Hydrothermal Conditions Jointly Drive the Spatial Distribution Pattern of Plant Richness in Xinjiang Wetlands Postprint

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Abstract

At geographic spatial scales, climatic factors (such as thermal energy, precipitation, etc.) have long been considered the primary drivers of species diversity. However, whether climatic factors can explain wetland plant diversity patterns remains unclear. This study investigated the influence of environmental factors, particularly moisture and thermal conditions, on wetland species distribution, specifically including seven indicators: longitude, latitude, altitude, mean annual precipitation, mean annual temperature, mean annual evaporation, and mean annual sunshine hours. The study encompassed 26 wetland parks across three secondary-level watersheds in Xinjiang. Structural Equation Modeling (SEM) was applied to analyze the relative magnitude of each indicator' s impact on wetland plant richness and their interaction relationships. Additionally, Moran's I was used to conduct spatial autocorrelation analysis on the residuals of each variable to assess the influence of spatial correlation. The results indicated: (1) The SEM explained a total of 41.8% of the variation in species richness, with mean annual precipitation having the highest total effect on species richness at 0.47, followed by mean annual sunshine hours at -0.42, where mean annual precipitation exhibited a positive effect and mean annual sunshine hours a negative effect. The effects of all other indicators on species richness were not significant. (2) The impact of mean annual precipitation on plant richness was primarily manifested as a direct effect, accounting for 92.86% of the total effect, while the impact of mean annual sunshine hours on plant richness was mainly indirect, accounting for 54.76% of the total effect. (3) Spatial autocorrelation analysis revealed that the residuals of both mean annual precipitation and mean annual sunshine hours showed no spatial autocorrelation, with Moran' s I fluctuating within the range of -0.15~0.10, suggesting they can be considered reliable predictive indicators. In summary, Xinjiang wetland plant richness is mainly driven by the combined effects of moisture and thermal conditions, and the effect of heat is dependent on moisture conditions. In future conservation efforts for wetland

plant diversity, the assessment of climate change impacts on plant diversity and corresponding countermeasures should be strengthened.

Full Text

Spatial Distribution Pattern of Wetland Plant Species Richness Driven Collectively by Water and Heat Conditions in Xinjiang

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Abstract

At geographic spatial scales, climate factors (such as thermal energy and precipitation) have long been considered the primary drivers of species diversity. However, whether climatic factors can explain patterns of wetland plant diversity remains unclear. This study examined the influence of environmental factors, particularly water and heat conditions, on wetland species distribution. Specifically, we analyzed seven indicators including longitude, latitude, altitude, mean annual precipitation, mean annual temperature, mean annual evaporation, and mean annual sunshine hours across 26 wetland parks in three secondary river basins in Xinjiang. We applied structural equation modeling to analyze the relative magnitude and interactions of these factors on wetland plant richness. Additionally, we used Moran' s I to conduct spatial correlation analysis of variable residuals to assess the impact of spatial autocorrelation. The results show that: (1) The structural equation model explained 41.8% of the variation in plant species richness. Mean annual precipitation had the highest total effect on species richness (0.47), followed by mean annual sunshine hours (-0.42). Mean annual precipitation exhibited a positive effect, while mean annual sunshine hours showed a negative effect. The effects of other indicators were not significant. (2) The influence of mean annual precipitation on plant richness was primarily direct, accounting for 92.86% of the total effect. The influence of mean annual sunshine hours was mainly indirect, accounting for 54.76% of the total effect. (3) Spatial correlation analysis revealed no spatial autocorrelation in the residuals of mean annual precipitation and sunshine hours across different spatial scales, with Moran' s I fluctuating between -0.15 and 0.10, indicating these are reliable predictors. (4) The direct effects of spatial factors such as longitude and latitude on plant richness were not significant, while their indirect effects were significant. Longitude significantly affected mean annual precipitation, and latitude significantly affected mean annual sunshine hours and temperature, indicating that spatial factors indirectly influence species richness by affecting precipitation and sunshine hours. In conclusion, wetland plant richness in Xinjiang is primarily driven by the combined effects of water and heat conditions, with the role of heat depending on water conditions. Future wetland plant diversity conservation efforts should strengthen assessment and response measures regarding climate change impacts on plant diversity.

Key words: water-energy dynamics hypothesis; structural equation model; spatial correlation; arid area; wetland protection

Introduction

Water and heat conditions are important factors influencing regional species diversity and are crucial for understanding spatial distribution patterns of biodiversity. The water-energy dynamics hypothesis effectively explains the effects of water and heat factors on plant richness and has been widely validated in ecosystems such as deserts and mountain forests, as well as for specific biological groups. However, the dominant roles of water and heat conditions in species richness still require further verification for different geographic regions or ecosystem types.

Wetlands are ecosystems at the transition between aquatic and terrestrial environments. Previous studies have paid relatively little attention to the influence of climate factors on wetland plant diversity patterns at larger geographic scales. According to the renowned Chinese mire scientist Huang Xichou, even though wetlands (originally termed mires) are intrazonal, their soils and vegetation all bear the imprint of zonal characteristics. In other words, wetland plant distribution remains strongly constrained by zonal climate factors. Studies have found that herbaceous plant diversity in permafrost wetlands of the Greater Khingan Mountains increases with decreasing latitude, and that aquatic plant community distribution in the Hexi Corridor is related to environmental factors such as altitude, longitude, and latitude, demonstrating the controlling role of large-scale geographic factors.

Xinjiang is located deep inland, with wetlands generally showing a pattern of isolated islands distributed within a desert "ocean." The water systems are not interconnected, so both riverine and lacustrine wetlands bear the mark of aridity, characterized by large water level fluctuations, strong surface evaporation, soil salinization, high water mineralization, and vegetation containing many Mediterranean and Central Asian xerophytic components. Therefore, how zonal climate factors (water and heat conditions) influence the spatial distribution pattern of wetland plant richness in Xinjiang is a question worth exploring.

Xinjiang has widely distributed, diverse, and large-area wetlands with remarkable conservation achievements. According to the Third National Land Survey data of Xinjiang Uygur Autonomous Region, the total wetland area in Xinjiang reaches 152.45$\times10^{4}$ hm^2, belonging to 3 primary-level, 6 secondary-level, and 18 tertiary-level river basins. Current wetland ecological conservation in Xinjiang is at a critical juncture for establishing national and internationally important wetlands. Understanding the spatial distribution patterns and driving factors of wetland species diversity is crucial for advancing wetland ecological conservation and developing scientific protection measures. Therefore, this study selected 26 important and representative wetland parks or reserves from 6 secondary river basins in Xinjiang. Through field surveys and data collection, we obtained species richness and climate data for these wetlands to explore the influence and mechanisms of water and heat conditions on wetland plant diversity in Xinjiang, providing theoretical support for wetland ecological construction.

1. Materials and Methods

1.1 Study Sites

This study involved 26 wetland parks belonging to six river basins: southern slopes of the Altai Mountains, northern slopes of the Tianshan Mountains, Central and West Asian inland river areas, Tarim River headwaters, Tarim Basin desert areas, and Turpan-Hami Basin small rivers. Spatially, the northernmost site is the Habahe Akeqi National Wetland Park in the Irtysh River basin, the southernmost is the Minfeng Niya National Wetland Park, the easternmost is the Turpan Ayding Lake National Wetland Park, and the westernmost is the Wenquan Bortala River National Wetland Park. Climatically, the study covers sub-arid regions (including Tianshan, Altai, and Yining areas), arid regions (including Tacheng, Irtysh-Ulungur, and Junggar Basin areas), and hyper-arid regions (Tarim Basin area), showing clear climatic differentiation.

1.2 Data Sources

Among the 26 wetlands, plant data for 13 sites (Table 1) were obtained through field surveys conducted from June to August 2021. Before surveying, we consulted relevant materials and interviewed wetland managers to identify main vegetation types and their distribution. Nominal surveys were conducted according to different vegetation types, including desert, saline meadow, meadow, swamp, shrub, and forest. For each vegetation type, 3-5 sample plots were established, each measuring 10 m × 10 m. Plant species and coverage were recorded, with all plant species encountered in the plots counted as the total plant species for the wetland park. Plant data for the remaining 13 wetlands, such as the Fuyun Koktokay National Wetland Park, were obtained from wetland (reserve) management agencies.

Geographic location, altitude, climate data, and area data for the wetland parks or reserves were obtained from the Wetland Division of Xinjiang Forestry and Grassland Bureau. Climate data came from microclimate station observations at each wetland park (reserve), calculating annual averages of climate elements from 2010 to 2020.

1.3 Data Analysis

Based on the obtained total plant species and area data for each wetland park or reserve, plant richness (D) was calculated using the Gleason index with the following formula:

$$D = \frac{S}{\ln A}$$

where S and A represent the total plant species number and total area (hm^2) of the wetland park or reserve, respectively.

We used structural equation modeling to analyze relationships between various factors and wetland species richness. Since SEM is essentially linear regression analysis, data were standardized before analysis to meet normality requirements. Preliminary univariate linear regression analysis revealed that wetland area was not related to species richness, so area data were not included in the SEM. Only seven variables were included: longitude (°), latitude (°), altitude (m), mean annual sunshine hours (h), mean annual precipitation (mm), mean annual temperature (°C), and mean annual evaporation (mm). Variance inflation factor (VIF) was calculated for variables included in the model to remove collinearity effects. All variables had VIF < 5, indicating no significant collinearity.

When constructing the SEM, we followed the causal relationships among factors: spatial factors (longitude and latitude) as primary influences, followed by topographic factor (altitude), and finally climatic factors. Among climatic factors, the sequence was mean annual sunshine hours, mean annual temperature, and mean annual precipitation. Mean annual evaporation is influenced by the above three factors and was placed last in the model. Based on this approach, the basic model is shown in Figure 1.

We used partial least squares to estimate path coefficients and Monte Carlo permutation tests (999 permutations) to test coefficient significance. The final model displayed all direct paths and indirect paths with significant path coefficients. Direct and indirect effects of each factor on plant species richness were measured based on path coefficients, with the sum of direct and indirect effects equaling the total effect.

When processing geographic data, spatial autocorrelation increases the risk of Type I error, making it easier to reject null hypotheses and overestimate the effects of climate factors on species richness. In this study, we conducted preliminary global tests for spatial autocorrelation, which showed significant spatial correlation for all climate factors ($P < 0.05$), suggesting that species richness might exhibit dependent spatial correlation. Although SEM can distinguish direct and indirect effects of influencing factors, it cannot determine spatial correlation. Therefore, we applied Moran' s I to test spatial correlation of regression residuals between environmental factors and species richness (ordinary least squares regression) at different spatial distances, plotting spatial correlation diagrams of residuals for regression models between climate factors and species richness. Moran' s I significance was tested using Monte Carlo permutation (999 permutations). If residuals show no spatial correlation at various spatial distances, the interpretation of climate factors on species richness is credible without spatial correlation effects; otherwise, spatial structure effects (such as spatial distance) on species richness cannot be excluded.

Data analysis was completed using R statistical language (R Development Core Team 2015). Packages used included "rgdal" , "vegan" , "plspm" , and "spdep" . All statistical significance levels were set at P = 0.05.

2. Results and Analysis

A total of 271 plant species were recorded across the 26 wetlands. At the individual wetland level, Sayram Lake National Wetland Park had the most species (126), while Ayding Lake National Wetland Park had the fewest (17 species), with corresponding plant richness values of 11.69 and 2.86, respectively. In terms of river basins, wetlands in the Ili River and Irtysh River basins generally had higher plant richness, while those in the Tarim River basin had lower richness (Figure 2).

Structural equation model analysis results indicate that all environmental variables collectively explained 41.8% of the variation in plant richness, with different factors showing varying degrees of influence. Among climatic factors, only mean annual precipitation and mean annual sunshine hours had significant direct effects on plant richness, with path coefficients of 0.39 and -0.19, respectively. The direct effects of spatial factors on plant richness were not significant, but indirect effects were significant. For example, both latitude and altitude had significant negative effects on mean annual sunshine hours (path coefficients of -0.33 and -0.34, respectively), while longitude had a significant negative effect on mean annual precipitation (path coefficient of -0.31). Spatial factors thus indirectly affected species richness by influencing mean annual precipitation and sunshine hours. Mean annual evaporation had no significant effect on plant richness (Figure 3).

In terms of total effects, the importance ranking of environmental factors was: mean annual precipitation > mean annual sunshine hours > mean annual evaporation. Mean annual precipitation had the greatest total effect (0.47) on plant richness, with a direct effect of 0.39 and indirect effect of 0.08. Mean annual sunshine hours had a total effect of -0.42, with a direct effect of -0.19, indicating that Xinjiang wetland plant richness is jointly constrained by water and heat conditions (Figure 4).

Spatial correlation analysis showed that residuals of all factors exhibited no spatial autocorrelation at any spatial distance scale, with Moran' s I fluctuating between -0.15 and 0.10, failing to reject the null hypothesis. This indicates that the interpretation of plant richness by environmental factors in this study is credible without spatial correlation effects (Figure 5).

3. Discussion

Geographic patterns of species richness distribution and their influencing factors constitute a core issue in macroecology. Regional species diversity at large scales is related to both evolutionary history and regional water-heat conditions. This study examined the effects of spatial, topographic, and climatic factors on wetland plant diversity in Xinjiang, with results supporting previous conclusions that wetland plant richness in arid regions is jointly constrained by water and heat conditions, with mean annual precipitation and sunshine hours as significant environmental factors affecting wetland plant richness.

The reasons are: (1) Xinjiang wetlands generally contain considerable areas of dryland. For instance, both Ebinur Lake and Bosten Lake wetlands have large areas of saline-alkali land or sandy land. Therefore, water conditions remain the primary factor constraining wetland plant diversity in Xinjiang. Increased precipitation promotes the development of mesophytic and hygrophytic plants in wetlands, thereby increasing plant diversity. (2) Mean annual sunshine hours affect regional heat conditions, representing the amount of solar radiation energy. Since Xinjiang is located in the temperate zone, its floristic composition is dominated by North Temperate and Old World Temperate distributions, so improved heat conditions also benefit wetland plant diversity.

Previous studies have shown considerable regional variation in the roles of water and heat on species diversity patterns. Some studies indicate that heat affects species diversity, while others demonstrate interactions between water and heat jointly influencing species richness. This study used SEM to explore direct and indirect effects of various factors, finding that mean annual precipitation had the greatest impact, primarily through direct effects, with indirect effects mainly through influencing mean annual evaporation and subsequently species diversity. Mean annual sunshine hours, however, affected species richness through both direct and indirect pathways: mean annual sunshine hours $\rightarrow$ mean annual temperature $\rightarrow$ mean annual precipitation $\rightarrow$ species richness. Thus, the mechanisms by which mean annual precipitation and sunshine hours influence plant richness differ. Compared with mean annual precipitation, the indirect effect of mean annual sunshine hours is greater, indicating that heat effects depend largely on water conditions, with interactions existing between the two factors. These results deepen our understanding of the processes and mechanisms of various climate elements.

At the global scale, species diversity generally decreases with increasing latitude. In this study, species diversity showed no clear trend with latitude and exhibited no correlation, which relates to the distribution pattern of wetlands in this study. Xinjiang wetland development strictly depends on mountain snowmelt, and results show that wetlands with high species diversity are all distributed in the Tianshan or Altai Mountains. Although 8 wetlands in the Ili River basin belong to the Central and West Asian inland river secondary basin, they also depend on Tianshan snowmelt. Consequently, large wetland areas have developed around rivers and lakes originating from major mountain systems, leading to relatively concentrated wetland distribution—exactly reflecting the intrazonal nature of wetland distribution. Although the direct effects of longitude and latitude were not significant, SEM results showed significant indirect effects. Latitude significantly affected mean annual sunshine hours and temperature but not precipitation (not shown in the model), indicating that latitude influenced heat conditions. Longitude had significant direct effects on mean annual precipitation, thereby affecting species richness. Similarly, altitude significantly affected mean annual sunshine, temperature, precipitation, and evaporation, simultaneously influencing water-heat conditions and thus having significant indirect effects on species richness. In summary, despite the intrazonal distribution nature of wetlands, species distribution remains constrained by zonal water-heat conditions, supporting Huang Xichou’ s viewpoint.

At geographic scales, both species richness and environmental factors exhibit spatial autocorrelation, so species richness patterns may either have inherent spatial correlation or derive from spatial correlation in environmental factors. In this study, Moran’ s I tests on residuals of influencing factors showed no spatial autocorrelation at any spatial scale. The reason may be that the 26 wetlands are distributed across 6 major basins, primarily influenced by snowmelt from the Tianshan and Altai Mountains, with isolated and poorly connected water systems and limited species exchange. Therefore, the isolation of wetland biota development processes across basins results in weak spatial correlation.

4. Conclusion

This study applied structural equation modeling to analyze the effects of longitude, latitude, altitude, mean annual precipitation, mean annual temperature, mean annual evaporation, and mean annual sunshine hours on plant richness in 26 wetland parks (reserves) in Xinjiang. The main conclusions are: (1) Xinjiang wetland plant richness is jointly constrained by water and heat conditions, with mean annual precipitation and mean annual sunshine hours as significant environmental factors affecting wetland plant richness. (2) Mean annual precipitation has the greatest impact on species richness, with a total effect of 0.47; mean annual sunshine hours rank second, with a total effect of -0.42. Water primarily affects plant richness through direct effects, while heat mainly affects plant richness through indirect effects. (3) Heat effects on plant richness depend largely on water conditions. (4) This study deepens our understanding of how water-heat conditions affect wetland plant richness. To better promote wetland ecological conservation, we should strengthen assessment and response measures regarding climate change impacts on plant diversity.

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Note: Figure translations are in progress. See original paper for figures.