Postprint: Different Vegetation Types and Their Soil Nutrient Variation Patterns in the Li River Riparian Zone

Authors: Wang Jing, Pan Fujing, Lu Qianqian, Wang Bin

Date: 2024-03-26T00:00:00+00:00

Abstract

To promote the restoration and reconstruction of riparian zone ecosystems, this study investigated the variation patterns of vegetation species composition and diversity, as well as soil nutrients, under different vegetation types in the Lijiang River riparian zone using Pearson correlation coefficient method and redundancy analysis based on typical sample plot surveys. The results showed that: (1) Plant community structure and species diversity differed significantly among different vegetation types (gravel beach, grassland, shrub-grassland, and sparse forestland). With decreasing inundation time, the riparian zone gradually evolved from sporadically distributed herbaceous plant communities to grass, shrub, and tree plant communities, with vegetation species α-diversity (Shannon-Wiener index, Pielou index, and Simpson index) and vegetation coverage showing an increasing trend, being lowest in gravel beaches and highest in sparse forestlands. (2) Soil nutrient contents differed significantly among different vegetation types. With decreasing inundation time, soil organic matter content gradually increased, while soil water content, available nitrogen, available phosphorus, and readily available potassium showed a trend of initially increasing and then decreasing, with the maximum values of these nutrients mostly occurring in shrub-grasslands or sparse forestlands, followed by grasslands, and being lowest in gravel beaches. (3) Correlation and redundancy analysis revealed that soil available nitrogen, readily available potassium, available phosphorus, and organic matter were highly significantly positively correlated with various indicators of vegetation species α-diversity, among which soil available nitrogen and readily available potassium showed the strongest correlation with vegetation species diversity. In summary: vegetation species composition and diversity, as well as soil nutrients, exhibited heterogeneous distribution patterns under different vegetation types in the Lijiang River riparian zone; moderate inundation was conducive to vegetation community aggregation and promoted soil nutrient accumulation to some extent; herbaceous plants showed stronger adaptability

to moderately inundated environments; during the ecological restoration of the Lijiang River riparian zone, targeted restoration schemes should be designed for different vegetation type areas, and the relationship between vegetation species diversity and soil available nutrients should be fully considered.

Full Text

Variation Patterns of Different Vegetation Types and Soil Nutrients in the Water-Land Ecotone of the Li River

WANG Jing[1],[2], **PAN Fujing**[3], **LU Qianqian**[2], **WANG Bin**[1]*

[1]Guangxi Key Laboratory of Plant Conservation and Restoration Ecology in Karst Terrain, Guangxi Institute of Botany, Guangxi Zhuang Autonomous Region and Chinese Academy of Sciences, Guilin 541006, Guangxi, China
[2]College of Earth Sciences, Guilin University of Technology, Guilin 541006, Guangxi, China
[3]College of Environmental Science and Engineering, Guilin University of Technology, Guilin 541006, Guangxi, China

Abstract: To promote ecosystem restoration and reconstruction in water-land ecotones, this study investigated vegetation species composition and diversity, as well as soil nutrient variation patterns under different vegetation types in the Li River water-land ecotone using Pearson correlation coefficient and redundancy analysis methods based on typical sample plot surveys. The results showed that: (1) Plant community structure and species diversity differed significantly among vegetation types (gravel zone, grass zone, shrub-grass zone, and sparse forest zone). As submersion duration decreased, the water-land ecotone gradually evolved from scattered herbaceous communities to mixed grass-shrub-tree communities, with vegetation species α-diversity (Shannon-Wiener index, Pielou index, and Simpson index) and vegetation coverage showing an increasing trend—lowest in gravel zones and highest in sparse forest zones. (2) Soil nutrient content also varied significantly among vegetation types. With decreasing submersion duration, soil organic matter content increased gradually, while soil water content, available nitrogen, available phosphorus, and available potassium showed a trend of initial increase followed by decrease. Maximum values of these nutrients occurred primarily in shrub-grass or sparse forest zones, followed by grass zones, with gravel zones showing the lowest values. (3) Correlation and redundancy analyses revealed that soil available nitrogen, available potassium, available phosphorus, and organic matter were extremely significantly positively correlated with vegetation species α-diversity indicators, with soil available nitrogen and available potassium showing the strongest associations. In conclusion, vegetation species composition, diversity, and soil nutrients exhibit heterogeneous distribution patterns across different vegetation types in the Li River water-land ecotone. Moderate submersion facilitates vegetation community aggregation and promotes soil nutrient accumulation, with herbaceous plants demonstrating stronger adaptability to moderately submerged environments. Ecological restoration efforts in the Li River water-land ecotone should incorporate targeted restoration plans for different vegetation zones and fully consider the relationship between vegetation species diversity and soil available nutrients.

Keywords: vegetation type, plant species diversity, soil nutrient, water-land ecotone, Li River

Introduction

The water-land ecotone, also known as the riparian zone or riparian buffer, extends from the lowest water level of a river channel to the area where riverine influence completely disappears (Naiman & Decamps, 1997). As a transitional zone between aquatic and terrestrial ecosystems, its unique environmental factors (seasonal flooding, edge effects, etc.), plant community characteristics, and ecological processes enable it to play crucial roles in flood regulation, soil erosion mitigation, pollution purification, and biodiversity maintenance (Yi et al., 2020; Zheng et al., 2021). In southern China, seasonal rainfall causes substantial water level fluctuations in river channels, subjecting water-land ecotone vegetation to frequent flooding or drought stress. In recent years, increasingly frequent extreme climate events (e.g., extreme droughts and floods) have severely impacted plant survival and community characteristics in these zones, causing vegetation destruction and soil nutrient loss that ultimately leads to ecosystem degradation (Fang et al., 2007). Numerous studies have confirmed that changes in hydrological characteristics are important factors affecting vegetation patterns and community succession in water-land ecotones, as well as key constraints on soil nutrient migration and cycling (Huang et al., 2007; McDaniel et al., 2013; Gill et al., 2018; Yang et al., 2018). Accurate understanding of plant community structure and soil nutrient variation patterns provides a scientific basis for restoring degraded water-land ecotone vegetation and reconstructing ecosystems (Capon & Pettit, 2018; Guo et al., 2021).

Hydrological changes (flood dynamics) create a continuously varying gradient of submersion environments across the water-land ecotone. This gradient begins near the riverbed at low elevations where gravel beaches form due to prolonged submersion and erosion, and extends to higher elevations where riparian forests are only submerged during flood periods. Importantly, this submersion gradient exhibits significant differences in submersion duration (frequency), community species composition, and soil nutrient content (Naiman et al., 2005). Studies on the Li River water-land ecotone, Sanjiang Plain wetlands, and Three Gorges Reservoir drawdown zone have all found that plant species and coverage are closely related to elevation or submersion gradients, with different plants showing varying tolerance and adaptability to submersion, resulting in heterogeneous vegetation distribution patterns where moderate inundation facilitates plant community aggregation (Shan et al., 2019; Chen et al., 2020). Flow regulation studies on ten Swedish rivers demonstrated that changes in flow and water level alter the relative abundance of herbaceous and woody plants, thereby affecting community species composition and diversity (Bejarano et al., 2020). Changes in river water level or inundation status also affect the spatial distribution and transformation processes of soil physicochemical properties such as carbon, nitrogen, and phosphorus, with appropriate submersion promoting soil nutrient accumulation in riparian zones (Li et al., 2018; Qian et al., 2018; Wang et al., 2019).

The Li River is a rain-fed river with distinct wet and dry seasons, representing one of the most typical karst river basins in China and worldwide. In recent years, changes in hydrological characteristics and human disturbances have intensified ecological and environmental problems in the Li River basin, including frequent flooding, dry-season water shortages, vegetation degradation, and exposed water-land ecotones. Vegetation and soil in the Li River water-land ecotone undergo complex hydrological processes of repeated submersion and drying, causing significant changes in plant communities and soil properties that affect ecosystem structure and function (Liang et al., 2016; Chen et al., 2023). Therefore, understanding the impacts of hydrological processes on plant communities and soil physicochemical properties is fundamental to water-land ecotone ecosystem restoration. Current research on the Li River water-land ecotone has primarily focused on vegetation species, leaf traits, soil physicochemical properties and microbial distribution (Li et al., 2013; Liang et al., 2019; Li et al., 2015; Huang et al., 2019; Wang et al., 2019), vegetation configuration and restoration (Ren, 2019), and soil enzyme activities (Chen et al., 2023). However, few studies have examined variation patterns of plant species diversity and soil nutrients under different vegetation types in water-land ecotones. This study investigates four vegetation types formed by hydrological processes in the Li River water-land ecotone to address two scientific questions: (1) What adaptive variations occur in plant species composition, diversity, and soil nutrients across different vegetation types (gravel zone, grass zone, shrub-grass zone, and sparse forest zone)? (2) Which key soil nutrient factors are significantly correlated with plant community species diversity? The results provide scientific guidance for vegetation restoration and reconstruction, as well as management and protection of degraded water-land ecotone systems.

1. Study Area Overview

The Li River basin is located in Guilin City, Guangxi, and belongs to the Xijiang River system of the Pearl River basin (Liu et al., 2003). The basin lies in a subtropical monsoon humid climate zone with an annual average temperature of 17-20 °C and annual precipitation of 1,814-1,941 mm. Annual runoff is abundant but unevenly distributed, with the wet season generally occurring from March to August (accounting for 80% of annual runoff) and the dry season from September to February of the following year (Huang et al., 2005). The Li River basin features typical karst landforms with widespread carbonate rocks;

the 83 km section from Guilin to Yangshuo represents the most scenic stretch. The river channel in this section is distributed with sand and gravel. Gravel beaches in the water-land ecotone near the river channel experience prolonged erosion and immersion, resulting in thin soil layers with high sand and gravel content. Sparse forest zones farther from the river channel have deeper soil layers with relatively lower gravel content. Dominant vegetation includes: trees such as *Pterocarya stenoptera*, *Cinnamomum burmanni*, and *Triadica sebifera*; shrubs such as *Geum aleppicum* and *Vitex negundo*; and herbs primarily including *Polygonum hydropiper*, *Cynodon dactylon*, and *Humulus scandens*.

2. Methods

2.1 Sample Plot Setup

The left-side water-land ecotone of the Guilin-Yangshuo Li River section (facing downstream, the left side is defined as the left water-land ecotone) was selected as the study area. Ten typical natural landscape water-land ecotone sample plots with minimal human disturbance were established following principles of representativeness and typicality, each measuring 200 m × 200 m. Based on nearly one year of fixed-point observation data and comprehensive consideration of aboveground vegetation, average annual submersion duration, and relative elevation (relative to dry season water level), each plot was further subdivided into four vegetation types: gravel zone, grass zone, shrub-grass zone, and sparse forest zone (Li et al., 2013; Wang et al., 2019). Gravel zones contained only scattered herbaceous plants, with average annual submersion duration $ $7 months and relative elevation $ $0.6 m. Sparse forest zones contained combined tree-shrub-grass communities, with average annual submersion duration $ $2 months and relative elevation $ $2.1 m. Soil sand content (0.02–2 mm) in gravel, grass, shrub-grass, and sparse forest zones was 88.44%, 81.59%, 77.70%, and 74.99%, respectively. The lateral widths of gravel, grass, and shrub-grass zones were 20–40 m, while sparse forest zones were 50–100 m. Basic characteristics of the sample plots and different vegetation types are shown in Table 1 and Figure 1 [Figure 1: see original paper].

Vegetation surveys were conducted in each vegetation type during September-October 2022 (the Li River dry season). In each vegetation type, one 20 m × 20 m quadrat was established away from edge areas to survey tree and shrub vegetation. At the center point and four corners of each 20 m × 20 m quadrat, five 1 m × 1 m quadrats were established to survey herbaceous vegetation. Species composition, height, and coverage of all plants in each quadrat were recorded, along with latitude, longitude, altitude, aspect, and slope for each vegetation type. Soil samples were collected from three 1 m × 1 m quadrats established at two diagonal corners and the center point of each 20 m × 20 m quadrat.

2.2 Vegetation Quadrat Survey

Vegetation within quadrats was divided into three layers—tree, shrub, and herb—for stratified investigation and statistical analysis. The tree layer recorded species name, height, diameter at breast height (DBH) $ $3 cm, and crown width. The shrub layer recorded species name, cluster number, base diameter, height, crown width, and coverage. The herb layer recorded species name, cluster number, average coverage, and height. This information was used to calculate species importance values, species richness, α-diversity indices, and to assess vegetation coverage.

2.3 Soil Sampling

Within each 1 m × 1 m quadrat, soil was collected from 5–8 locations along an "S" pattern and mixed to form one composite sample. Due to shallow soil layers in the Li River water-land ecotone, sampling depth was limited to 0–20 cm. In the laboratory, each soil sample was manually cleared of visible roots and stones, passed through a 2 mm sieve, mixed thoroughly, and air-dried for analysis of soil mechanical composition, organic matter, total nitrogen, and other physicochemical properties. Aluminum boxes were used to collect soil samples for water content determination. Due to high gravel content in gravel zones, field-mixed samples were first passed through a 5 mm nylon sieve to discard larger gravel before being bagged and weighed. After delivery to the laboratory, each sample was passed through a 2 mm sieve, mixed thoroughly, and air-dried for physicochemical analysis.

2.4 Soil Measurement Methods

Soil water content (SWC, %) was determined by oven-drying at 105 °C. Soil pH was measured using the potentiometric method. Soil organic matter (SOM, $g \cdot kg^{-1}$) was determined by potassium dichromate oxidation. Total nitrogen (TN, $g \cdot kg^{-1}$) was measured by the Kjeldahl method. Total phosphorus (TP, $g \cdot kg^{-1}$) was determined by molybdenum-antimony anti-colorimetry. Total potassium (TK, $g \cdot kg^{-1}$) was measured by flame photometry. Available nitrogen (AN, $mg \cdot kg^{-1}$) was determined by alkali hydrolysis diffusion. Available phosphorus (AP, $mg \cdot kg^{-1}$) was extracted with sodium bicarbonate and measured by molybdenum-antimony anti-colorimetry. Available potassium (AK, $mg \cdot kg^{-1}$) was extracted with ammonium acetate and measured by flame photometry. Each soil sample was measured three times.

Soil mechanical composition was determined by combining sieving and suspension analysis methods. Particle size ranges were: sand 2–0.05 mm, silt 0.05–0.002 mm, and clay <0.002 mm (Li et al., 2013).

2.5 Data Calculation and Analysis

(1) Species Importance Value (IV) (Song, 2002):

For tree and shrub layers:

$$IV(\%) = \frac{\text{Relative Abundance} + \text{Relative Frequency} + \text{Relative Dominance}}{3}$$

where Relative Abundance = number of individuals of a species / total number of individuals of all species; Relative Frequency = number of quadrats where a species occurs / total occurrences of all species; Relative Dominance = 100 × basal area at breast height of a species / sum of basal areas of all species.

For herb layer:

$$IV(\%) = \frac{\text{Relative Density} + \text{Relative Frequency}}{2}$$

(2) Species Richness (S)

$$S = \text{Total number of all species occurring in the quadrat}$$

(3) Species α-Diversity (Fang et al., 2004):

Shannon-Wiener diversity index (H):

$$H' = -\sum_{i=1}^{S} P_i \ln P_i$$

Pielou evenness index (E):

$$E = \frac{H'}{\ln S}$$

Simpson dominance index (P):

$$P = \sum_{i=1}^{S} P_i^2$$

where S is total species number in the quadrat, P = N /N, N is the number of individuals of species i, and N is total individuals in the quadrat.

(4) Vegetation Coverage

Coverage was estimated using a grid visual method: the percentage of vertical projection area of all vegetation canopies (trees, shrubs, herbs) to total quadrat area. Each quadrat was divided into 1 m × 1 m grids, with vegetation coverage visually estimated for each grid and averaged to obtain quadrat coverage.

Data were processed using Excel. One-way ANOVA and Pearson correlation analysis were performed using R. Redundancy analysis (RDA) of vegetation species diversity indices and soil nutrient indicators was conducted using the vegan package in R.

3. Results

3.1 Plant Species Classification and Composition in the Water-Land Ecotone

Field survey results identified 95 plant species in the Li River water-land ecotone, belonging to 45 families and 88 genera, dominated by Poaceae, Asteraceae, Lamiaceae, and Fabaceae. The flora included 3 fern species, 2 gymnosperm species, and 90 angiosperm species; 50 herbs, 19 shrubs, 22 trees, and 4 lianas. There were 5 aquatic plants, 53 hygrophytic and semi-hygrophytic plants, 3 amphibious plants, and 34 mesophytic plants. In terms of community types, constructive species were mainly hygrophytic and semi-hygrophytic species with strong submersion tolerance, such as *Polygonum hydropiper*, *Cynodon dactylon*, *Humulus scandens*, *Vitex negundo*, and *Pterocarya stenoptera*. Numerically, herbs were absolutely dominant, accounting for 56.84% of total species, while trees and shrubs accounted for only 23.16% and 20.00%, respectively.

3.2 Species Diversity Variation Across Vegetation Types

Plant species number and composition differed significantly among vegetation types in the Li River water-land ecotone (Figure 1 and Table 2). As submersion duration decreased, total plant species number increased progressively: gravel zones had 10 species, grass zones 44, shrub-grass zones 59, and sparse forest zones 68. Community structure evolved from herbaceous communities to mixed grass-shrub-tree communities. Gravel zones contained no shrubs or trees, only scattered herbaceous vegetation dominated by *Polygonum hydropiper*, *Cynodon dactylon*, and *Polygonum aviculare*. Grass zones contained no trees, with herbs and shrubs accounting for 90.90% and 9.10% of species, respectively. Both shrub-grass and sparse forest zones contained all three layers, with sparse forest zones comprising 54.41% herbs, 20.59% shrubs, and 25% trees. Dominant herb species in sparse forests were *Oxalis corniculata*, *Artemisia argyi*, and *Oxalis corymbosa*; dominant shrubs were *Vitex negundo*, *Geum aleppicum*, and *Nerium oleander*; and dominant trees were *Pterocarya stenoptera*, *Cinnamomum burmanni*, and *Triadica sebifera*.

Plant species α-diversity and coverage differed significantly among vegetation types (Figure 2 [Figure 2: see original paper]). All diversity indices and vegetation coverage showed similar patterns, increasing gradually with decreasing submersion duration, with minimum values in gravel zones, intermediate values in grass zones, and maximum values in sparse forest zones (not significantly different from shrub-grass zones). Shannon-Wiener index ranged from 0.135 to 1.734, Pielou index from 0.129 to 0.779, Simpson index from 0.123 to 0.755, and vegetation coverage from 0.166 to 0.703. These results demonstrate heterogeneous distribution patterns in the Li River water-land ecotone, with greater species diversity, more even composition, and higher coverage as submersion duration decreases.

3.3 Soil Nutrient Variation Across Vegetation Types

Soil nutrient content differed significantly among vegetation types in the Li River water-land ecotone (Table 3). With decreasing submersion duration, soil pH, water content, available nitrogen, available phosphorus, and available potassium showed initial increases followed by decreases. Except for pH, all other four indicators reached maximum values in shrub-grass zones: 23.50% water content, 106.88 $\text{mg} \cdot \text{kg}^{-1}$ available nitrogen, 12.12 $\text{mg} \cdot \text{kg}^{-1}$ available phosphorus, and 68.80 $\text{mg} \cdot \text{kg}^{-1}$ available potassium, with minimum values in gravel zones (14.13%, 41.69 $\text{mg} \cdot \text{kg}^{-1}$, 6.03 $\text{mg} \cdot \text{kg}^{-1}$, and 30.67 $\text{mg} \cdot \text{kg}^{-1}$, respectively). Organic matter content showed a gradual increasing trend, lowest in gravel zones and highest in sparse forest zones. Total nitrogen was lowest in gravel zones (0.93 $\text{g} \cdot \text{kg}^{-1}$) but did not differ significantly among the other three vegetation types. Total phosphorus showed no significant differences across vegetation types. Overall, soil nutrients exhibited heterogeneous distribution patterns, with shrub-grass zones having relatively highest nutrient levels, sparse forest and shrub-grass zones having moderate levels, and gravel zones having the lowest.

3.4 Correlation Analysis Between Vegetation Species Diversity and Soil Nutrients

Pearson correlation analysis between vegetation species α-diversity and soil physicochemical properties (Table 4) showed that all diversity indices (Shannon-Wiener, Pielou, Simpson) and vegetation coverage were extremely significantly positively correlated with soil available nitrogen, available potassium, available phosphorus, organic matter, total nitrogen, and water content. Specifically, Shannon-Wiener, Pielou, Simpson indices, and vegetation coverage were most closely associated with soil available nitrogen (correlation coefficient $R > 0.50$), followed by available potassium ($R > 0.40$), and less strongly with available phosphorus and organic matter ($R > 0.30$). This indicates that soil available nitrogen and available potassium have the greatest influence on vegetation species diversity and coverage, while available phosphorus has a secondary effect.

3.5 Redundancy Analysis Between Vegetation Species Diversity and Soil Nutrients

Redundancy analysis (RDA) was used to explore the effects of soil nutrient factors on vegetation species α-diversity (Figure 3 [Figure 3: see original paper]). Forward selection testing screened out soil nutrient indicators without significant correlation to vegetation species diversity. The final analysis revealed that soil available nitrogen, available potassium, and total phosphorus significantly affected vegetation species α-diversity indicators and coverage. These three factors jointly explained 37.99% of plant species diversity variation, with RDA axis 1 accounting for 34.39% of the explanation. Notably, RDA axis 1 (primarily explained by available nitrogen and available potassium) was extremely significantly correlated with vegetation coverage, Pielou index, Simpson index, and

Shannon-Wiener index. In summary, soil available nitrogen and available potassium are important factors affecting vegetation coverage and species diversity, evenness, and dominance.

4. Discussion

4.1 Plant Community Species Diversity Response to Submersion Duration

As a transitional region between aquatic and terrestrial ecosystems, water-land ecotones possess complex, dynamic ecological characteristics (Malanson, 1993). Periodic hydrological fluctuations serve as the primary disturbance factor, endowing water-land ecotone vegetation with submersion tolerance, rapid growth, and strong adaptability (Deng et al., 2001). Constructive species in the Li River water-land ecotone are mainly hygrophytic and semi-hygrophytic plants, consistent with submersion tolerance characteristics. Herbaceous species constitute the absolute majority (56.84% of total species), while trees and shrubs account for only 23.16% and 20.00%, respectively. Previous research has shown that herbaceous plants, as pioneer species in riparian ecosystems, have rapid replacement rates and strong adaptability, often dominating riparian plant community composition in temperate and subtropical regions (Ling et al., 2023). For example, in the upper Tarim River riparian zone in Xinjiang, China, herbs, shrubs, and trees accounted for 61.5%, 30.8%, and 7.7% of total species, respectively (Zeng et al., 2019). In the Jialing River riparian zone, grasses, shrubs, and trees comprised 73.78%, 17.07%, and 4.27% of species, respectively (Shen & Wu, 2012). In the Colorado River riparian zone in Texas, USA, grasses, shrubs, and trees accounted for 67.3%, 17.2%, and 15.5% of species, respectively (Nelson et al., 2023). In contrast, woody plants dominate riparian vegetation in tropical regions. For instance, woody plants accounted for 59.8% and 66.1% of vegetation species in the Nandu River riparian zone in Henan Province, China, and the Sebangau River riparian zone in Indonesia, respectively, while herbs comprised only 31.3% and 33.9% (Wang et al., 2013; Lukas et al., 2021). Therefore, this study confirms that the Li River water-land ecotone is dominated by hygrophytic and semi-hygrophytic species, with herbaceous plants being most numerous.

Hydrological disturbance, as a key factor affecting water-land ecotones, creates a continuously varying hydrological gradient from riverbed to floodplain (Naiman et al., 2005), with plant community composition and soil physicochemical properties showing certain spatial patterns (Baattrup-pedersen et al., 2018; Xiu et al., 2014). This study found significant differences in community structure and species diversity among vegetation types in the Li River water-land ecotone. As submersion duration decreased, the ecotone evolved from scattered herbaceous communities to mixed grass-shrub-tree communities, with vegetation species α-diversity and coverage increasing gradually—lowest in gravel zones and highest in sparse forest zones (not significantly different from shrub-grass zones). Previous studies have shown that different plants have varying submersion tolerance and adaptability, creating heterogeneous vegetation distribution patterns across different water level gradients (Shan et al., 2019). When submersion duration extends, the number of flood-tolerant annual herbs in riparian zones typically increases, while woody and perennial herb numbers decrease, ultimately altering vegetation species composition and diversity (Bejarano et al., 2020). In the Li River water-land ecotone, gravel zones have an average annual submersion duration of 8.2 months, with short exposure periods. Most vegetation cannot establish and survive under long-term waterlogged and hypoxic conditions, resulting in only scattered pioneer herbaceous communities of highly flood-tolerant, short-lived species such as *Polygonum hydropiper* and *Cynodon dactylon*, and the lowest diversity and coverage values. In contrast, shrub-grass and sparse forest zones have short average annual submersion durations (3.5 months and 1.42 months, respectively), with longer exposure periods more favorable for vegetation survival and growth, allowing the establishment of perennial shrubs and tall trees, greater species diversity, more even composition, and higher coverage. Therefore, this study demonstrates heterogeneous distribution patterns of vegetation species composition and diversity across different vegetation types, with moderate submersion of 1–3 months potentially facilitating vegetation community species diversity development, while prolonged submersion hinders community aggregation. Herbaceous plants show stronger adaptability to riparian submersion environments.

4.2 Soil Nutrient Response to Submersion Duration

This study found that as submersion duration decreased, soil organic matter content in different vegetation types showed a gradual increasing trend, lowest in gravel zones and highest in sparse forest zones. Soil water content, available nitrogen, available phosphorus, and available potassium showed initial increases followed by decreases, with minimum values in gravel zones and maximum values in intermediate shrub-grass zones. Different submersion durations and hydrological disturbance levels across the water-land ecotone affect soil structure, aeration, permeability, and nutrient content (Li et al., 2018; Qian et al., 2018). Generally, soil organic matter content is determined by the difference between organic matter input and output. Input occurs mainly through litter and dead roots, while output occurs primarily through decomposition loss and runoff erosion (Liang et al., 2019). Across the Li River water-land ecotone, vegetation species α-diversity and coverage increased gradually with decreasing submersion duration, transitioning from almost no vegetation cover in gravel zones to multi-species grass-shrub-tree combinations in sparse forest zones. The presence of deciduous trees such as *Pterocarya stenoptera* and *Triadica sebifera* increased organic matter input through litter and dead roots. Therefore, soil organic matter input increased as submersion duration decreased. Meanwhile, gravel zones near the river channel experienced prolonged submersion, with river water scouring and eroding soils, causing large organic matter output, while sparse forest zones farther from the channel experienced less runoff erosion and smaller organic matter output, ultimately leading to gradually increasing soil organic matter content with decreasing submersion duration. Wang et al. (2019) and Woodward et al. (2015) similarly found that soil organic matter content increased with distance from riverbed to floodplain.

Soil available nutrients are those that can be absorbed and utilized by plants, most of which are leachable and thus highly susceptible to environmental influences (Li & Wang, 2016). In this study, gravel zones closest to the river channel had the longest average annual submersion duration, frequent scouring and erosion, thin soil layers, high gravel content, and poor water and nutrient retention capacity, resulting in loss of soil moisture and easily leachable nutrients through surface runoff, and thus the lowest values for water content, available nitrogen, available phosphorus, and available potassium. As submersion duration decreased, reduced soil erosion in shrub-grass zones led to more reasonable soil particle composition and increased water and nutrient storage capacity. High diversity and coverage of shrubs and herbs in these zones increased litter input and intercepted animal and plant residues brought by floods, which after decomposition increased soil available nutrients, resulting in the highest levels of soil water content and available nutrients. Although sparse forest zones had high species diversity, their greatest distance from the river channel minimized river interference, with soil available nutrients derived primarily from vegetation litter, resulting in lower available nutrient levels than shrub-grass zones. Wang et al. (2018) studied the interception effects of Li River riparian vegetation on floating debris, finding that withered grass accounted for 85.32% of four types of intercepted debris, and that interception capacity followed the order *Geum aleppicum* > *Flueggea suffruticosa* > *Pterocarya stenoptera*, demonstrating that shrubs have stronger interception capacity for withered grass and other dead plant residues than trees. In summary, this study demonstrates heterogeneous distribution patterns of soil nutrients across different vegetation types, with moderate submersion having some promotional effect on soil nutrient accumulation.

4.3 Relationship Between Plant Species Diversity and Soil Nutrients

Soil serves as the growth substrate for vegetation, critically affecting plant development and profoundly influencing plant ecosystem structure and productivity. Conversely, vegetation biomass and species diversity also affect soil structure and nutrient content (Wang et al., 2015). This study found that vegetation species α-diversity indices and most soil nutrient contents (organic matter, available nitrogen, available phosphorus, etc.) showed similar variation patterns along the submersion duration gradient. Correlation analysis revealed that vegetation coverage and species α-diversity indices were extremely significantly positively correlated with soil available nutrients (available nitrogen, available potassium, available phosphorus) and organic matter. Yang et al. (2021) showed that higher vegetation coverage and species diversity lead to greater litter and vegetation residue input to the surface, which after decomposition produces more humus, increasing soil organic matter content. Soil available nutrients can be directly absorbed by plants and are water-soluble, thus being influenced by many factors, with vegetation distribution and species diversity having significant impacts, making soil available nutrient content more volatile and responsive (Li & Wang, 2016). Therefore, to a certain extent, vegetation species diversity in the Li River water-land ecotone can promote accumulation of soil available nutrients (available nitrogen, available potassium, available phosphorus) and organic matter, while increased available nutrients and organic matter can also enhance vegetation species diversity, stabilizing plant communities. Redundancy analysis between vegetation species α-diversity indices and soil nutrients identified available nitrogen and available potassium as important factors affecting vegetation coverage and Shannon-Wiener diversity, Pielou evenness, and Simpson dominance indices. Thus, soil available nutrients (available nitrogen, available potassium) and organic matter are closely linked to vegetation species α-diversity, with mutual promotion and co-development. Ecological restoration of the Li River water-land ecotone should fully consider the relationship between soil available nutrients and vegetation species diversity, adopting effective measures to increase soil available nitrogen, available potassium, and organic matter content, improve soil properties, and enhance vegetation community species diversity and stability for healthier, more stable riparian ecosystem development.

5. Implications for Water-Land Ecotone Ecosystem Restoration

Based on this study of plant and soil variation patterns across different vegetation types in the Li River water-land ecotone, several implications for ecosystem restoration emerge. First, vegetation is a crucial component of water-land ecotones. Understanding plant community variation patterns helps identify which species are better suited for specific hydrological conditions and enables measures to protect and restore vegetation species diversity. Restoration efforts should consider planting native species to enhance ecosystem stability. Second, hydrological disturbance affects soil properties and structure, such as moisture and organic matter, which in turn influence vegetation growth and soil biological activity. Therefore, restoration must fully consider hydrological impacts on soil and improve soil environments to promote vegetation recovery and stability. Third, water-land ecotone vegetation and soil change with hydrological conditions, necessitating long-term monitoring and assessment mechanisms during ecological restoration to timely understand conditions and adjust restoration measures based on monitoring results. Finally, water-land ecotone ecosystems are dynamic systems influenced by multiple factors including climate, hydrology, soil, and biology. Restoration requires adaptive management strategies that adjust and optimize measures according to ecosystem changes to improve stability and health. In summary, we must fully recognize the importance of water-land ecotone vegetation, soil, and hydrological disturbance in riparian ecosystems and adopt effective measures to protect and restore these systems to enhance their health, balance, and stability.

References

BAATTRUP-PEDERSEN A, GARSSEN A, GOTHE E, et al., 2018. Structural and functional responses of plant communities to climate change-mediated alterations in the hydrology of riparian areas in temperate Europe [J]. *Ecol Evol*, 8 (8): 4120-4135.

BEJARANO MD, SARNEEL J, SU XL, et al., 2020. Shifts in riparian plant life forms following flow regulation[J]. *Forests*, 11(518): 1-19.

CAPON SJ, PETTIT NE, 2018. Turquoise is the new green: restoring and enhancing riparian function in the anthropocene[J]. *Ecol Manag Restor*, 19 (S1): 44-53.

CHEN RS, WANG RR, SUN JH, et al., 2023. Effects of altitude, soil and vegetation of the Lijiang River Basin on soil nutrient contents and enzyme stoichiometric ratios[J]. *Guihaia*, 43 (2): 242-252.

CHEN ZL, YUAN XZ, ROβ-NICKOLL M et al., 2020. Moderate inundation stimulates plant community assembly in the draw down zone of China' s Three Gorges Reservoir[J]. *Environ Sci Europe*, 32: 1-11.

DENG HB, WANG QC, WANG QL et al., 2001. On riparian forest buffers and riparian management[J]. *Chin J Appl Ecol*, 12 (6): 951-954.

FANG JY, SHEN ZH, TANG ZY et al., 2004. The protocol for the survey plan for plant species diversity of China' s mountains[J]. *Biodivers Sci*, 12 (1): 5-9.

FANG XQ, CHEN L, LI S, 2007. Changes of dominant periods of flood disaster in China during 1644–2004[J]. *Adv Water Sci*, 18 (5): 656-661.

GILL KM, GOATER LA, BRAATNE JH et al., 2018. The irrigation effect: how river regulation can promote some riparian vegetation[J]. *Environ Manag*, 61 (4): 650-660.

GUO EH, FAN ZH, ZHANG RX, et al., 2021. Research progress on responses of vegetation and soil to hydrological changes in riparian Ecosystems[J]. *Acta Ecol Sin*, 41 (23): 9164-9173.

HUANG D, WANG DM, REN Y, 2019. Using leaf nutrient stoichiometry as an indicator of flood tolerance and eutrophication in the riparian zone of the Lijang River[J]. *Ecol Ind*, 98.

HUANG K, GUO HC, LIU Y, et al., 2007. Research progress on the degradation mechanisms and restoration of riparian ecosystem[J]. *Chin J Appl Ecol*, 18 (6): 1373-1382.

HUANG ZW, CHEN YD, JIANG YP, et al., 2005. Analysis on Water Resources of Lijiang River Basin[J]. *J Guangxi Acad Sci*, 21 (1): 56-60.

LIANG SC, TIAN HL, TIAN F, et al., 2016. *Plants and vegetation in the Lijiang Wetland*[M]. Beijing: Science Press: 6-10.

LIANG SC, YUAN XX, LU XM, et al., 2019. Soil physico-chemical properties and distribution characteristics in an aquatic-terrestrial ecotone of the Lijiang River, southwest China[J]. *Acta Ecol Sin*, 39 (8): 2752-2761.

LIU JR, FENG H, YU XL, et al., 2003. A preliminary discussion on the historic change of the name for the Lijiang River system[J]. *Carsol Sin*, 22 (1): 77-82.

LI SP, WANG KL, 2016. Effect of human disturbance on soil nutrients and plant diversity of grassland in Karst mountain[J]. *Res Soil Water Conserv*, 23 (5): 20-27.

LI Y, WANG DM, XIN ZB, 2013. Spatial distribution of vegetation and soil in aquatic-terrestrial ecotone, Li River [J]. *Trans Chin Soc Agricultural Engineer*, 29 (6): 121-128.

LI Y, WANG DM, XIN ZB, et al., 2015. Plant diversity and soil characteristics of different inundation zones in an aquatic-terrestrial ecotone, Li River[J]. *Acta Ecol Sin*, 35 (15): 5121-5130.

LIX F, SU DR, LV SH, et al., 2018. Comparison of soil carbon, nitrogen, and phosphorus characteristics of Hulun Buir grassland under different flooding conditions in the Hui River wetland[J]. *Acta Ecol Sin*, 38 (6): 2204-2212.

LUKAS, HASTARI B, ARDIANOR, et al., 2021. Diversity of riparian plants of black water ecosystem in the Sebangau River of Central Kalimantan Indonesian[J]. *IOP Conf Ser: Earth Environ Sci*, 744: 012040.

MALANSON GP. 1993. *Riparian landscapes* [M]. New York: Cambridge University Press: 1-10.

MCDANIEL MD, KAYE JP, KAYE MW, 2013. Increased temperature and precipitation had limited effects on soil extracellular enzyme activities in post-harvest forest[J]. *Soil Biol Biochem*, 56: 90-98.

NAIMA RJ, DECAMPS H, 1997. The ecology of interface: riparian zones[J]. *Ann Review Ecol Syst*, 28: 621-658.

NAIMAN RJ, BECHTOLD JS, DRAKE DC, et al., 2005. Origins, patterns, and importance of heterogeneity in riparian systems[M]//LOVETT GM, TURNER MG, JONES CG, et al. *Ecosystem Function in Heterogeneous Landscapes.* New York: Springer: 279-309.

NELSON A D, ROSIERE R, BROWN T C A S, et al., 2023. Near-riparian vegetation of the Colorado River at Colorado Bend State Park and Regency, Texas[J]. *Phytologia*, 105 (1).

QIAN J, LIU JJ, WANG PF, et al., 2018. Effects of riparian land-use changes on soil aggregates and organic Carbon[J]. *Ecol Engineer*, 112: 82-88.

REN Y, 2019. *Research on Mechanism of vegetation degradation and vegetation restoration in the riparian zone of Li River*[D]. Beijing: Beijing Forestry University: 1-111.

SHAN LP, SONG C, ZHANG XH, et al., 2019. Plant defence allocation patterns following an increasing water level gradient in a freshwater wetland[J]. *Ecol Indicat*, 107: 105542.

SHEN JY, WU JQ, 2012. Floristic analysis of vascular plants in riparian zone of Jialing River[J]. *J Huazhong Norm Univ (Nat Sci)*, 46 (6): 733-739.

WANG JY, YAN XY, GONG W. Effect of long-term fertilization on soil productivity on the North China Plain[J]. *Pedosphere*, 2015, 25 (3): 450-458.

WANG XH, ZHU JJ, QIN XS, et al., 2013. Nature vegetation community characteristic analysis of Nandujiang River in Hainan Province[J]. *J Fujian For Sci Technol*, 40 (4): 1-6.

WANG J, WANG DM, REN Y, et al., 2019. Coupling relationships between soil microorganisms and soil nutrients under different hydrological conditions in the riparian Zone of the Lijiang River[J]. *Acta Ecol Sin*, 39 (8): 2687-2695.

WANG J, WANG DM, WANG B, 2019. Effects of hydrological environmental gradient on soil and microbial properties in Lijiang riparian zones of China[J]. *Fresen Environ Bull*, 28 (2A).

WANG DM, LIANG SC, REN Y, et al., 2018. *Theory and technology of ecological restoration in the aquatic-terrestrial ecotone of the Lijiang River Basin*[M]. Beijing: Chin Water Power Press: 25-26.

WOODWAR KB, FELLOWS CS, MITROVIC SM, et al., 2015. Patterns and bioavailability of soil nutrients and carbon across a gradient of inundation frequencies in a lowland river channel, Murray-Darling Basin Australia[J]. *Agric Ecosyst Environ*, 205: 1-8.

XIU C, OUYANG Z Y, ZHENG H, 2014. Flora analysis of riparian vegetation in Yongding-Haihe river system, China[J]. *Acta Ecol Sin*, 34 (6): 1535-1547.

YANG J, YU ZJ, WANG C, et al., 2021. Spatial distribution features of soil properties from Xiongan New Area: A case study of Rongcheng County[J]. *Acta Ecol Sin*, 41 (17): 6764-6772.

YANG ST, BAI J, ZHAO CS et al., 2018. The assessment of the change of biomass and riparian buffer width in the terminal reservoir under the impact of the South-to North Water Diversion Project in China[J]. *Ecol Indicat*, 85: 932-943.

YI XM, HUANG YY, MA MH et al., 2020. Plant trait-based analysis reveals greater focus needed for mid-channel bar downstream form the Three Gorges Dam of the Yangtze River[J]. *Ecol Indicat*, 111: 105950.

ZHENG J, ARIF M, ZHANG SL et al., 2021. Dam inundation simplifies the plant community composition[J]. *Sci Total Environ*, 801: 149827.

ZENG Y, ZHAO C Y, LI J, et al., 2019. Effect of groundwater depth on riparian plant diversity along riverside-desert gradients in the Tarim River[J]. *J Plant*

Ecol, 12 (3).

Institute of soil science, Chinese academy of sciences, 1978. *Soil physicochemical analysis*[M]. Shanghai: Shanghai Science and Technology Press: 62-93.

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