direction	Root Morphology Traits	Principal Component			
		F1	F2	Comprehensive Score	Sort
Horizontal	Root surface area	−0.072	−0.065	−0.072	−0.065
	Root length	−0.091	−0.045	−0.091	−0.045
	Root volume	−0.083	−0.053	−0.083	−0.053
	Root diameter	−0.268	0.378	−0.268	0.378

Table 3. *Cont.*

Root Growth Direction	Root Morphology Traits	Principal Component			
		F1	F2	Comprehensive Score	Sort
Inclined	Root surface area	0.072	−0.204	0.072	−0.203
	Root length	0.006	−0.138	0.006	−0.138
	Root volume	−0.101	0.23	−0.101	0.23
	Root diameter	−0.12	0.25	−0.12	0.25
Vertical	Root surface area	0.281	−0.161	0.281	−0.161
	Root length	0.299	−0.186	0.299	−0.186
	Root volume	0.305	−0.191	0.305	−0.191
	Root diameter	0.191	−0.061	0.192	−0.061

Notes: Extraction method: principal component analysis. Rotation method: varimax with Kaiser normalization.

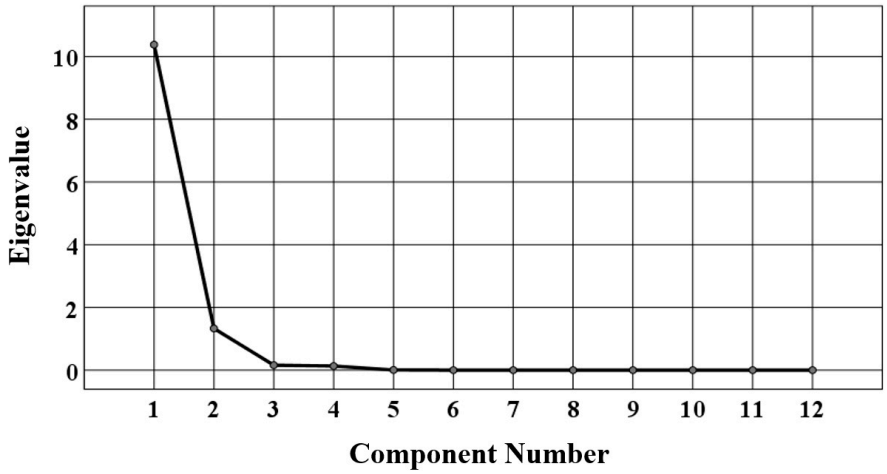


Figure 5. Scree plot of principal component analysis of root morphology traits.

Based on the analysis in Table 3 and Figure 6, the root characteristic factors influencing nitrogen load reduction can be categorized into two groups: principal component 1 contributes to 86.47% of the variance, with key factors being the characteristics of the vertical and horizontal root systems, and principal component 2 accounts for 11.08% of the variance, with main factors related to the characteristics of the inclined root system. This observation aligns with the study findings reported by Xiao et al. [47]. The comprehensive scores of the principal components of the root characteristic factors influencing nitrogen load reduction were in the order of vertical root volume > vertical root length > vertical root surface area > vertical root diameter > inclined root surface area > inclined root length > inclined root volume > horizontal root surface area > inclined root diameter > horizontal root volume > horizontal root length > horizontal root diameter. These studies highlight the importance of plant root channels in controlling the movement of nitrogen runoff through the soil, and the crucial role played by different root structures in this process. Liao et al. [48] found that as plants grow, their roots alter the soil's porosity by penetrating and winding through it, thus affecting soil infiltration. Additionally, Ghestem et al. [49] showed that horizontal roots may hinder water infiltration, whereas vertical and inclined roots can enhance the movement of water into deeper soil layers.

The characteristics of plant roots are closely tied to soil infiltration performance, with morphological features like root surface area, length, volume, and diameter in different directions playing a key role in managing nitrogen runoff in GIs [50]. In situations of severe surface contamination or the presence of harmful substances, the presence of roots can elevate the risk of groundwater pollution, posing a threat to the groundwater environment. In regions facing significant surface pollution and limited rainfall, plants with well-developed horizontal root systems can be recommended to slow down the infiltration of rainwater

runoff into groundwater. This strategy can increase the hydraulic retention time, subsequently boosting the efficiency of soil adsorption and biological absorption in treating rainwater runoff. Conversely, in areas with substantial surface pollution and high rainfall, it is essential to consider pre-treating surface runoff (using initial rainwater treatment devices) alongside the deployment of GIs to mitigate risks to the groundwater environment.

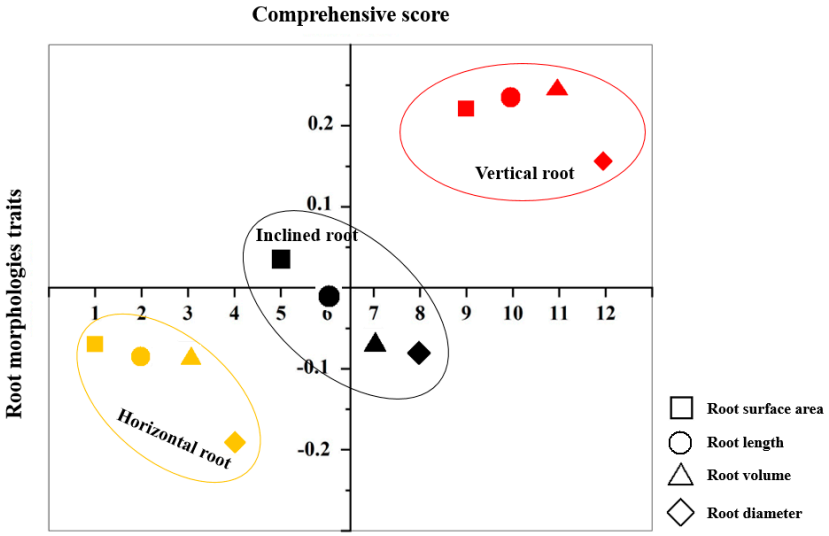


Figure 6. Comprehensive score of root morphology traits.

4. Conclusions

In this study, the amount of ammonia and nitrate infiltration in stormwater runoff had a strong influence on soil N content in GIs. Plants are one of the main factors affecting the performance of GI treatment.

Root Morphology Comparison: The study highlights a comprehensive comparison between the tap root system of *S. japonica* and the fibrous root system of *M. baccata*, revealing distinct characteristics such as root diameter and density, as well as significant differences in the proportion of fine and thick roots between the two species. Furthermore, it unveils the substantial disparity in horizontal root characteristics, where *M. baccata* demonstrates a significantly higher total root length (10.95 times), surface area (6.25 times), and volume (3.93 times) compared to *S. japonica*.

Quantification of Pollutant Reduction: The study presents the quantification of load reduction rates for ammonia, nitrate, and total nitrogen in GIs with different root morphologies. It is revealed that *S. japonica* GI exhibits superior purification effects, leading to notably higher average reduction rates higher than those of the control). Additionally, the study demonstrates that both *S. japonica* and *M. baccata GIs* result in increased soil infiltration rates and the enhancement of soil water-stable aggregates (which were 35.11% and 25.54% higher than those of the control), indicating a substantive effect on pollutant retention and soil quality improvement.

Contribution of Root Characteristics and Environmental Recommendations: The study highlights the variance contribution rates of vertical and horizontal root characteristics to the reduction of nitrogen load in stormwater runoff. It identifies vertical root volume as the most influential characteristic factor in mitigating nitrogen load, shedding light on the specific root features that significantly impact pollutant reduction in GIs. Therefore, for areas with serious surface environmental pollution and low rainfall, plants with developed horizontal root systems can be considered to slow down the infiltration of runoff rainwater into groundwater and increase the effects of soil adsorption and biological absorption on the treatment effect of runoff rainwater.

In this study, we primarily chose only three groups to represent the tap root system of *S. japonica* and the fibrous root system of *M. baccata* GIs. Looking ahead, it is crucial for future research to consider employing larger sample sizes and conducting repeated

experiments to validate our findings and gain a more comprehensive understanding of the essence of the research problem.

Author Contributions: B.Z.: Conceptualization, Formal analysis, Writing—original draft. L.C.: Conceptualization, Methodology, Writing—review and editing. T.G.: Investigation, Writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the China Postdoctoral Science Foundation (No. 2023M742865) and the National Natural Science Foundation of China (Grant No. 42277046 and 41772245).

Data Availability Statement: The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Acknowledgments: We thank Ankit Garg from Shantou University, for editing the English text of a draft of this manuscript.

Conflicts of Interest: The authors declare that there are no conflicts of interest regarding the publication of this paper.

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