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Original Research

Relationships between Soil Nutrients and Plant Diversity in Riparian Woodlands Along the Middle and Lower Reaches of the Yellow River, China

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Abstract

Riparian woodlands play a significant role in hosting plant diversity and maintaining soil and water resources. However, riparian woodlands are highly sensitive to fluvial and human disturbances, and most are now degraded as a result. In this study, we analyze variation in soil nutrients and plant diversity and their relationships in riparian woodlands along the middle and lower reaches of the Yellow River in China, based on field investigation. Our results indicate that soil nutrient content and plant diversity were lowest in plots located closest to the river. Specifically, we found a hump-shaped relationship with increasing distance from river. This result can be attributed to the intermediate disturbance hypothesis,which explains that species diversity increase at intermediate disturbance levels. However, total species richness within each subzone was greatest close to the river, due primarily to the high level of species turnover observed among plots located closest to the river. Soil nutrients in the riparian woodlands were positively correlated with plant diversity across all distances. Specifically, soil TC, NO_3^--N, and A-P contents were significantly correlated with plant species richness and diversity. This relationship also conformed to a hump-shaped response curve between species richness and soil nutrients, though species richness increases with increasing nutrient levels. Results from this study can provide a basis for sustainable management of riparian ecosystems.

Keywords: hump-shaped relationship, soil properties, plant community characteristics, riparian woodlands, distance to river

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Introduction

Riparian ecosystems are the linkages between aquatic and terrestrial ecosystems [1, 2]. However, riparian ecosystems are also a highly fragile and sensitive system that needs to be conserved [2]. This is especially true given that riparian ecosystems have been greatly threatened and altered by anthropogenic activities [2, 3-5]. Therefore, studying riparian vegetation characteristics such as plant composition, structure, and diversity, as well as their dynamics, remains an important area of research [2]. This is especially true for riparian woodlands, which are an important part of riparian ecosystems that play a crucial role in providing habitat for terrestrial organisms [6-9].

Riparian ecosystems are known to have a unique set of plant species that are maintained via interactions among various environmental factors [6]. These environmental factors include both natural factors and anthropogenic activities. The natural factors influencing plant species diversity include hydrological characteristics (e.g., river discharge and periodic flooding) [10, 11], topographic and geomorphic features [12, 13], soil nutrients, and biogeochemistry [9, 14]. Furthermore, altitudinal climate shifts, global climate change [6, 15], and outbreaks of plant diseases and pests [14] are important as well. Anthropogenic activities have dramatically increased in intensity and extent over recent years due to growing demands for plant and water resources in China [2]. Such activities include land use change [16, 17], irrigation [18], tourism [14, 19], dam construction, canalization [15], and livestock grazing [14]. Due to these environmental factors, important changes in riparian plant species composition, abundance, richness, and structure have been observed [3, 4, 20]. Several studies have sought to identify the drivers of plant species diversity in riparian zones [9, 17, 21, 22]. However, this is still a developing area of research, and consensus is lacking as a result.

Riparian soils can be temporally and spatially dynamic in terms of texture, organic matter content, and nutrient content due to frequent fluvial and human disturbances [16]. These types of disturbances can facilitate soil erosion, soil salinization, and soil nutrient loss, which eventually will lead to soil degeneration in the riparian zone [8, 10, 23]. However, research on the response of riparian soil nutrients and plant diversity to distance to river remains limited. This is especially true in riparian zones along the Yellow River in China, which are noted for their important biodiversity. Further research in this area is especially important given recent and serious ecological degradation from intense agricultural impacts [25]. Riparian woodlands along the middle and lower reaches of the Yellow River are the most important natural habitats for organisms, even though they occupy only a minor fraction of the overall agricultural landscape [25]. However, they are suffering serious threats derived from human activities, which have led to degradation of ecosystem services, particularly in the aspects of species diversity protection, soil and water conservation, and non-point source pollution control.

Soils and plants are key components of riparian ecosystems [24]. Soil properties can influence plant community structure in a multitude of different ways. For example, greater soil nutrient content and availability leads to lower abiotic stress, allowing for a rich diversity of species to coexistence [26]. In contrast, other studies have shown that increasing nutrient content favors competitive species that are capable of efficiently capturing resources [27]. In this case, competitive species become hyper dominant, resulting in overall declines in diversity. On the other hand, the fact that plant diversity affects soil chemical and physical properties, and thus ecosystem nutrient cycling, has been demonstrated in multiple studies [28, 29]. Among these studies, a humped-back relationship between soil nutrients and plant diversity is commonly observed [20]. This can be explained by the intermediate disturbance hypothesis [30, 31]. While multiple studies have found a hump-shaped relationship between species diversity and nutrient levels, other studies have found no such relationship [4, 26, 32]. Therefore, the relationships between soil nutrients and plant diversity are complex, as both soil nutrients and plant diversity depend on multiple factors. With respect to their relationship in the riparian zone, especially in the riparian zone along the middle and lower reaches of the Yellow River in China, little research has been done and further understanding is needed to understand the multiple factors influencing the relationships between soil nutrients and plant diversity [28].

The distribution of riparian soils and plants reflects the integrated effects of multiple environmental factors, which include hydrologic, geomorphic, and ecological conditions of a river system [13, 33]. Changes in these factors can produce and affect riparian soils and plants [13]. As such, it is difficult to identify the responses of riparian soils and plants to a single environmental factor [20]. Nevertheless, significant correlations between distance to river channels and degree of hydrologic dynamics (e.g., flooding frequency and duration) and geomorphic dynamics (e.g., elevation and slope gradient) [13, 21, 34, 35] have often been proved. Therefore, several studies have raised concerns regarding distance to river as an agency of multiple factors. These studies have highlighted the effects of distance to river on soil biodiversity and soil moisture rather than on plant biodiversity and soil nutrients in riparian woodlands [9].

The middle and lower reaches of the Yellow River are home to intensive agricultural activities. Specifically, these areas are highly important for grain production in China. Although the riparian zone is characterized by recurrent annual floods, almost 74.3% of the land area is under intense agricultural cultivation. Here, population growth and the expansion of agricultural practices have resulted in the cultivation of most of the riparian vegetation, negatively impacting the maintenance and sustainability of the ecosystem services. In particular, woodlands, which play vital role in maintaining sustainability of the riparian ecosystem, only account for 8.8% of the total land area. Ecosystem functions of the riparian zone along the middle and lower reaches of the Yellow River have gradually degenerated or even disappeared. Therefore, it is necessary to investigate the key components of riparian ecosystems (e.g., soils and plants) to provide a basis for the restoration of degraded riparian ecosystems.

The aim of our study is (1) to analyze the variation in soil nutrients in four subzones of the riparian zone along the middle and lower reaches of the Yellow River in China, (2) to estimate plant diversity indices and compare them among four subzones, and (3) to examine the relationship between riparian plant species diversity and soil nutrients. We tested two predictions: (1) that there exists a hump-shaped relationship between distance to river and soil nutrients and plant diversity, and (2) that plant diversity is positively correlated with soil nutrients in riparian woodlands in the study area.

Materials and Methods

Study Area

The study area is located between 113°03’-114°30’ E longitude and 34°48’-35°01’ N latitude. The 168 km river section covers the transition zone between the middle and lower reaches of the Yellow River in Henan Province, China (Figs 1a and 1b). The lower Yellow River is affected by heavy sediment deposition, forming a typical wandering "perched river" with its river bed higher than the ground elevation outside banks and a large riparian zone, which is well-restricted by and bordered with the left and right levees, and the total width extends from 5 to 20 km [36]. Field sampling was conducted within the levees on both sides of the river. The study area has a warm temperate continental semi-humid monsoon climate with a hot and rainy season in the summer. Annual mean temperature ranges from 12 to 16ºC. Average annual precipitation ranges from 550 to 650 mm. In recent years there has been a decrease in the number of total days of rain, but a subsequent increase in the frequency of heavy rainfall events [25]. The channel slope of the Yellow River in the study area ranges from 0.1 to 0.5‰ [36]. The gentle channel slope leads to a unique continuous transition landscape of hills-plain, providing a broad floodplain suitable for cultivation. Highly productive temperate crops are cultivated here, including winter wheat (*Triticum aestivum*), corn (*Zea mays*), rice (*Oryza sativa*), and plant oil. Woodlands in the study area are characterized by native trees such as *Populus tomentosa Carr.* and *Salix matsudana Koidz.* Along with many herbaceous plants, these species are important for trapping and filtering sediments [25]. The dominant soil type in the study area is a fluvo-aquic soil that consists primarily of sand and silt-sand.

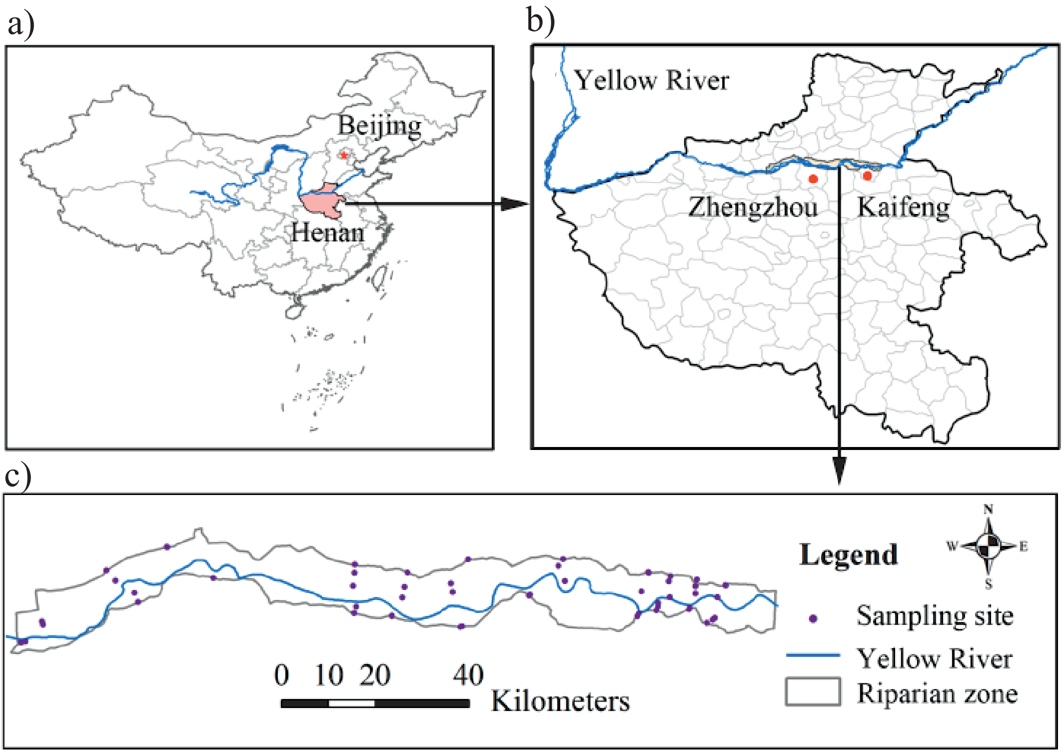

Fig. 1. Location of the study area and sampling sites. The investigation was conducted in Henan province, China a), located on the middle and lower Yellow River b). The sampling sites were a total of 52 woodland plots c) containing native trees and understory vegetation composed of a diverse array of annual and perennial grasses and forbs.

Field and Laboratory Analyses

Topography, hydrology, vegetation, and soil conditions vary in response to distance to river in the riparian zone [25, 36-38]. Therefore, we surveyed soil nutrient contents and plant community characteristics in woodlands across four lateral subzones on both sides of the river. The four subzones were 0-1.5 km, 1.5-3.0 km, 3.0-4.5 km, and 4.5-6.0 km from the river. Subzones from river to upland represent the influencing intensity of flood decreases gradually. However, in the 0-1.5 km subzone near the river, the intensity of human disturbance was highest because of the intensive agricultural practice, tourism, grazing activities, and sand mining activities. The intensity of human disturbance in the 1.5-3.0 km and 3.0-4.5 km subzones was moderate, since the main human disturbance was agricultural practice and grazing. In the 4.5-6.0 km subzone, the intensity of human disturbance was relatively high due to the clustered residential area, dense road network, and industrial activity. In May of 2014 a total of 52 woodland plots containing native understory vegetation were randomly established to collect soil samples and investigate plant community characteristics (Fig. 1c). The vegetation was composed of a diverse array of annual and perennial grasses and forbs, the descriptions of which are shown in Table 1.

In each plot, plant community characteristics were recorded. To facilitate the calculation of species diversity, species records of the undergrowth herbaceous plants were scored by the standard method of Braun-Blanquet with the traditional seven-step cover-abundance scale [39].

Five surface soil samples at 0-20 cm depth were collected at the centers of each of the 52 plots, and at another four locations randomly selected along two diagonal transects. Soil samples were collected using a soil auger, and the 5 samples were combined to form a single bulk sample. All soil samples were sealed in self-locking polythene bags and immediately stored in sealed containers at approximately 4ºC. Samples were then transported to the laboratory for further analysis. Soils were processed to remove plant roots, coarse debris, and pebbles. Soil samples were air dried at room temperature and then homogenized using the cone and quartering method [40]. The homogenized soil samples were then ground until all particles passed through a nylon sieve with mesh size of 2 mm.

In the laboratory, soil nutrient content such as total carbon (TC), total organic carbon (TOC), total nitrogen (TN), nitrate nitrogen (NO_3^--N), total phosphorus (TP), and available phosphorus (A-P) were quantified. TC and TN content were measured using a Nitrogen/Carbon Analyser (PrimacsSNC100-IC). NO_3^--N content was determined using the Nessler's reagent colorimetry method [40], TP was determined with the molybdenum blue method [40], and A-P content with the Olsen method [40].

Data Analyses

We measured species richness (S), Pielou's evenness (J), Shannon's diversity (H), and Simpson's diversity (D) for each plot. Total species richness in each subzone was used to estimate gamma (γ) diversity. Sørenson's similarity index (β_S) and Cody's index (β_C) were used to estimate species turnover (β) among the different subzones [41].

One-way analysis of variance (ANOVA) and the least significant difference (LSD) test were then used to compare plant diversity and soil nutrients among the four subzones. Correlations between plant diversity and soil nutrient content in the riparian zone were then determined with Pearson's correlation coefficients. The ANOVA and correlations tests were performed using the SPSS 17.0 software package (SPSS, Chicago, IL, USA).

Results

Variation in Plant Species Diversity

A total of 86 plant species from 36 families were recorded from all sites in the riparian zone. The most diverse families were Compositae (15 species), Gramineae (11 species), Leguminosae (6 species), and Brassicaceae (5 species). The frequency of occurrence of species was low as only six species (*Chenopodium album*, *Oxalis corniculata*, *Humulus scandens*, *Ixeridium chinense*, *Setaria riridis*, and *Conyza canadensis*) were identified in more than 50%

Table 1. Descriptions of vegetation within each subzone along the middle and lower reaches of the Yellow River.

Subzones (km)	NP	TH (m)	TC (%)	HH (cm)	HC (%)	ME (m)
0-1.5	15	13.2±5.81	61.7±15.7	30.0±21.30	42.2±26.0	86.7±9.88
1.5-3.0	13	16.2±3.78	65.4±11.6	21.2±10.2	37.3±25.1	92.0±9.0
3.0-4.5	12	17.8±3.28	65.4±15.9	22.1±11.6	49.2±19.3	87.3±9.2
4.5-6.0	12	17.4±2.74	55.4±15.1	17.9±8.9	45.4±28.3	88.6±6.8

Note: NP indicates number of plots, TH indicates average height of tree layer, TC indicates average cover of tree layer, HH indicates average height of herbaceous layer, HC indicates average cover of herbaceous layer, and ME indicates average elevation of plots

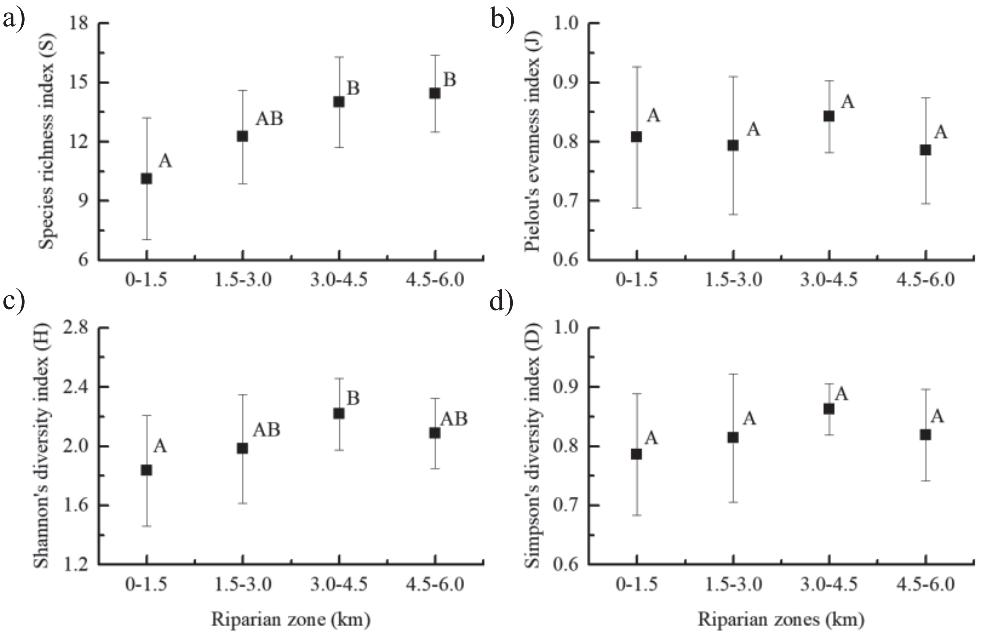

Fig. 2. Variation in species richness a), evenness b), and diversity c) and d) in the four riparian subzones along the middle and lower Yellow River; different capital letters indicate significant differences among the four subzones at the 0.05 level.

of plots, and 16 species were found only in one plot. Comparisons among the four subzones indicate that species richness in the closest subzone to the river showed the lowest value and was significantly lower than that in the further subzones (Fig. 2a). In contrast, species evenness did not differ among the four subzones (Fig. 2b). Diversity indices showed a hump-shaped relationship with increasing distance to the river (Figs 2c and 2d). However, differences among the four subzones were not significant, with the exception of *H* between the 0-1.5 km and 3.0-4.5 subzones. In contrast to species richness at the plot scale, total species richness of the four subzones was negatively correlated with distance to the river (Fig. 3). This shows that the species pool in the subzone nearest the river harbors the most species. In addition, the contrary response of alpha diversity and gamma diversity to distance to the river could be explained by the high beta diversity observed between each zone (Fig. 4). Traditional measures of beta diversity (Sørenson's similarity index (β_S) and Cody's index (β_C)) showed high levels of species turnover and low species similarity.

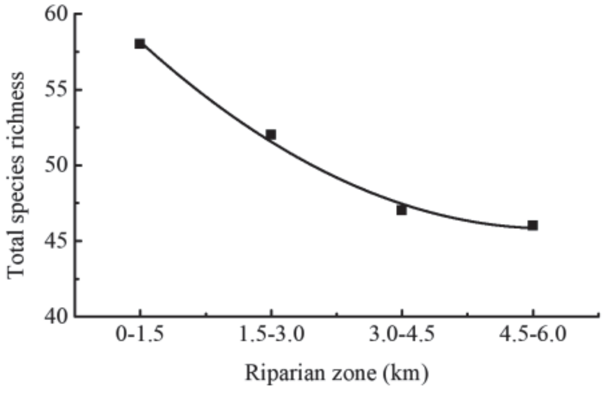

Fig. 3. Variation in total species richness in the four riparian subzones along the middle and lower Yellow River.

Variation in Soil Nutrients

Soil nutrients were spatially heterogeneous. A-P and NO_3^--N content had the highest variability, while TP was the least variable (Table 2). Soil nutrient content

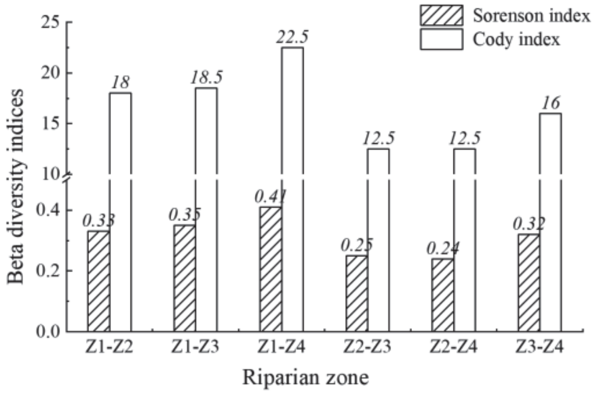

Fig. 4. Variation in beta diversity among the four riparian subzones along the middle and lower Yellow River; Z1, Z2, Z3, and Z4 represent the 0-1.5 km, 1.5-3.0 km, 3.0-4.5 km, and 4.5-6.0 km subzone, respectively; Z1-Z2, Z1-Z3, Z1-Z4, Z2-Z3, Z2-Z4, Z3-Z4 mean the species turnover from Z1 to Z2, Z1 to Z3, Z1 to Z4, Z2 to Z3, Z2 to Z4, Z3 to Z4, respectively.

Table 2. Statistical characteristics of soil nutrients in woodlands of the riparian zone.

Soil nutrients	Mean	Standard deviation	Minimum	Maximum	Coefficient of variation
TC (g/kg)	11.44	3.44	6.55	20.81	0.30
TOC (g/kg)	6.20	2.32	3.06	11.63	0.37
TN (g/kg)	0.61	0.19	0.32	0.98	0.32
NO_3^--N (mg/kg)	5.97	4.90	0.70	17.30	0.82
TP (g/kg)	0.60	0.09	0.47	0.96	0.15
A-P (mg/kg)	8.99	8.59	2.33	38.10	0.96

Note: TC indicates total carbon, TOC indicates total organic carbon, TN indicates total nitrogen, NO_3^--N indicates nitrate nitrogen, TP indicates total phosphorus, A-P indicates available phosphorus, and the same below

was low in the 0-1.5 km subzone and increased with increasing distance to the river (Fig. 5). Our ANOVA analysis indicated that significant differences (*P*<0.05) occurred between soils in the 0-1.5 km subzone and the other three subzones. This suggests that TC and TOC are significantly lower in the 0-1.5 km subzone compared to the other subzones (Figs 5a and 5b), with the exception of TC between the 0-1.5 km and the 1.5-3.0 km subzones. However, there was not any significant difference observed among the other three subzones, indicating that the effect of distance to the river on TC and TOC is little. TN and NO_3^--N were lowest in the 0-1.5 km subzone, and highest in the 3.0-4.5 km and 4.5-6.0 km subzones (Figs 5c and 5d). TN and NO_3^--N both differed among subzones. Importantly, the effect of distance to river on TN and NO_3^--N was hump-shaped. TP were found to be significantly different between different subzones with the exception between the 4.5-6.0 km subzone and the 1.5-3.0 km and 3.0-4.5 km subzones (Fig. 5e).

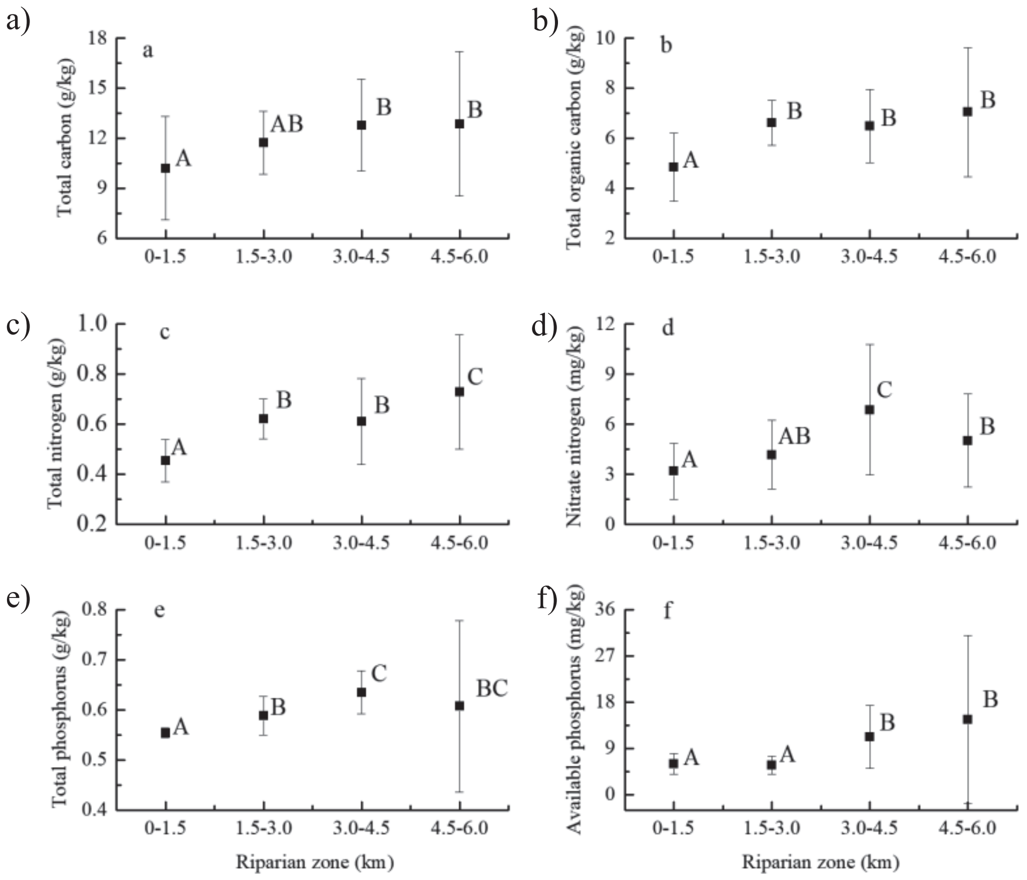

Fig. 5. Variations in total carbon a), total organic carbon b), total nitrogen c), nitrate nitrogen d), total phosphorus e), and available phosphorus f) in the four riparian subzones along the middle and lower Yellow River; different capital letters indicate significant differences among the four riparian subzones at the 0.05 level.

Table 3. Pearson correlation coefficient between riparian soil nutrients and plant species diversity.

Plant species diversity	TC	TOC	TN	NO_3^--N	TP	A-P
S	0.385^{**}	0.233	0.190	0.425^{**}	0.245	0.290^{*}
E	0.085	-0.045	-0.026	0.233	0.069	0.084
H	0.319^{*}	0.150	0.128	0.427^{**}	0.212	0.231
D	0.281^{*}	0.081	0.073	0.362^{*}	0.198	0.204

Note: Asterisks indicate statistical significance (*P<0.05, **P<0.01)

Results from the ANOVA analysis indicated that A-P content in the 3.0-4.5 km and 4.5-6.0 km subzones was significantly higher than in the 0-1.5 km and 1.5-3.0 km subzones (Fig. 5f), implying that phosphorus content available for plants in the subzones near the river is less than that far away the river.

Linkages between Soil Nutrients and Plant Species Diversity in the Riparian Zone

Regarding each subzone, we observed no significant correlation between soil nutrients and plant species diversity. This result could be attributed to the plot size and number of samples. However, this implies that the factor controlling their relationship should be the difference among different subzones. Therefore, we put all samples in the whole riparian zone together without considering the effects of distance to river to analyze the relationship between soil nutrients and plant species diversity. For the entire riparian zone, the Pearson correlation analysis indicated that TC content was significantly positively correlated with *S*, *H*, and *D* (Table 3). This indicates that TC is likely the main soil nutrient driving plant species diversity in the riparian zone, and vice versa. The general mechanism behind this should be C inputs to the soil via root and root uptake from soil to plant. NO_3^--N content was significantly positively correlated with *S*, *H*, and *D*. This suggests that soil nitrification in the riparian zone can facilitate the establishment of different species. A-P content was significantly positively correlated with *S* at the $P<0.05$ level. However, no significant relationship was observed between riparian soil TOC, TN, and TP contents and diversity of plant species.

Discussion

Variation in Plant Species Diversity Along Lateral Distance of Riparian Zone

In riparian ecosystems, different riparian subzones may control the distribution of riparian plant species diversity. This may arise via differences in groundwater table, groundwater salinity, river discharge, and periodic flooding, among others [4, 10, 11]. We found that plant species diversity in riparian woodlands along the middle and lower reaches of the Yellow River in China varied with distance from the river. Our results are inconsistent with those from Lite et al. [34], Zenner et al. [35], and Tsheboeng et al. [42], who found no overall variation in species richness as a function of distance from river. We expect that our results may differ due to the unique geomorphology of the Yellow River. The lower reaches of the Yellow River in China are famous as a perched river with heavy sediment deposition. As a result, the riverbed is 3 to 8 m higher than the surrounding land surface, and the water level is 3 to 5 m higher than ambient groundwater levels in the riparian zone and adjacent terrestrial areas [36, 37]. This unique fluvial geomorphology makes the Yellow River act as a groundwater divide that continuously discharges surface water to groundwater aquifers [38]. This leads to the unique hydrological characteristics and biological processes [36] that likely alter species richness across different distances from the river.

Plant species evenness and diversity also varied with distance from the river. We observed a hump-shaped curve, with evenness being highest in the intermediate 3.0-4.5 km subzone. This is consistent with Tsheboeng [30], who found that plant species diversity was highest at intermediate distance from the rivers in the Okavango Delta. Tsheboeng [30] attributed this to the intermediate disturbance hypothesis, suggesting that species diversity increases are due to coexistence of species that are tolerant to multiple factors at intermediate disturbance levels [31]. This, in turn, leads to habitat colonization by competitive and opportunistic plant species [9]. However, with regard to Pielou's evenness (*J*) and Simpson's diversity (*D*), there was no significant difference among the four subzones. On one hand, this suggests that distance from the river may either have no significant impact on the distribution of species inhabiting the riparian zone, or that they have a significant influence on species composition alone [42]. On the other hand, there might be other environmental gradients [9, 11, 43] or anthropogenic disturbances [14, 17, 18] that control the characteristics of species evenness or diversity in this ecosystem that were not included in the present study.

In contrast to plot-level diversity, total species richness (i.e., gamma diversity) at the different subzones decreased with increasing distance from the river. Higher gamma diversity within riparian subzones close to the river (0-1.5 km) implies that riparian woodlands harbor different species. We attribute these results to high species turnover (i.e., high beta-diversity) within the riparian zones [7].

Response of Soil Nutrients to Lateral Distance of Riparian Zone

In the present study, soil nutrients were significantly lower in the 0-1.5 km subzone compared to the other three subzones. This result is in contrast to results from many previous studies. For instance, Burger et al. [44] and Smith et al. [23] indicated that riparian soils close to the river have higher levels of organic C and N when compared with remnant riparian zones that were far distances from the river. However, several studies observed little or no effect of distance from the river on riparian soil physicochemical properties [45, 46-48], even though significant differences were observed among different riparian habitats. The authors attributed their findings to the habitat characteristics that they selected. These habitats were in a natural state that experienced little to no management intervention [45]. This observation implies that further investigation on heterogeneity of natural factors and intensity of anthropogenic factors (i.e., management intensity) should be conducted [12, 13, 33, 45], as these factors are always expected to be the main driving factors of change in soil nutrients [12, 23, 44, 49, 50]. For example, studies conducted in agricultural areas subjected to high management intensity showed significant differences between the riparian zone and adjacent riparian fields or upland areas [12, 23, 44, 49, 50]. In contrast, studies conducted in natural or semi-natural habitat conditions such as grassland, forests, and woodlands, showed no significant changes between riparian zones and adjacent fields or upland forests [45, 46-48]. Moreover, some studies have indicated that soil nutrient content increased significantly with distance to the river [49-51]. Our own data support these findings when analyzing TC, TOC, TN, and A-P. However, we found that soil NO_3^--N and TP content decreased in the 4.5-6.0 km subzone when compared to the 0-1.5 subzone. This implies that further investigation within the 4.5-6.0 km subzone, especially the vegetation community characteristics, is needed. In addition, temporal dynamics of soil nutrients can be of extreme importance. However, this study mainly focused on the spatial variation in soil nutrients in the riparian zone along the middle and lower reaches of the Yellow River in China. Further investigation on temporal variation in soil nutrients in the riparian zone is needed.

Moreover, the width of the subzone used may influence the observed pattern. Specifically, the width of the subzones in the present study was 0-1.5 km, 1.5-3.0 km, 3.0-4.5 km, and 4.5-6.0 km from the river, which was designed according to the unique geomorphologic characteristics of the study area. The lower Yellow River is a perched river with a main-channel width of 0.5 to 3.0 km and a riparian zone with width of 5 to 20 km that was restricted by the left and right levees [36, 37]. As such, the riparian zone is larger than that used in the studies conducted by Hazlett et al. [47] (5 m and 75 m from the lakeshore), Schilling et al. [48] (1, 20, and 40 m from river), Cierjacks et al. [49] (518±50 m from main channel), Smith et al. [23] (transects 36 m long and separated by 6 m), Lidman et al. [12] (4, 12 and 22 m from river), and de Sosa et al. [45] (2 and 50 m from river). These differences in distance used, which could be determined by river size and order, topographic feature, and land use and land cover [52], can lead to differences in hydrologic dynamics, geomorphic dynamics, and ecological processes. For instance, small rivers in montane areas have steeper side-slopes and lower alluvial developments, which can contribute to a more rapid transition from riparian zone to non-riparian zone [45,46-48]. In contrast, rivers that run through flat agricultural areas have more gradual slopes and more alluvial development. This results in a slower transition from riparian zone to non-riparian zone, thus leading to a wider overall riparian zone [36, 37, 49]. Therefore, we cannot attribute differences among these studies to distance from river alone. However, the measured soil nutrients in this study support our prediction that there is a hump-shaped trend for soil nutrients in the riparian zone along the middle and lower reaches of the Yellow River.

Relationship between Soil Nutrients and Plant Species Diversity in Riparian Woodlands

Previous studies have found that soil phosphorus content is an important factor controlling species diversity in riparian wetlands [50, 53]. Likewise, low phosphorus content in soils is needed to sustain a species-rich riparian wetland, because high phosphorus availability may lead to an increase in productivity in P-limited environment, which can promote exclusion of plant species [54]. However, our observations are inconsistent with the above findings, as P content was positively correlated with plant species richness. These differences can be explained by the widely assumed hump-shaped response curve between species richness and soil nutrients. The hump-shaped response curve suggests that maximum species richness is always predicted in the moderate nutrient level. Specifically, that species richness increases with increasing nutrient levels before the intermediate levels, and declines more gradually at high nutrient levels [20, 53]. P content in this study may obey the increasing function before the intermediate level. In addition to phosphorus content, TOC and TN content were significantly correlated with species diversity as well [55]. Part of the reason for this can be attributed to the fact that TOC and TN play an important role in plant colonization and establishment [23, 45]. However, the relationship between plant species richness, evenness, diversity and soil TOC and TN content in this study was not significant. This may be attributable to many factors, including not only site-specific environmental conditions, but also to landscape configuration and hydrological connectivity across riparian subzones [1, 53, 56].

Several studies have found that the relationship between soil nutrients and plant species diversity in riparian zones is significantly related to land use [3, 19, 26], human disturbance [28,50], and flooding regime [34]. However, our data all came from the same type of woodland community and the same landscape matrix [25]. This indicates that land use type maybe not the dominant factor influencing the relationship between soil nutrients and plant species diversity. However, human disturbance, including the level of intensive agricultural practice, tourism, grazing activities, and sand mining activities, and roads, which showed obvious differences in type and intensity among the four subzones [25], can partly be attributed to changing the relationship between soil nutrients and plant species diversity. These human disturbances can inevitably affect nutrient cycling and riparian plant habitat, which can, in turn, affect the relationship between soil nutrients and plant species diversity. With regard to hydrological processes, its impact on the relationship between soil nutrients and plant species diversity results from the combined effects of flood regime and groundwater discharge caused by the unique geomorphology of the study system [36, 37]. On the one hand, flood regimes impose stress and disturbance on riparian plants and soils near the river and redistribute sediment and organic matter. This can cause gradient distribution of plants and soils along the lateral distance of the riparian zone, according to flooding tolerance of riparian plants and deposition process of sediments, respectively [34, 51]. On the other hand, riparian plant species diversity is higher in areas with groundwater discharge because of the higher nutrient availability [4, 12]. The topographic feature of a perched river leads the far subzone with higher water table to be a permanent groundwater discharge area of the Yellow River [38]. Thus, the role of lateral groundwater discharge (i.e., lateral seepage) may control the number of riparian plant species and the content of nutrients in the subzone far from the river [12]. This is distinct from the fact in a general river that the subzone nearest the river acts as the discharge area than the recharge areas.

Conclusions

We conclude that riparian species richness in the closest subzone to the river is significantly lower than that in the farther subzones along the middle and lower reaches of the Yellow River, while species diversity shows a hump-shaped relationship with increasing distance to the river, but no significant difference is observed. Meanwhile, plants in the four subzones show high levels of species turnover and low species similarity.

Soil nutrients are spatially heterogeneous. Specifically, soil nutrient contents – especially TOC, TN, and TP – are low in the 0-1.5 km subzone and increase with increasing distance to the river, and significant differences ($P<0.05$) occur between soils in the 0-1.5 km subzone and the other three subzones.

Soil nutrients, especially soil TC, NO_3^--N, and A-P, are positively linked to plant species richness and diversity in riparian woodlands. Our results indicate that plant diversity corresponds to the increasing half of the hump-shaped response curve between species richness and soil nutrients. From this point of view, our results are consistent with our hypothesis that plant diversity is positively correlated with soil nutrients within the riparian zone.

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Conflict of Interest

The authors declare no conflict of interest.

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