agronomy

Article

Correlation Analysis of Riparian Plant Communities with Soil Ions in the Upper, Middle, and Lower Reaches of Heihe River Midstream in China

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Abstract: Our study examined the relationships between riparian plant communities and their soil properties along the midstream of the Heihe River in northwestern China's arid region. Significant variations in species composition were observed across the upper, middle, and lower reaches of this midstream (adonis2 and anosim, $p < 0.001$). The lower reaches exhibited higher species diversity (Shannon index up to 2.12) compared to the other reaches. Gramineous plants, particularly *Agropyron cristatum* (L.) Gaertn. and *Equisetum ramosissimum* Desf., dominated all reaches, with relative abundances exceeding 50% in the upper reach sites. The soil ionic concentration showed distinct spatial heterogeneity, peaking at site 9 (upper reaches) and lowest at site 3 (lower reaches). Species diversity indices negatively correlated with SO_4^{2-}, Mg^{2+}, and Ca^{2+} concentrations, while salt-tolerant species like *Agropyron cristatum* (L.) Gaertn. and *Phragmites australis* Trin. positively correlated with Na^+ and Cl^- levels. Soil nutrients had weaker but notable effects on the distribution of *Onopordum acanthium* L. and *Artemisia argyi* H. Lév. and Vaniot. These findings suggest that riparian plant community distribution along the Heihe River is influenced by complex interactions between hydrological processes, salt dynamics, and soil physicochemical properties, such as anion and cation concentrations and electrical conductivity (EC). Our research provides valuable insights for understanding and managing riparian ecosystems in arid regions.

Keywords: Heihe River; riparian zone; plant community; species diversity; soil nutrients; soil ions

Citation: Wang, Z.; Chen, G.; Li, J.; Jiao, J. Correlation Analysis of Riparian Plant Communities with Soil Ions in the Upper, Middle, and Lower Reaches of Heihe River Midstream in China. *Agronomy* **2024**, *14*, 1868. https://doi.org/10.3390/agronomy14081868

Received: 4 July 2024
Revised: 8 August 2024
Accepted: 16 August 2024
Published: 22 August 2024

1. Introduction

Riparian zones, as transitional areas between terrestrial and aquatic ecosystems, play a vital role in maintaining biodiversity, regulating nutrient cycling, and providing critical ecosystem services [1,2]. The composition and distribution of riparian plant communities are influenced by a complex interplay of environmental factors, including soil properties, hydrological conditions, topography, climatic conditions, and anthropogenic disturbances [3,4]. A thorough understanding of the interrelationships between riparian vegetation and soil characteristics is crucial for developing effective management and conservation strategies for riparian ecosystems.

The soil ionic status and nutrient conditions are among the key factors influencing the structure and function of riparian plant communities. The concentrations and ratios of cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), and sodium (Na^+), as well as anions like chloride (Cl^-), sulfate (SO_4^{2-}), and bicarbonate (HCO_3^-), can significantly affect plant growth, productivity, and species composition by influencing processes such as osmotic regulation, nutrient uptake, and physiological metabolism [5,6]. Soil physicochemical properties, including pH, EC, CEC, and nutrient availability, significantly influence riparian vegetation distribution and diversity through multiple pathways:

directly affecting plant growth, altering competitive dynamics, enhancing microbial activity [7], improving the soil structure [8], and modifying plant–soil–water interactions, ultimately shaping community composition and ecosystem function [9,10]. Differences in the adaptive strategies of plant species to soil ionic and nutrient conditions may lead to pronounced spatial heterogeneity in riparian plant communities.

The Heihe River, a major inland river in the arid and semi-arid regions of northwestern China, has a catchment area of approximately 143,000 km^2 and a total length of 821 km, spanning across the Qinghai and Gansu provinces [11,12]. The river basin's complex ecological landscape encompasses plateaus, mountains, deserts, and oases, creating a fragile yet diverse environment [13]. Riparian zones along the Heihe River host rich plant communities, including trees, shrubs, and herbaceous vegetation, which play crucial roles in wind erosion control, soil and water conservation, and biodiversity maintenance [14]. However, climate change and human activities increasingly threaten the basin's ecological integrity, leading to the significant degradation of riparian ecosystems [15]. Despite these challenges, there remains a notable gap in research regarding the relationships between riparian plant communities and soil ionic and nutrient profiles, particularly in the middle reaches of the Heihe River. This knowledge deficit underscores the need for systematic, in-depth investigations.

Our study aims to elucidate the associations between riparian plant communities and soil ionic and nutrient conditions across the upper, middle, and lower reaches of the Heihe River. To this end, we have formulated three specific research questions: (1) How do plant species' composition and diversity vary in the riparian zones of the upper, middle, and lower reaches of the Heihe River midstream? (2) What are the differences in the soil ion concentrations and physicochemical properties among the Heihe River midstream and their main environmental driving factors? (3) What correlations exist between riparian plant species' responses and soil ions variations and how do different plant species respond to soil environmental gradients?

By addressing these questions, our study will yield valuable theoretical insights into the ecological adaptation mechanisms of riparian plant communities in arid and semi-arid regions. Furthermore, we will provide targeted recommendations for water-saving irrigation, establish buffer zones, control invasives, restore native vegetation, monitor water, and regulate human activities in riparian ecosystems in the Heihe River Basin. Given the potential impacts of global changes and human activities on riparian ecosystems, this research is of great importance for maintaining the ecological integrity and sustainable development of riparian zones.

2. Materials and Methods

2.1. Study Area Description

Our study area is located in the Heihe River Basin (37°–43° N, 98°–102° E) in northwestern China. The region has a temperate continental climate with an average annual temperature of −5–9 °C and an average annual precipitation of 50–300 mm. The elevation ranges from 1200 to 5000 m. The Heihe River originates from the Qilian Mountains and flows from south to north through Qinghai and Gansu provinces, with a total length of 821 km and a basin area of 143,000 km^2 [16]. Our study was conducted in the midstream of the Heihe River (37°20′–40°20′ N,99°20′–100°35′ E), where the main land use types are agricultural irrigation districts and oases, dominated by farmland and artificial forests (Figure 1).

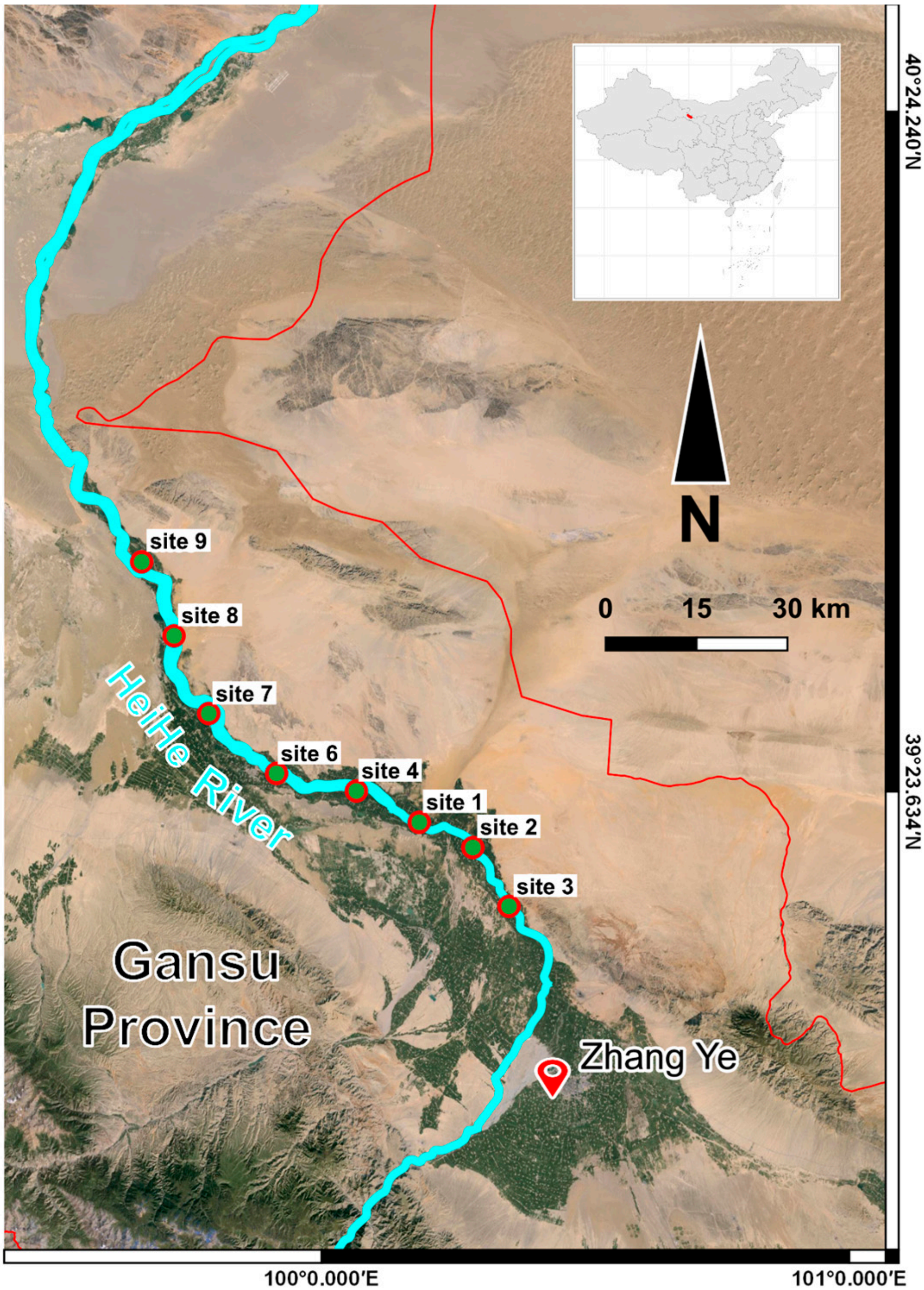

Figure 1. Geographic location of the study area and sampling sites. The sites were numbered sequentially based on the order of our visits. Due to the proximity of the sixth visited site (site 6) to the fifth one (site 5), we decided to omit site 5 from our analysis. The red polyline in the figure delineates the boundary of Gansu Province.

2.2. Sample Site Selection and Vegetation Survey

In July and August 2021, eight sample sites were established in the riparian zone of the middle reaches of the Heihe River (Figure 1). At each site, three replicate plots of 5 m × 5 m were set up, totaling 24 plots. Within each plot, all vascular plants were identified, and their abundance and coverage were recorded. Specimens were collected for subsequent identification and archiving. These samples were archived in a laboratory (20°C, 40% humidity) and uniquely labeled. Species identification was mainly based on the

Flora of China [17] and Flora of Chinese Higher Plants [18], and species' names followed the Angiosperm Phylogeny Group system (APG IV system).

2.3. Soil Sampling and Physicochemical Properties Determination

In each plot, five points were randomly selected, and surface soil (0–20 cm) was collected using a soil auger, targeting the most active root zone and nutrient-rich layer [19]. The soil samples were mixed, sieved, and divided into two parts: one part was air-dried for determining soil physicochemical properties, and the other part was stored under refrigeration for determining soil nutrients. Soil pH and electrical conductivity (EC) were measured using the electrode method (model PHS-EC-3C, INESA Scientific Instrument Co., Ltd., Shanghai, China). Soil anions (Cl^-, SO_4^{2-}, HCO_3^-) and cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) were determined using an ion chromatograph (model ICS-1100, Thermo Fisher Scientific Inc., Bannockburn, IL, USA), and the total concentration of these anions and cations was referred to as the total ion concentration in this study. Soil total carbon (TC), total nitrogen (TN), and total phosphorus (TP) were determined using an elemental analyzer (model vario MAX CN, Elementar Analysensysteme Gmbh, Hanau, Germany), the Kjeldahl method (model K9860, Hanon Instruments Co., Ltd, Jinan, China), and the molybdenum-antimony anti-colorimetric method (model UV-1800, Shimadzu Corp., Kyoto, Japan) [20], respectively.

2.4. Data Analysis

One-way analysis of variance (ANOVA) was used to test the differences in plant community composition and soil physicochemical properties among different river reaches, and the least significant difference (LSD) method was used for multiple comparisons. Multivariate analysis of variance (adonis2) and analysis of similarities (anosim) were used to test the differences in plant community composition among different river reaches [21]. Pearson's correlation analysis was used to explore the relationships between plant species and soil cation, anion concentrations, and physicochemical properties. Canonical correspondence analysis (CCA) was used to investigate the relationships between plant community composition and soil environmental factors [22]. Species diversity was represented by the Shannon–Wiener index (H) and Pielou evenness index (J). The richness was measured using the number of species present in each site. Data analysis was performed using R-4.1.2 software [23], with the vegan package [24] for multivariate analysis and the ggplot2 package [25] for visualization.

3. Results

3.1. Differences in Plant Diversity and Community Composition among Different Reaches of the Heihe River Midstream

The plant species composition differed significantly among the sample sites in the upper, middle, and lower reaches of the Heihe River (adonis2, $p < 0.001$; anosim, $R^2 = 0.041$, $p < 0.001$). The species diversity indices of the sample sites in the lower reaches were higher than those in the middle and upper reaches, with site 3 having the highest Shannon index (2.12). The differences in the diversity indices between the middle and upper reaches were not obvious, and the order of the sites was 7 > 1 > 8 > 4 > 9 > 6. The trend of species evenness was similar to that of the species diversity indices (Table 1).

Table 1. Alpha diversity at each sampling site.

Site Position	Site Number	Richness	Menhinick Index	Margalef Index	Shannon–Wiener Index	Simpson's Index of Diversity	Pielou Evenness Index
Upstream	Site 7	8.00	0.18	0.82	1.52	0.73	0.73
	Site 8	7.00	0.47	0.99	1.33	0.62	0.69
	Site 9	5.00	0.11	0.53	0.98	0.57	0.61
Midstream	Site 1	13.00	0.28	1.47	1.52	0.69	0.59
	Site 4	4.00	0.58	0.77	1.24	0.69	0.89
	Site 6	4.00	0.22	0.52	0.64	0.42	0.46
Downstream	Site 2	11.00	0.27	1.24	1.94	0.82	0.81
	Site 3	10.00	0.24	1.10	2.12	0.87	0.92

A total of 26 plant species were recorded in the plots across the eight sample sites. Plant identification relied on a visual field comparison with flora guides. This method has limitations, potentially leading to the genus-level identification or misidentification of some species. The top five species in terms of relative abundance were *Agropyron cristatum* (L.) Gaertn., *Equisetum ramosissimum* Desf., *Phragmites australis* Trin., *Artemisia argyi* H. Lév. and Vaniot, and *Eragrostis pilosa* (L.) Beauv., accounting for 72.76% of the total relative abundance. In the upper reaches, the dominant species were *Equisetum ramosissimum* Desf., *Agropyron cristatum* (L.) Gaertn., *Eragrostis pilosa* (L.) Beauv., *Phragmites australis* Trin., and *Cynanchum chinense* R. Br. The relative abundance of *Agropyron cristatum* (L.) Gaertn. and *Equisetum ramosissimum* Desf. in sites 9 and 8 was significantly higher than that in other sites, exceeding 50%. The relative abundance of *Phragmites australis* Trin. in site 9 (41.5%) and *Cynanchum chinense* R. Br. in site 8 (10.4%) was significantly higher than that in other sites (Figure 2).

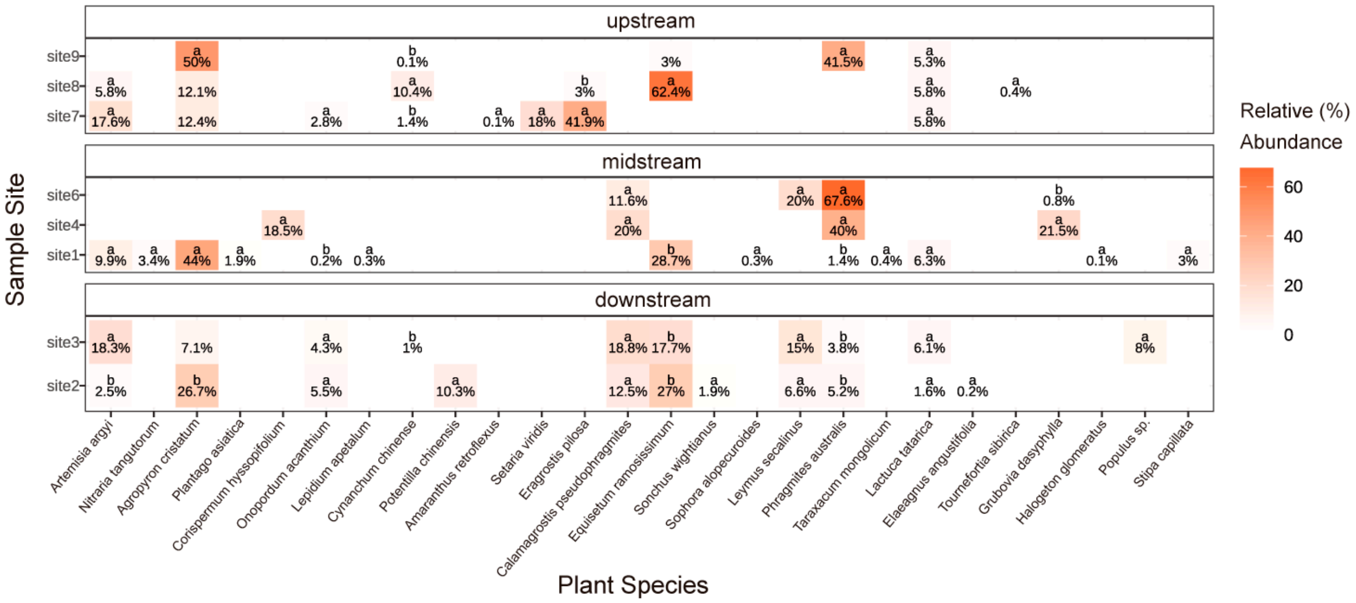

Figure 2. Relative abundance of plant species at sampling sites and the significance of their differences. The different letter in cells indicates ($p < 0.05$) significant differences among the relative abundance of plant species between sites after LSD-based means comparisons.

The sample sites in the middle reaches also had a high relative abundance of *Agropyron cristatum* (L.) Gaertn., *Equisetum ramosissimum* Desf., and *Phragmites australis* Trin., with the abundance of *Phragmites australis* Trin. being higher than that in the upper reach sites. However, the abundance of other species was lower. The middle reach sites also had species that were not present in the upper reaches, such as *Calamagrostis pseudophragmites* (Hall f.) Koel., *Leymus secalinus* (Georgi) Tzvelev, *Corispermum hyssopifolium* L., and *Grubovia dasyphylla* (Fisch. and C. A. Mey.) Freitag and G. Kadereit, with their relative abundance exceeding 10%.

The dominant species in the lower reach sites were similar to those in the middle reaches, including *Agropyron cristatum* (L.) Gaertn., *Calamagrostis pseudophragmites* (Hall f.) Koel., *Artemisia argyi* H. Lév. and Vaniot, and *Equisetum ramosissimum* Desf., but with a lower relative abundance. The lower reach sites also had *Potentilla chinensis* Ser., which was not found in the middle and upper reaches.

3.2. Differences in Soil Nutrient and Ion Concentrations and Physicochemical Properties among Different Locations in the Heihe River Basin

The concentrations of anions, cations, and soil nutrients differed significantly among the sample sites. Site 9 in the upper reaches had the highest anion and cation concentrations, which were significantly higher than those in other sites. The concentrations in sites 7, 6, and 4 in the middle reaches were significantly higher than those in other sites in the upper and lower reaches. Site 3 in the lower reaches had the lowest anion and cation concentrations (Figure 3, Table S1).

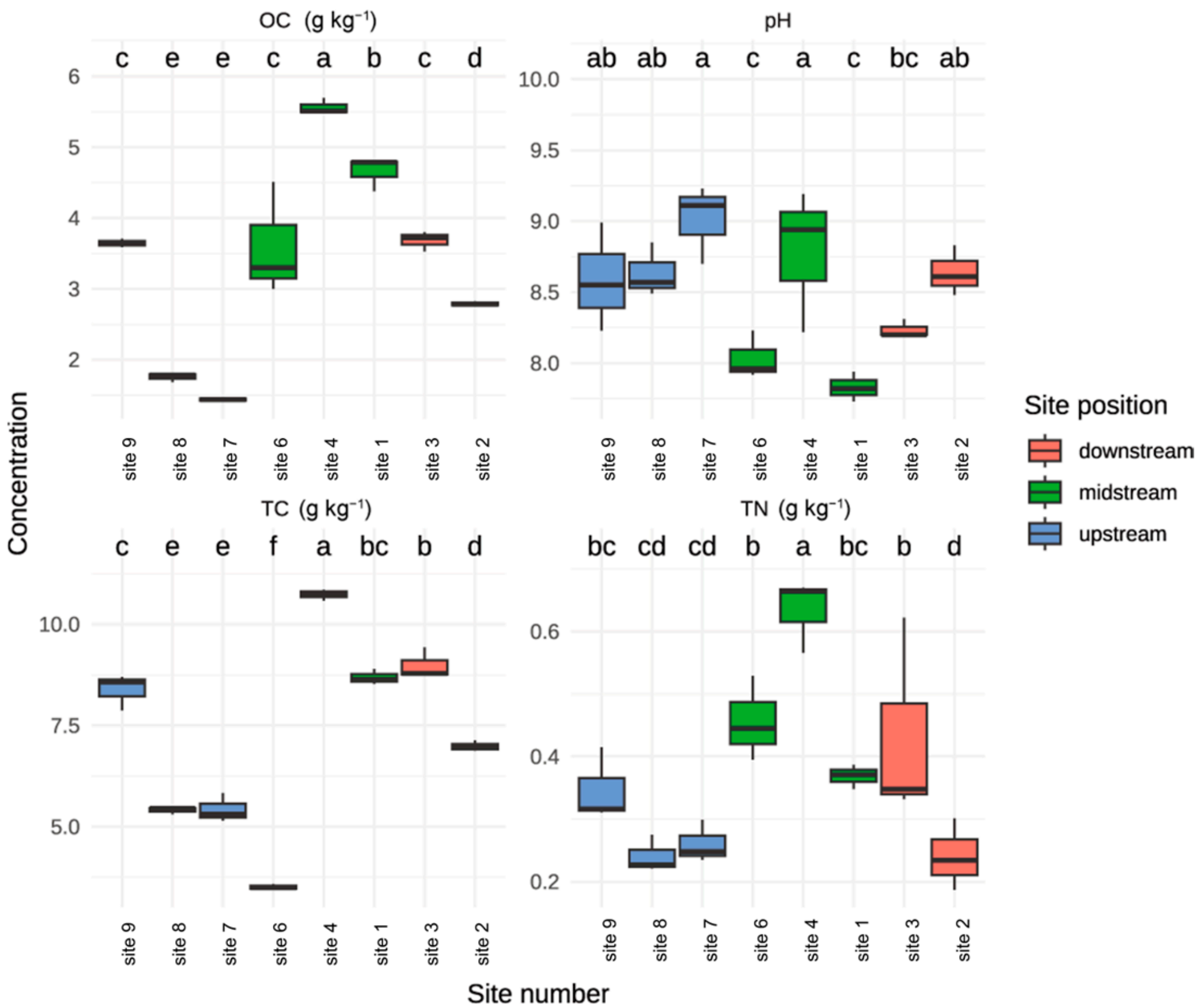

Figure 3. Differences in soil nutrients and pH and their significance. Site position illustrates the position of the sites in the midstream of Heihe River; downstream: the down reaches; midstream: the middle reaches; upstream: the upper reaches. Different lowercase letters indicate statistically significant differences among treatments ($p < 0.05$), the same as the following.

The concentrations of Ca^{2+}, K^+, and Na^+ in site 9 were significantly higher than those in other sites, while the Mg^{2+} concentrations in sites 1 and 7 were significantly higher. The concentrations of Ca^{2+}, Na^+, and Mg^{2+} in the middle reach sites were higher than those in the lower reach sites. Except for site 9, the Na^+ concentrations in the middle reach sites were higher than those in the upper reach sites. Except for site 9, the K^+ concentrations in the lower reach sites were higher than those in the upper and middle reach sites (Figure 4, Table S2). The concentrations of Cl^- and SO_4^{2-} in site 9 were significantly higher than those in other sites. The Cl^- concentrations in the middle reach sites were higher than those in sites 7 and 8 in the upper reaches. The HCO_3^- concentration in site 4 in the middle reaches was significantly higher than that in other sites. The concentrations of Cl^-, SO_4^{2-}, and HCO_3^- in site 3 were significantly lower than those in other sites.

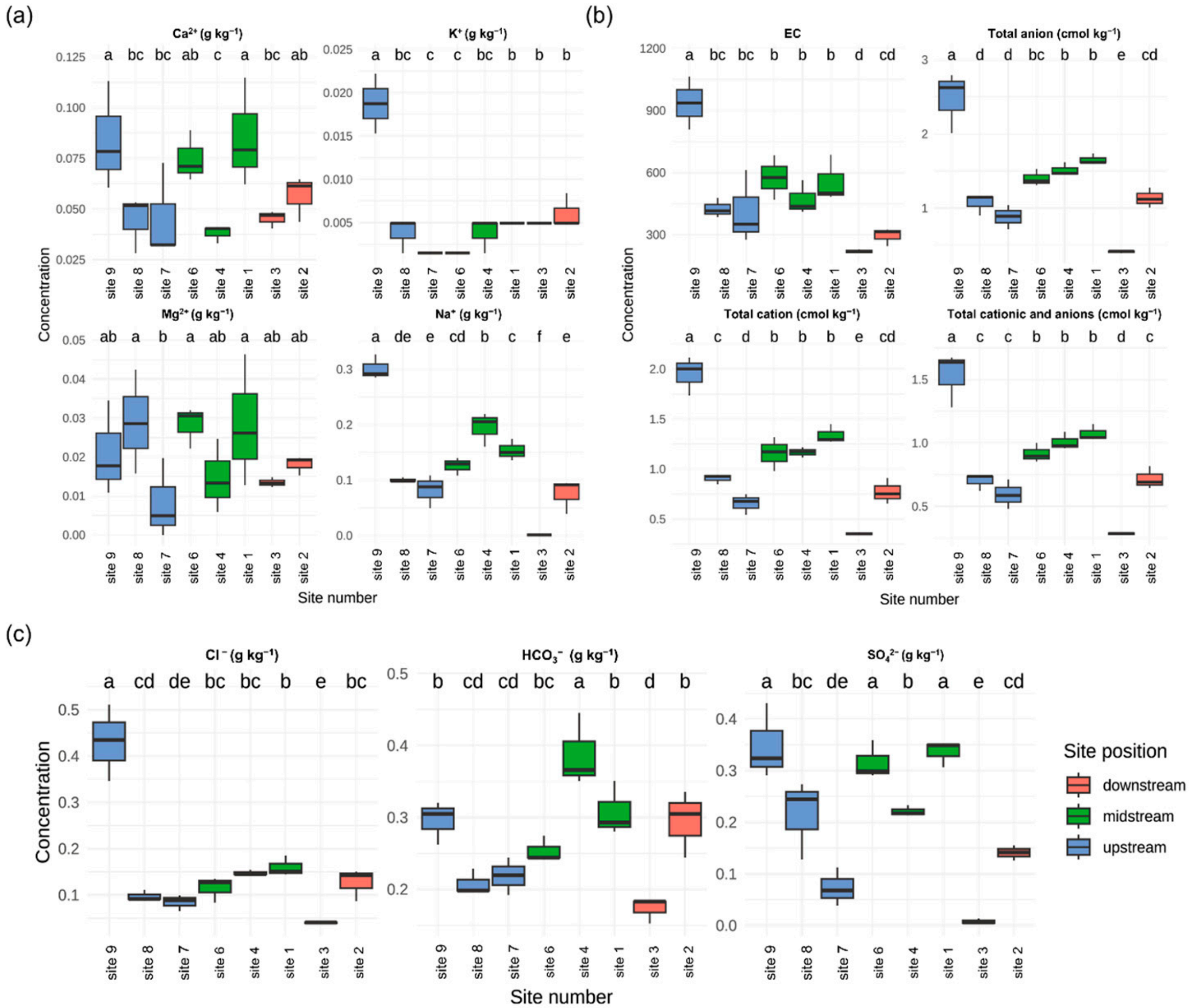

Figure 4. Differences in cation concentrations (**a**), electrical conductivity and total ion concentrations (**b**), and anion concentrations (**c**) among sampling sites and their significance.

3.3. Relationships between Soil Characteristic Ions and Plant Community Composition in the Heihe River Basin

The correlation analysis showed that different plant species exhibited unique adaptation strategies to anions, cations, and other environmental factors. The species diversity index was significantly negatively correlated with SO_4^{2-}, Mg^{2+}, and Ca^{2+} concentrations, while species evenness was significantly positively correlated with the total carbon content. *Agropyron cristatum* (L.) Gaertn. and *Phragmites australis* Trin. had similar relationships with Cl^-, Ca^{2+}, K^+, and electrical conductivity (EC), showing significant positive correlations. Additionally, *Phragmites australis* Trin. was significantly positively correlated with Na^+. *Onopordum acanthium* L., *C.* (Hall f.) Koel. and *Leymus secalinus* (Georgi) Tzvelev were significantly negatively correlated with SO_4^{2-}, Na^+, and EC. *Setaria viridis* (L.) P. Beauv. and *Eragrostis pilosa* (L.) Beauv. were significantly negatively correlated with Mg^{2+}, while *Populus L.* was significantly negatively correlated with SO_4^{2-}. The correlations between soil nutrients, pH, and plant species were not significant (Figure 5).

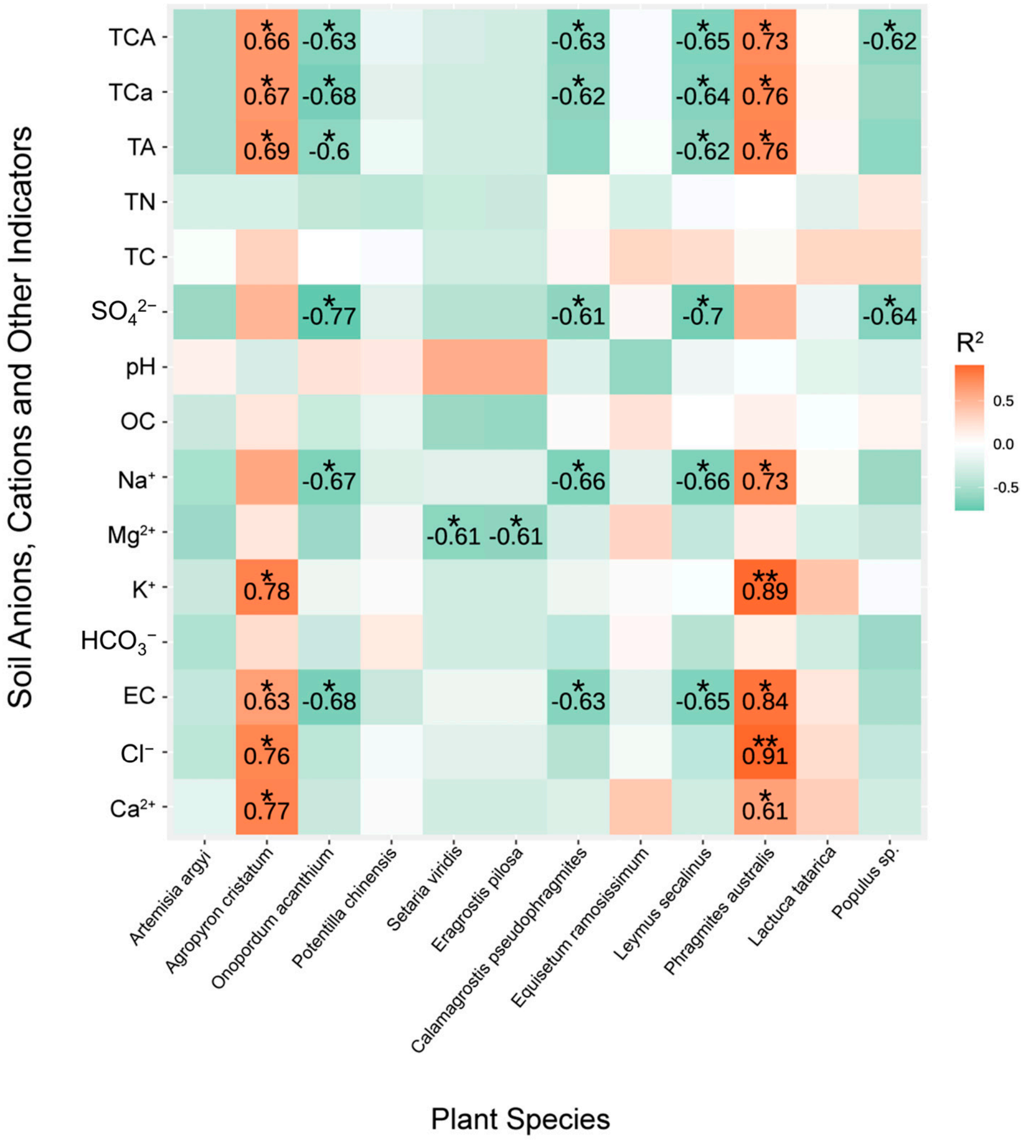

Figure 5. Correlations between relative abundance of plant species and ion concentrations, soil nutrients, and soil pH. The abbreviations mean as follows: TCA, Total Cation Amount; TCa, Total Cations; TA, Total Anions; TN, Total Nitrogen; TC, Total Carbon; OC, Organic Carbon. Different number of "*" indicates significant relations between the variables ("*": $p < 0.05$, "**": $p < 0.01$).

Consistent with the correlation analysis results, CCA indicated that the cation and anion concentrations had positive effects on *Agropyron cristatum* (L.) Gaertn., *Phragmites australis* Trin., and *Potentilla chinensis* Ser., but negative effects on *Lactuca tatarica* (L.) C. A. Mey., *Artemisia argyi* H. Lév. and Vaniot, *Onopordum acanthium* L., *Calamagrostis pseudophragmites* (Hall f.) Koel., *Leymus secalinus* (Georgi) Tzvelev, *Populus* L., *Eragrostis pilosa* (L.) Beauv., and *Setaria viridis* (L.) P. Beauv. Soil nutrients had negative effects on *Onopordum acanthium* L., *Artemisia argyi* H. Lév. and Vaniot, *Lactuca tatarica* (L.) C. A. Mey., Eragrostis pilosa (L.) Beauv., and *Setaria viridis* (L.) P. Beauv., while they positively influenced other plant species. The impact of soil nutrients on *Populus* L., *Equisetum ramosissimum* Desf., *Lactuca tatarica* (L.) C. A. Mey., and *Calamagrostis pseudophragmites* (Hall f.) Koel. was relatively weak (Figure 6).

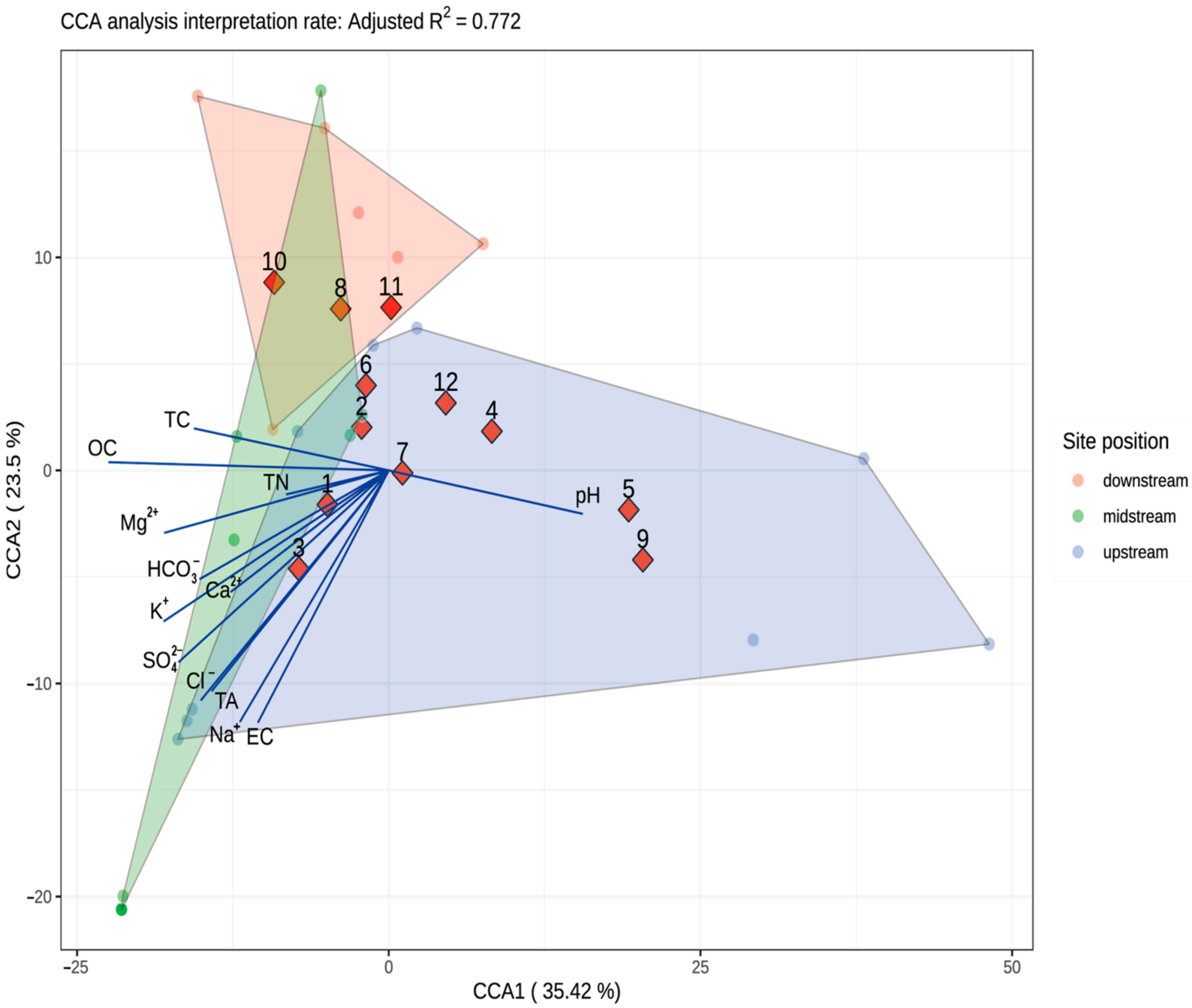

Figure 6. CCA of soil physicochemical properties, soil cations, soil anions, plant species, and sampling sites. The numbers adjacent to the diamonds represent plant species' names, specifically: 1. *Agropyron cristatum* (L.) Gaertn., 2. *Equisetum ramosissimum* Desf. 3. *Phragmites australis* Trin., 4. *Artemisia argyi* H. Lév. and Vaniot, 5. *Eragrostis pilosa* (L.) Beauv., 6. *Calamagrostis pseudophragmites* (Hall f.) Koel., 7. *Lactuca tatarica* (L.) C. A. Mey., 8. *Leymus secalinus* (Georgi) Tzvelev, 9. *Setaria viridis* (L.) P. Beauv., 10. *Potentilla chinensis* Ser., 11. *Populus* L., and 12, *Onopordum acanthium* L.

4. Discussion

This study unveiled substantial variations in the composition and diversity of riparian plant communities along the middle reaches of the Heihe River. Furthermore, it highlighted the strong correlations between ion concentrations, the soil nutrient status, and the distribution of plant species. These findings provide important insights into understanding the structure and function of riparian ecosystems in arid and semi-arid regions.

The species composition of riparian plant communities in the upper, middle, and lower reaches of the middle Heihe River differed markedly, which may be related to changes in environmental conditions such as the hydrology, topography, and climate along the longitudinal gradient of the river [26,27]. Previous studies have shown that the upstream sections of rivers typically have higher flow velocities, coarser sediments, and lower nutrient contents, while the opposite is true for downstream sections [28]. These changes in the environmental gradient have a significant impact on the species composition and diversity of plant communities. This study found that the species diversity index in the downstream section of the river was significantly higher than that in the middle and upper sections, which is consistent with the findings of Zhang [29] in the Heihe River. The high species diversity may be related to the more complex habitat heterogeneity and more stable moisture conditions in the riparian zone of the downstream section [30,31]. Wang [32] also pointed out that geomorphological units such as floodplains and islands developed in the downstream section can provide diverse microhabitats and promote species coexistence. Poaceae plants such as *Agropyron cristatum* (L.) Gaertn., *Equisetum ramosissimum* Desf., and *Phragmites australis* Trin. dominated in all sections of the middle reaches of the midstream of the Heihe River, reflecting their strong tolerance and adaptability. Liu [33] found that the distribution of *Agropyron cristatum* (L.) Gaertn. and *Phragmites australis* Trin. in the lower reaches of the Tarim River was closely related to the groundwater level, indicating that they can absorb deep soil moisture through their root systems to adapt to arid environments. In addition, *Phragmites australis* Trin. has a well-developed rhizome system and high asexual reproduction capacity, enabling it to expand rapidly in the riparian zone [34,35]. *Equisetum ramosissimum* Desf. also exhibits strong growth and physiological regulation abilities under water and salt stress [36]. The ecological adaptability of these species may be an important reason for their widespread distribution in the riparian zone of the middle reaches of the Heihe River.

The spatial distribution pattern of soil ion concentrations in the riparian zone of the middle reaches of the Heihe River is closely related to water and salt dynamics. The cation and anion concentrations at site 9 in the upstream section of this river segment were significantly higher than those at other sites, which may be related to the special geological conditions and hydrological processes of the upper Heihe River connected to this section. Wei found that the Qilian Mountains in the upper reaches of the Heihe River are rich in soluble salts, which can enter the river through rock weathering and groundwater recharge [37]. In addition, the narrow upstream valleys and faster river flow velocities may also intensify rock erosion and salt leaching [38]. The soil ion concentrations in the middle reaches were generally higher than those in the downstream section, which may be due to strong evaporation in the middle reaches, leading to salt accumulation in the topsoil. Zhao also showed that the soil salinization problem in the oasis area of the middle reaches of the Heihe River is relatively severe and is related to agricultural irrigation and a groundwater level rise [39]. The lowest ion concentrations were found at site 3 in the downstream section, which may be influenced by the dilution and leaching effects of the river water connected to the lower reaches of the Heihe River. Zhao found that the soil salt content in the riparian zone of the lower reaches of the Heihe River was generally lower than that in the inland areas [40], indicating a significant leaching effect of river water.

The results of this study demonstrate that the correlation analysis and canonical correspondence analysis reveal distinct response patterns of different plant species to soil ion and nutrient conditions. These findings align with previous research. For instance, Wang [41] discovered that perennial grasses in the lower reaches of the Tarim River were positively correlated with soil salinity, while *Populus* L. species showed a negative correlation with salinity. Similarly, Yang's [42] study in the Yellow River Delta revealed that salt-tolerant plants such as *Phragmites australis* Trin. dominated in high-salinity environments, whereas salt-sensitive plants like *Tamarix chinensis* Lour. were less abundant. In the present study, *Agropyron cristatum* (L.) Gaertn. and *Phragmites australis* Trin. were positively correlated with ions such as Na^+ and Cl^-, reflecting their salt tolerance adaptation mechanisms. Previous research has shown that white clover can maintain cell turgor and growth through Na^+ compartmentalization and osmotic adjustment [43], while *Phragmites australis* Trin. reduces salt toxicity by secreting salt from roots and excluding ions [44]. Some salt-sensitive plants, such as *Onopordum acanthium* L., *Calamagrostis pseudophragmites* (Hall f.) Koel., and *Leymus secalinus* (Georgi) Tzvelev, were negatively correlated with high concentrations of Na^+ and $SO4^{2-}$. This may be because excessive Na^+ can interfere with the K^+ uptake and enzyme activity in these species, while $SO4^{2-}$ can cause nutritional imbalances and growth inhibition [45,46].

Our study revealed a relatively weak relationship between the soil nutrient status and plant species distribution in the riparian zone of the Heihe River. This may be attributed to the generally low soil nutrient levels in this area, which could limit the influence of nutrients on vegetation. Tong investigated soil nutrients in the middle reaches of the Heihe River and found that the organic matter and total nitrogen contents in the riparian soil were generally lower than those in farmland and woodland [47]. These findings reflect the nutrient-poor characteristics of the riparian habitat in this river segment. Moreover, riparian plant communities may be primarily constrained by water conditions and ionic stress rather than nutrient limitation. Yu [48] discovered through controlled experiments that water treatment had the greatest impact on the growth of *Populus euphratica* seedlings, while the effect of a nitrogen addition was relatively small. However, soil nutrients still showed certain negative effects on some species, such as *Onopordum acanthium* L. and *Artemisia argyi* H. Lév. and Vaniot, indicating that excessive nutrients may also stress riparian vegetation. Therefore, appropriate soil nutrient concentrations are crucial for plant growth and distribution. Zou [49] pointed out that under high nitrogen conditions, the growth and photosynthetic efficiency of some riparian plants may be inhibited, leading to population decline.

In summary, this study reveals the complex associations between riparian plant communities and the soil ion and nutrient status in the middle reaches of the Heihe River. These results are consistent with previous studies in other arid region riparian zones. The distribution patterns and community characteristics of plant species are jointly influenced by the hydrological processes, salt dynamics, and soil physicochemical properties of different river segments. These findings are of great significance for understanding the structure and function of riparian ecosystems in arid regions and provide a scientific basis for the management, conservation, and restoration of riparian zones. However, there is currently insufficient research on the effects of factors such as climate change and human activities on riparian vegetation. Future studies should conduct long-term monitoring and controlled experiments to further explore the physiological and ecological response mechanisms of plants under different environmental stresses and carry out population ecology research on key species. Simultaneously, the assessment of ecosystem service functions in riparian zones should be strengthened to provide support for the development of sustainable watershed management policies. Only by comprehensively considering the interactions between riparian vegetation and environmental factors and coordinating the relationship between ecological protection and socio-economic development can the healthy maintenance and long-term sustainable development of riparian zones in arid regions be achieved.

5. Conclusions

This study elucidates the complex interactions between riparian plant communities and soil physicochemical properties along the midstream of the Heihe River. Significant spatial variations in plant diversity, community composition, and soil characteristics were observed across the upper, middle, and lower reaches. The sites in the lower reaches exhibited higher species diversity, likely due to increased habitat heterogeneity and more stable moisture conditions. Soil ion concentrations showed distinct spatial patterns, decreasing from upper to lower reaches, influenced by geological and hydrological factors. Strong correlations between the soil ion concentrations and plant species distribution were evident, with species demonstrating unique adaptation strategies to ionic stress. The weak relationship between soil nutrients and plant distribution suggests that riparian vegetation in this area may be primarily constrained by water conditions and ionic stress rather than nutrient limitations. These findings provide crucial insights into the structure and function of riparian ecosystems in arid and semi-arid regions. Future research should focus on long-term monitoring, controlled experiments on plant physiological responses, and ecosystem service assessments. Such a comprehensive understanding is essential for developing effective management strategies that balance ecological conservation with socio-economic development in these vital riparian ecosystems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14081868/s1, Table S1: Soil property and ion status differences and significance; Table S2: Soil anion and cation differences and significance.

Author Contributions: Conceptualization, J.L. and Z.W.; methodology, G.C.; investigation, J.J.; writing—original draft preparation, Z.W.; writing—review and editing, J.L.; visualization, J.L. and Z.W.; funding acquisition, J.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China Regional Science Fund, grant number 41967057.

Data Availability Statement: The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author/s.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Cole, L.J.; Stockan, J.; Helliwell, R. Managing riparian buffer strips to optimise ecosystem services: A review. *Agric. Ecosyst. Environ.* **2020**, *296*, 106891. [CrossRef]
2. Stutter, M.; Baggaley, N.; Wang, C. The utility of spatial data to delineate river riparian functions and management zones: A review. *Sci. Total Environ.* **2021**, *757*, 143982. [CrossRef]
3. Janssen, P.; Couloigner, C.; Piégay, H.; Evette, A. The accumulation of anthropogenic stressors induces a progressive shift in the ecological preferences and morphological traits shared by riparian plant communities. *Freshw. Biol.* **2023**, *68*, 1981–1994. [CrossRef]
4. Breton, V.; Girel, J.; Janssen, P. Long-term changes in the riparian vegetation of a large, highly anthropized river: Towards less hygrophilous and more competitive communities. *Ecol. Indic.* **2023**, *155*, 111015. [CrossRef]
5. Fijani, E.; Meysami, S. Assessment of hydrochemical characteristics and groundwater suitability for drinking and irrigation purposes in Garmsar Plain, Iran. *Geopersia* **2023**, *13*, 83–102.
6. Abugu, H.O.; Egbueri, J.C.; Agbasi, J.C.; Ezugwu, A.L.; Omeka, M.E.; Ucheana, I.A.; Aralu, C.C. Hydrochemical characterization of ground and surface water for irrigation application in nigeria: A review of progress. *Chem. Afr.* **2024**, *7*, 3011–3036. [CrossRef]
7. Arunrat, N.; Sansupa, C.; Sereenonchai, S.; Hatano, R.; Lal, R. Fire-Induced Changes in Soil Properties and Bacterial Communities in Rotational Shifting Cultivation Fields in Northern Thailand. *Biology* **2024**, *13*, 383. [CrossRef] [PubMed]
8. Yang, M.; Zhou, D.; Hang, H.; Chen, S.; Liu, H.; Su, J.; Lv, H.; Jia, H.; Zhao, G. Effects of balancing exchangeable cations Ca, Mg, and K on the growth of tomato seedlings (*Solanum lycopersicum* L.) based on increased soil cation exchange capacity. *Agronomy* **2024**, *14*, 629. [CrossRef]
9. Wang, A.; Zhang, Y.; Wang, G.; Zhang, Z. Soil physicochemical properties and microorganisms jointly regulate the variations of soil carbon and nitrogen cycles along vegetation restoration on the Loess Plateau, China. *Plant Soil* **2024**, *494*, 413–436. [CrossRef]
10. Zhao, Q.; Ding, S.; Liu, Q.; Wang, S.; Jing, Y.; Lu, M. Vegetation influences soil properties along riparian zones of the Beijiang River in Southern China. *PeerJ* **2020**, *8*, e9699. [CrossRef]
11. Cheng, G.; Li, X.; Zhao, W.; Xu, Z.; Feng, Q.; Xiao, S.; Xiao, H. Integrated study of the water–ecosystem–economy in the Heihe River Basin. *Natl. Sci. Rev.* **2014**, *1*, 413–428. [CrossRef]
12. Li, X.; Lu, L.; Cheng, G.; Xiao, H. Quantifying landscape structure of the Heihe River Basin, north-west China using FRAGSTATS. *J. Arid. Environ.* **2001**, *48*, 521–535. [CrossRef]
13. Wang, C.; Jiang, Q.O.; Shao, Y.; Sun, S.; Xiao, L.; Guo, J. Ecological environment assessment based on land use simulation: A case study in the Heihe River Basin. *Sci. Total Environ.* **2019**, *697*, 133928. [CrossRef]
14. Ding, J.; Zhao, W.; Daryanto, S.; Wang, L.; Fan, H.; Feng, Q.; Wang, Y. The spatial distribution and temporal variation of desert riparian forests and their influencing factors in the downstream Heihe River basin, China. *Hydrol. Earth Syst. Sci.* **2017**, *21*, 2405–2419. [CrossRef]
15. Wu, Y.; Han, Z.; Meng, J.; Zhu, L. Circuit theory-based ecological security pattern could promote ecological protection in the Heihe River Basin of China. *Environ. Sci. Pollut. Res.* **2023**, *30*, 27340–27356. [CrossRef]
16. Jiang, S.; Meng, J.; Zhu, L. Spatial and temporal analyses of potential land use conflict under the constraints of water resources in the middle reaches of the Heihe River. *Land Use Policy* **2020**, *97*, 104773. [CrossRef]
17. Brach, A.R.; Song, H. eFloras: New directions for online floras exemplified by the Flora of China Project. *Taxon* **2006**, *55*, 188–192. [CrossRef]
18. Li, J. Flora of China. *Harv. Pap. Bot.* **2007**, *13*, 301–302. [CrossRef]
19. Jobbagy, E.G.; Jackson, R.B. The distribution of soil nutrients with depth: Global patterns and the imprint of plants. *Biogeochemistry* **2001**, *53*, 51–77. [CrossRef]
20. Yang, Y.; Wang, H.; Li, C.; Liu, H.; Fang, X.; Wu, M.; Lv, J. Identification of the soil physicochemical and bacterial indicators for soil organic carbon and nitrogen transformation under the wheat straw returning. *PLoS ONE* **2024**, *19*, e0299054. [CrossRef]

21. Oksanen, J.; Kindt, R.; Legendre, P.; O'Hara, B.; Stevens, M.H.H.; Oksanen, M.J.; Suggests, M. The vegan package. *Community Ecol. Package* **2007**, *10*, 631–637.
22. Cleophas, T.J.; Zwinderman, A.H.; Cleophas, T.J.; Zwinderman, A.H. Bayesian Pearson correlation analysis. In *Modern Bayesian Statistics in Clinical Research*; Springer: Cham, Switzerland, 2018; pp. 111–118.
23. de Micheaux, P.L.; Drouilhet, R.; Liquet, B. The R software. In *Fundamentals of Programming and Statistical Analysis*; Springer: New York, NY, USA, 2013; pp. 971–978.
24. Dixon, P. VEGAN, a package of R functions for community ecology. *J. Veg. Sci.* **2003**, *14*, 927–930. [CrossRef]
25. Villanueva, R.A.M.; Chen, Z.J. ggplot2: Elegant graphics for data analysis. *Meas. Interdiscip. Res. Perspect.* **2019**, *17*, 160–167. [CrossRef]
26. Liu, Q.; Niu, J.; Wood, J.D.; Kang, S. Spatial optimization of cropping pattern in the upper-middle reaches of the Heihe River basin, Northwest China. *Agric. Water Manag.* **2022**, *264*, 107479. [CrossRef]
27. Han, M. Mutual Interactions between Geomorphology and Riparian Vegetation along Four Anabranching Reaches of the Upper Yellow River. Ph.D. Thesis, The University of Auckland, Auckland, New Zealand, 2020.
28. Khurram, D.; Tang, Q.; Bao, Y.; He, X.; Li, J. Flow regulation controls sediment, carbon, and nutrient dynamics across the elevation gradient in the water level fluctuation zone of the Three Gorges Reservoir, China. *J. Soils Sediments* **2023**, *23*, 3201–3218. [CrossRef]
29. Zhang, D.; Heng, W.; Chu, L.; Xu, D.; Kang, B.; Yan, Y. Taxonomic and functional diversity in a subtropical stream: A longitudinal pattern analysis. *Ecol. Freshw. Fish* **2020**, *29*, 752–763. [CrossRef]
30. Wang, Y.; Li, B.-L.; Zhu, J.-L.; Feng, Q.; Liu, W.; He, Y.-H.; Wang, X. Assessment of heavy metals in surface water, sediment and macrozoobenthos in inland rivers: A case study of the Heihe River, Northwest China. *Environ. Sci. Pollut. Res.* **2022**, *29*, 35253–35268. [CrossRef] [PubMed]
31. Wang, Y.; Liu, J.-J.; Liu, W.; Feng, Q.; Li, B.-L.; Lu, H.; Wang, S. Spatial variation in macrobenthic assemblages and their relationship with environmental factors in the upstream and midstream regions of the Heihe River Basin, China. *Environ. Monit. Assess.* **2021**, *193*, 1–22. [CrossRef]
32. Wang, Y.; Liu, J.-J.; Li, B.-L.; Liu, W.; Zuo, Y.-F.; Kong, D.-X.; Zhu, J.-L. Relationships between characteristics of macrobenthic assemblages and environmental variables in the Heihe River Basin, China. *AQUA Water Infrastruct. Ecosyst. Soc.* **2021**, *70*, 710–730. [CrossRef]
33. Liu, X.-H.; Zhang, Q.-Q.; Zhang, G.-P.; Li, H. Analysis of spatial distribution and influencing factors of plant communities in the lower reaches of Tarim river. *J. Agric. Sci. Technol.* **2021**, *23*, 131–144.
34. Coles, Z.S.; Lall, N. Sustainable production of aquatic and wetland plants. In *Aquatic Plants*; CRC Press: Boca Raton, FL, USA, 2020; pp. 291–329.
35. Wolski, K.; Tymiński, T. Studies on the threshold density of *Phragmites australis* plant concentration as a factor of hydraulic interactions in the riverbed. *Ecol. Eng.* **2020**, *151*, 105822. [CrossRef]
36. Husby, C.E.; Delatorre, J.; Oreste, V.; Oberbauer, S.F.; Palow, D.T.; Novara, L.; Grau, A. Salinity tolerance ecophysiology of *Equisetum giganteum* in South America: A study of 11 sites providing a natural gradient of salinity stress. *AoB Plants* **2011**, *2011*, plr022. [CrossRef] [PubMed]
37. Wei, L.; Zongjie, L.; Lingling, S. The evolution of hydrochemistry at a cold alpine basin in the Qilian Mountains. *Arab. J. Geosci.* **2016**, *9*, 306. [CrossRef]
38. Gaofeng, Z.; Yonghong, S.; Chunlin, H.; Qi, F.; Zhiguang, L. Hydrogeochemical processes in the groundwater environment of Heihe River Basin, northwest China. *Environ. Earth Sci.* **2010**, *60*, 139–153. [CrossRef]
39. Zhao, Y.; Feng, Q.; Lu, A.; Deo, R.C. Assessment of soil salinisation in the Ejina Oasis located in the lower reaches of Heihe River, Northwestern China. *Chem. Ecol.* **2019**, *35*, 330–343. [CrossRef]
40. Zhao, Y.; Feng, Q.; Yang, H. Soil salinity distribution and its relationship with soil particle size in the lower reaches of Heihe River, Northwestern China. *Environ. Earth Sci.* **2016**, *75*, 1–18. [CrossRef]
41. Wang, Y.; Li, J.; Qian, K.; Ye, M. Response of plant species diversity to flood irrigation in the Tarim River Basin, Northwest China. *Sustainability* **2023**, *15*, 1243. [CrossRef]
42. Yang, H.; Xia, J.; Cui, Q.; Liu, J.; Wei, S.; Feng, L.; Dong, K. Effects of different Tamarix chinensis-grass patterns on the soil quality of coastal saline soil in the Yellow River Delta, China. *Sci. Total Environ.* **2021**, *772*, 145501. [CrossRef]
43. Li, Z.; Peng, D.; Zhang, X.; Peng, Y.; Chen, M.; Ma, X.; Huang, L.; Yan, Y. Na^+ induces the tolerance to water stress in white clover associated with osmotic adjustment and aquaporins-mediated water transport and balance in root and leaf. *Environ. Exp. Bot.* **2017**, *144*, 11–24. [CrossRef]
44. Xie, E.; Wei, X.; Ding, A.; Zheng, L.; Wu, X.; Anderson, B. Short-term effects of salt stress on the amino acids of Phragmites australis root exudates in constructed wetlands. *Water* **2020**, *12*, 569. [CrossRef]
45. Xia, F.; Hao, H.; Qi, Y.; Bai, H.; Li, H.; Shi, Z.; Shi, L. Effect of salt stress on microbiome structure and diversity in chamomile (*Matricaria chamomilla* L.) rhizosphere soil. *Agronomy* **2023**, *13*, 1444. [CrossRef]
46. Yan, G.; Shi, Y.; Chen, F.; Mu, C.; Wang, J. Physiological and metabolic responses of *Leymus chinensis* seedlings to alkali stress. *Plants* **2022**, *11*, 1494. [CrossRef] [PubMed]
47. Tong, S.; Cao, G.; Zhang, Z.; Zhang, J. The spatial variation and driving factors of soil total carbon and nitrogen in the Heihe River source region. *Environ. Monit. Assess.* **2023**, *195*, 724. [CrossRef]

48. Yu, L.; Dong, H.; Li, Z.; Han, Z.; Korpelainen, H.; Li, C. Species-specific responses to drought, salinity and their interactions in *Populus euphratica* and *P. pruinosa* seedlings. *J. Plant Ecol.* **2020**, *13*, 563–573. [CrossRef]
49. Zou, H.; Wang, W.; Huang, J.; Li, X.; Ma, M.; Wu, S.; Zhao, C. Soil nitrogen and flooding intensity determine the trade-off between leaf and root traits of riparian plant species. *Plants* **2024**, *13*, 978. [CrossRef] [PubMed]