diversity

MDPI

Article

Effects of Environment and Human Activities on Plant Diversity in Wetlands along the Yellow River in Henan Province, China

Zhiliang Yuan [1,†], Man Xiao [1,†], Xiao Su [1], He Zhao [2], Yushan Li [1], Huiping Zhang [1], Ziyu Zhou [1], Rui Qi [3], Yun Chen [1,*] and Wei Wang [4,*]

1 College of Life Sciences, Henan Agricultural University, No.63 Agricultural Road, Zhengzhou 450002, China; yzlsci@163.com (Z.Y.); xxmmmandy@163.com (M.X.); suxiao198127@163.com (X.S.); liyushan123456@163.com (Y.L.); zhp20208090@163.com (H.Z.); zzy246296@163.com (Z.Z.)
2 Henan Institute of Geological Survey, No.81 Science Avenue, Zhengzhou 450053, China; zh2015ecology@sina.com
3 College of Forestry, Henan Agricultural University, No.63 Agricultural Road, Zhengzhou 450002, China; qicailianyi@yeah.net
4 Zhengzhou Yellow River Wetland Nature Reserve Management Center, Donggang Middle Road, Huayuankou Town, Zhengzhou 450040, China
* Correspondence: cyecology@163.com (Y.C.); hhwetlands@163.com (W.W.); Tel.: +151-3856-8663 (W.W.)
† These authors contributed equally to this work.

check for updates

Citation: Yuan, Z.; Xiao, M.; Su, X.; Zhao, H.; Li, Y.; Zhang, H.; Zhou, Z.; Qi, R.; Chen, Y.; Wang, W. Effects of Environment and Human Activities on Plant Diversity in Wetlands along the Yellow River in Henan Province, China. *Diversity* **2022**, *14*, 470. https://doi.org/10.3390/d14060470

Academic Editors: Mateja Germ, Igor Zelnik, Matthew Simpson and Michael Wink

Received: 21 April 2022
Accepted: 9 June 2022
Published: 12 June 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Abstract: *Background and Objectives:* The Yellow River is the sixth longest river in the world, and it is considered the mother river of China. Biodiversity conservation in the middle and lower reaches of the Yellow River is an urgent concern due to the impact of topography, sediment deposition, and human activities. Therefore, in this study, we aimed to investigate the diversity of plant communities in wetlands along the middle and lower reaches of the Yellow River from the perspectives of the natural environment and human disturbance. *Materials and Methods:* In this study, 830 plots were set up in seven nature reserves in the middle and lower reaches of the Yellow River to investigate wetland plant diversity. The distribution characteristics of plant diversity and the effects of environmental and human activities on plant diversity were analyzed. *Results:* (1) A total of 184 plant species belonging to 52 families and 135 genera were found in the seven nature reserves. Network analysis showed that the connectance index was 0.3018. (2) Betadisper analysis followed by ANOVA revealed differences in the community composition of the wetland plants ($F = 21.123$, $p < 0.001$) in the different nature reserves. (3) Analysis of variation partitioning indicated that the effects of pure environmental factors (elevation, precipitation, evaporation, and temperature) on the beta diversity of the wetland plants in the nature reserves was the strongest (15.45% and 17.08%, respectively), followed by the effects of pure human disturbance factors (population density, industrial output value, and agricultural output value) (15.13% and 16.71%, respectively). *Conclusions:* Variations occurred in the assemblage characteristics of the wetland plants in the different Yellow River wetland nature reserves. The wetland species exhibited strong associations with the reserves in the Yellow River wetland in Henan Province. Elevation, longitude, precipitation, and evaporation were important factors that affected the diversity of wetland plants in the middle and lower reaches of the Yellow River in China. The findings provide insights into plant biodiversity conservation in riverine wetlands.

Keywords: riverine wetland; species diversity; space distribution; habitat heterogeneity; species protection

1. Introduction

Wetland plant diversity plays a vital role in maintaining wetland ecological functions and ecosystem stability [1,2]. The wetland ecosystem in some areas has been seriously degraded due to the misuse and over-exploitation of wetland resources, leading to the destruction of wetland resources [3,4]. Research on wetland plant diversity has always been a popular issue among ecologists.

The Yellow River basin (32–42° N, 96–119° E) covers an area of 800 × 10^3 km^2 and spans many geographically distinct regions [5]. Given that the topography, climate, hydrology, and human activities in the various sections of the Yellow River basin vary greatly [6–8], evident differences in the presence of plant species exist among wetlands. Existing studies have shown that the vegetation distribution of the upper reaches of the Yellow River wetland is mainly affected by climate change [9], and the plant diversity of the wetland in the lower Yellow River is significantly related to water depth and human activities [10–12]. Therefore, examining the composition of wetland plants and the determinants of plant diversity is crucial for the protection of river ecosystems.

Henan Province has a large population and is among the main food production areas in China. Over-cultivation of land during agriculture development has affected the ecological environment of the riparian wetlands in the middle and lower reaches of the Yellow River [13]. At the same time, the Yellow River basin is continuously affected by human activities and industrial agglomeration. These factors lead to unprecedented challenges in the wetland plant diversity of the basin [14,15]. Current research on wetlands along the Yellow River in Henan Province mainly involves changes in the patterns of the Yellow River wetlands [16], the ecological environment of the Yellow River wetlands [17,18], countermeasures for forestry development in the lower reaches of the Yellow River [19], and local wetland vegetation diversity [20]. However, the impact of human disturbance and natural environment on the wetland plant diversity of the Yellow River in Henan Province is unclear.

Ecological protection and high-quality development of the Yellow River basin have become national strategies. This study is expected to provide a reference for ecological protection of the Yellow River basin. It investigates the diversity of plant communities in the middle and lower reaches of the Yellow River from the perspectives of the natural environment and human disturbance. This study aims to (1) determine the spatial distribution characteristics of wetland plant communities and (2) explore the main driving factors that affect wetland plant diversity.

2. Materials and Methods

2.1. Study Site and Sampling

The Yellow River is the sixth longest river in the world. The Chinese call the Yellow River their "mother river." The Yellow River basin is designated as the "the cradle of Chinese civilization" and has played an important role in China's social, cultural, economic, and political development [21]. The upper reaches of the Yellow River is the birthplace of the river, and it has high mountains, valleys with steep slopes, a large drop, and abundant hydraulic resources [22]. The middle reaches of the Yellow River have a large water flow and a high content of suspended solids, coming from the fine particulate sediments, thus making the Yellow River a renowned sandy river. The lower reaches of the Yellow River, with low terrain and slow water flow, represent the estuary of the Yellow River [23]. The middle and lower reaches of the Yellow River make up the transition zone from high mountains to plains; the zone has a large elevation drop, large water flow, and high accumulation of sediments, and it forms the world-famous "Hanging River" [24].

The study area was the Yellow River wetland in Henan Province located in the middle and lower reaches of the Yellow River (34°34′–36°08′ N, 110°22′–116°07′ E). The Yellow River wetland in Henan Province spans 711 km, and the overall elevation gradually decreases from west to east, with an average elevation of 124 m [25]. The climate of the studied area in Henan province is warm temperate and semi-humid monsoon. The annual temperature is 12–16 °C, the annual precipitation is 500–900 mm, the annual evaporation is 1300–2100 mm, and the annual sunshine is 2083–2246 h [26,27].

To protect the ecosystem and biological groups in the Yellow River wetlands, the Chinese government has established different nature reserves along the banks of the Yellow

River. National nature reserves are a combination of one or more ecosystems approved and established by the Chinese government. Local nature reserves at all levels are nature reserves approved and established by the local government in China. They are important biodiversity-rich areas, vital habitats for species or other protected objects, and have areas of protection value.

To protect the species diversity of the wetlands in the middle and lower reaches of the Yellow River, the Chinese government has established seven nature reserves along the banks of the Yellow River in Henan Province. Henan Yellow River wetland national nature reserve (HHG) is located in the middle and lower reaches of the Yellow River in the northwest of Henan Province, starting from the junction of Shaanxi and Henan in the west (34°34′35.10″–35°58′12″ N, 110°22′49″–112°47′56.03″ E). Sanmenxia reservoir area wetland (SMX) is located at the junction of Henan, Shaanxi, and Shanxi provinces (34°34′17.2″–34°48′23.1″ N, 110°22′48″–111°15′25.9″ E). Henan Zhengzhou Yellow River wetland provincial nature reserve (ZZS) is located in the north of Zhengzhou City (34°50′04″–34°57′59″ N, 112°54′49″–113°54′59″ E). Henan Zhengzhou Yellow River national wetland park (ZZG) is located in the north of Zhengzhou City (34°54′25″–34°55′30″ N, 113°29′23″–113°39′24″E). Henan Kaifeng Liuyuankou wetland provincial nature reserve (KFS) is located in the east of Henan Province and north of Kaifeng City (34°28′24″–34°59′49″ N, 114°15′57″–114°49′55″ E). Henan Xinxiang Yellow River wetland birds national nature reserve (XXG) is located in the east of Xinxiang City, Henan Province (34°55′46.4″–35°56′13.9″ N, 114°25′30.1″–115°00′23.6″ E). Meanwhile, Henan Puyang Yellow River wetland provincial nature reserve (PYS) belongs to the upper reaches of the lower part of the Yellow River and is located in the south of Puyang City, Henan Province (34°56′41.4″–35°25′38.5″ N, 114°42′27.8″–115°10′04.4″ E).

Through a comprehensive investigation, 830 plots were set up in the Yellow River wetland. Our quadrats were randomly selected based on the vegetation types of the nature reserves, and the detailed sampling site distribution is shown in Figure 1. The herb plot size was 1 m × 1 m, the shrub plot size was 5 m × 5 m, and the tree plot size was 20 m × 20 m. The collected data included species name of all plants, number of individual plants, average height, and average coverage. A detailed description of the seven nature reserves is given in Supplementary Table S1. A list of plant species names and plant stand data is shown in Supplementary Table S2.

2.2. Spatial, Environmental and Antropogenic Variables

The spatial factors, such as the longitude, latitude, and elevation of the plots were recorded by GPS. The environmental factors, such as precipitation, evaporation, and temperature data were obtained from the meteorological stations in the various nature reserves of the Yellow River in Henan Province, China "The China Meteorological Data Service Center. Available online: https://data.cma.cn/ (accessed on 8 June 2022)". Population density (PD), industrial output value (IOV), and agricultural output value (AOV) to some extent reflect the intensity of human activities. Population density (10,000 people/Km^2) is the number of people living on a unit area of land. The industrial output value refers to the quality of the final industrial products and the total price of the industrial labor activities in monetary form produced by industrial enterprises. The calculation method of total agricultural output value is usually obtained by adding the output value of agricultural products, forestry products, animal husbandry products, and fishery products [28]. Data on population density, industrial output value, and agricultural output value come from local government statistical reports "Henan Province Bureau of Statistics. Available online: http://tjj.henan.gov.cn/ (accessed on 8 June 2022).

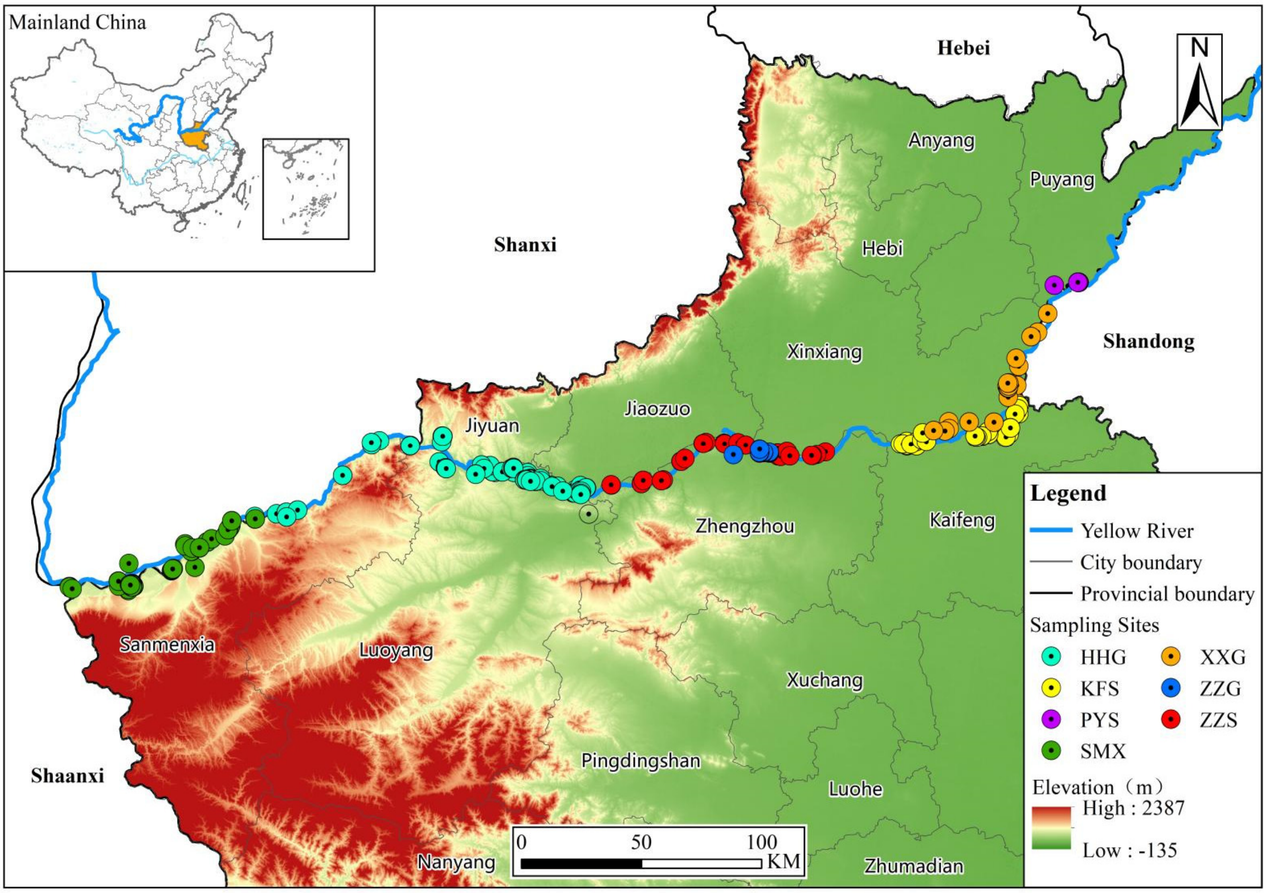

Figure 1. Geographical location distribution of the group of the 830 quadrats set in this study. HHG, Henan Yellow River wetland national nature reserve. SMX, Sanmenxia reservoir area wetland. ZZS, Henan Zhengzhou Yellow River wetland provincial nature reserve. ZZG, Henan Zhengzhou Yellow River national wetland park. KFS, Henan Kaifeng Liuyuankou wetland provincial nature reserve. XXN, Henan Xinxiang Yellow River wetland birds national nature reserve. PYS, Henan Puyang Yellow River wetland provincial nature reserve.

2.3. Data Analysis

In this study, the Shannon–Wiener index (H′) and the Pielou evenness index (E) were used to compare the species diversity of plant communities in the seven nature reserves [29,30]. Jaccard's index (βj) [31] and Sorenson's index (βs) [32] were adopted to measure the beta diversity of plant communities in the seven nature reserves [33]. The diversity index was calculated using the Vegan package in R 3.5.2 [34].

A Venn diagram was created to show the number of wetland plants in the different nature reserves [35]. A correlation network was used to visualize the relationships between wetland plants and nature reserves. We evaluated the structure of the network by using the H2′ metric of specialization and the connectance index [36]. The architecture of the wetland plants and habitat network was visualized with Gephi 0.9.2 software [37].

Indicator species analysis was conducted using the "indicspecies" package of R to delineate the indicator species of wetland plants in the seven nature reserves [38]. The dependent variable in the indicator species analysis was the species abundance matrix of plants.

The Kruskal–Wallis test was employed to explore the alpha diversity differences among the wetland plants of the seven nature reserves ($p < 0.05$ level of significance). We assessed the impact of the nature reserves on the beta diversity of wetland plants by running the betadisper function. ANOVA was conducted to test the significant differences in beta diversity among the wetland plants in the seven nature reserves. A betadisper test was conducted using the betadisper command in the Vegan package [39,40].

Moreover, a Mantel test [41] was performed to examine the linkage between environmental factors (longitude, latitude, elevation, precipitation, evaporation, temperature, PD, IOV, and AOV) and the beta diversity of the wetland plant community. Pearson correlation analysis was performed to estimate the autocorrelation among environmental factors. A correlation diagram was plotted using the "ggcor" package in R 3.4.0.

We used variance partitioning [42] to evaluate the relative importance of spatial distance (longitude and latitude), environmental factors (elevation, precipitation, evaporation, and temperature), and human disturbance (population density, industrial output value, and agricultural output value) in the beta diversity of the wetland plant community. We utilized beta diversity (βj and βs) as the response variable and three explanatory variables, namely, spatial distance, environmental factors, and human disturbance. A correlation diagram was plotted using the Vegan package in R [43].

For the analysis of invasive alien species, we used Venn diagrams to show the number of invasive alien species in the different nature reserves [35] and a box plot to visualize the species richness of the invasive alien species in the seven nature reserves [44].

3. Results

3.1. Species Composition in Nature Reserves

A total of 184 plant species belonging to 52 families and 135 genera were found in the seven nature reserves. HHG had the most plant species, with 117 wetland plants. PYS had the fewest plant species, with 17 wetland plants. Forty-seven and two species of wetland plants were found in only one community in HHG and ZZS, respectively. Furthermore, six plant species, namely, *Phragmites australis*, *Cynodon dactylon*, *Typha latifolia*, *Polygonum hydropiper*, *Erigeron canadensis*, and *Glycine soja* were shared by the seven nature reserves in Henan Province, accounting for 3.26% of the total number of species (Figure 2).

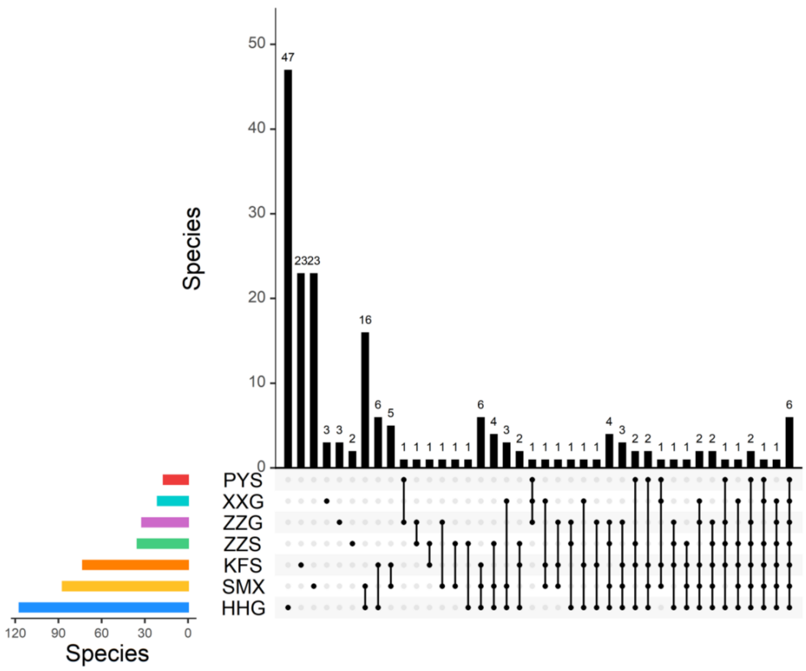

Figure 2. Venn diagram of wetland plants in the seven nature reserves of the Yellow River in Henan Province, China. HHG, Henan Yellow River wetland national nature reserve. SMX, Sanmenxia reservoir area wetland. ZZS, Henan Zhengzhou Yellow River wetland provincial nature reserve. ZZG, Henan Zhengzhou Yellow River national wetland park. KFS, Henan Kaifeng Liuyuankou wetland provincial nature reserve. XXN, Henan Xinxiang Yellow River wetland birds national nature reserve. PYS, Henan Puyang Yellow River wetland provincial nature reserve.

According to the network analysis, 30.18% of the interactions occurred in the observed interactions between wetland plants and nature reserves on the basis of the connectance index (Figure 3).

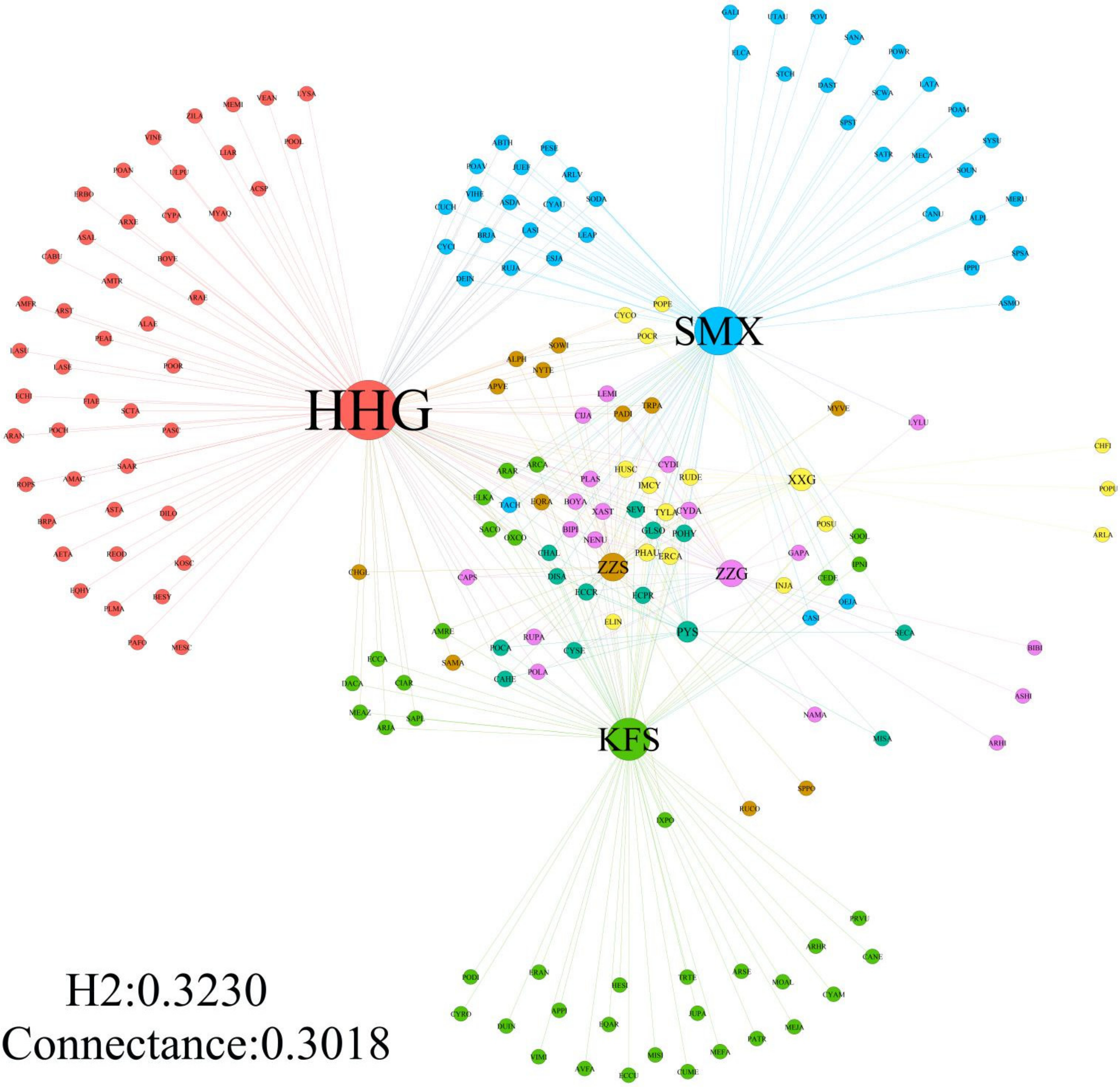

Figure 3. Network analysis of wetland plant composition in the seven nature reserves of the Yellow River in Henan Province, China. The size of the dot indicates the abundance of species. Small letters in small circles indicate plant species. Different colors represent different nature reserves. HHG, Henan Yellow River wetland national nature reserve. SMX, Sanmenxia reservoir area wetland. ZZS, Henan Zhengzhou Yellow River wetland provincial nature reserve. ZZG, Henan Zhengzhou Yellow River national wetland park. KFS, Henan Kaifeng Liuyuankou wetland provincial nature reserve. XXN, Henan Xinxiang Yellow River wetland birds national nature reserve. PYS, Henan Puyang Yellow River wetland provincial nature reserve.

The indicator species analysis showed that the indicator species of the wetland plant community varied among the seven nature reserves. For example, the indicator species of HHG were primarily composed of *Aster altaicus*, *Setaria viridis*, and *Erigeron canadensis*. The indicator species of SMX primarily consisted of *Cynanchum auriculatum*, *Apocynum venetum*, and *Datura stramonium*. The indicator species of ZZS were primarily composed of *Calamagrostis pseudophragmites*, *Paspalum distichum*, and *Cyperus serotinus*. Meanwhile, the indicator species of ZZG primarily consisted of *Bidens biternata*, *Morus alba*, and *Echinochloa crus-galli*. The indicator species of KFS were primarily composed of *Miscanthus sinensis*, *Erigeron canadensis*, and *Calystegia hederacea*. The indicator species of XXG consisted of *Chenopodium ficifolium*, *Cyperus difformis*, and *Potamogeton crispus*. The indicator species of PYS were *Miscanthus sacchariflorus* and *Eclipta prostrata* (Table 1).

3.2. Species Differences among Nature Reserves

The Kruskal–Wallis test revealed differences in the Shannon–Wiener and Pielou evenness indices of plants among the seven nature reserves ($p < 0.01$). Moreover, the two indices of wetland plant alpha diversity in ZZG were higher than those in HHG, SMX, ZZS, KFS, and XXG. Meanwhile, the two indices of wetland plant alpha diversity in KFS were lower than those in XXG and PYS (Figure 4). The betadisper analysis followed by ANOVA showed differences in the community composition of the wetland plants ($F = 21.123$, $p < 0.001$) among the different nature reserves. Among the seven nature reserves, HHG and SMX had a similar species composition (Figure 5).

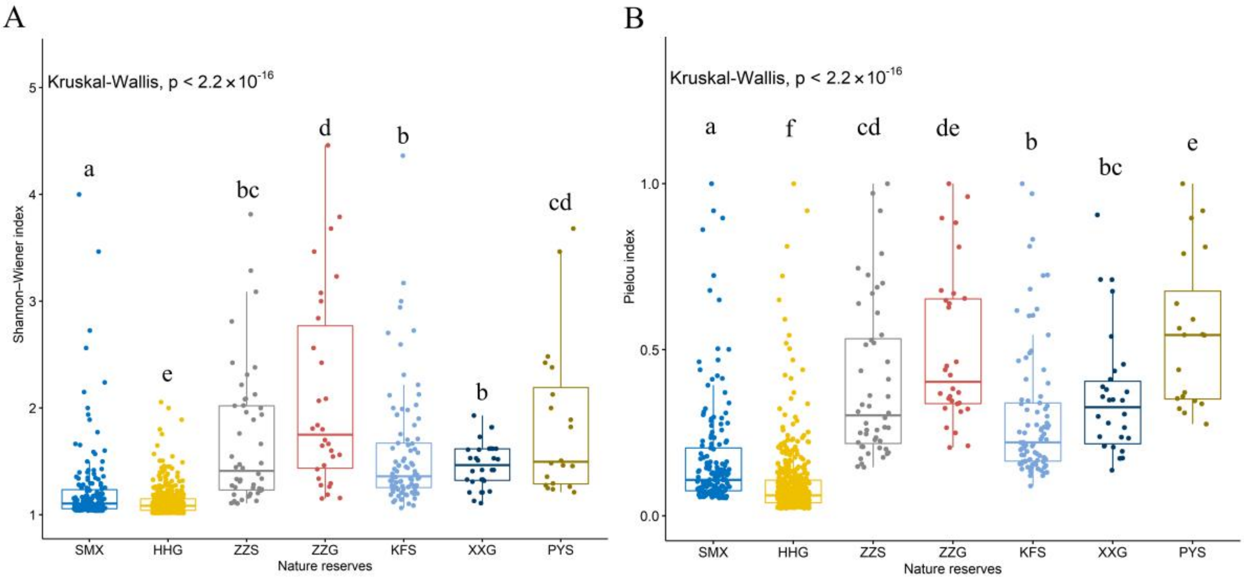

Figure 4. Differences in wetland plant diversity in the seven nature reserves of the Yellow River in Henan Province, China. The number on the black line represents the significance value. Letters are used to distinguish whether there is a significant difference between the protected areas, and different letters indicate that there is a display difference between the protected areas ($p < 0.05$). (**A**) Differences in the Shannon–Wiener index of wetland plants in the seven nature reserves; (**B**) Differences in the Pielou index of wetland plants in the seven nature reserves. HHG, Henan Yellow River wetland national nature reserve. SMX, Sanmenxia reservoir area wetland. ZZS, Henan Zhengzhou Yellow River wetland provincial nature reserve. ZZG, Henan Zhengzhou Yellow River national wetland park. KFS, Henan Kaifeng Liuyuankou wetland provincial nature reserve. XXN, Henan Xinxiang Yellow River wetland birds national nature reserve. PYS, Henan Puyang Yellow River wetland provincial nature reserve.

3.3. Correlation between Plant Diversity and Environmental Factors

The results of the Mantel test indicated that longitude, elevation, and evaporation had the strongest correlation with wetland plant species (Figure 6). Longitude, elevation, evaporation, and population density had positive effects on the beta diversity of the wetland plants in the nature reserves. The beta diversity of the wetland plants in the nature reserves was negatively affected by precipitation and industrial output value.

Table 1. Indicator species analysis in seven nature reserves of the Yellow River in Henan Province, China.

Name of the Seven Nature Reserves	Species	*p*. Value
Henan Yellow River wetland national nature reserve (HHG)	*Aster altaicus*	0.007
	Setaria viridis	0.006
	Erigeron canadensis (IAS)	0.004
	Oxalis corniculata	0.018
	Rumex dentatus	0.017
	Plantago asiatica	0.016
	Bidens pilosa (IAS)	0.020
	Polygonum lapathifolium	0.022
	Chenopodium glaucum (IAS)	0.046
	Myosoton aquaticum (IAS)	0.025
	Artemisia anethoides	0.036
Sanmenxia reservoir area wetland (SMX)	*Cynanchum auriculatum*	0.018
	Lycopus lucidus	0.031
	Apocynum venetum	0.009
	Datura stramonium (IAS)	0.009
	Polygonum persicaria	0.038
	Polygonum aviculare	0.032
	Eschenbachia japonica	0.030
	Equisetum ramosissimum	0.046
Henan Zhengzhou Yellow River wetland provincial nature reserve (ZZS)	*Calamagrostis pseudophragmites*	0.012
	Paspalum distichum (IAS)	0.012
	Cyperus serotinus	0.009
	Tripolium pannonicum	0.008
	Imperata cylindrica	0.012
	Glycine soja	0.046
	Phragmites australis	0.045
Henan Zhengzhou Yellow River national wetland park (ZZG)	*Bidens biternata*	0.011
	Morus alba	0.049
	Echinochloa crus-galli	0.013
Henan Kaifeng Liuyuankou wetland provincial nature reserve (KFS)	*Miscanthus sinensis*	0.012
	Erigeron canadensis (IAS)	0.012
	Calystegia hederacea	0.009
	Parthenocissus tricuspidata	0.009
	Avena fatua (IAS)	0.014
	Digitaria sanguinalis	0.009
	Cirsium arvense var. *integrifolium*	0.011
	Duchesnea indica	0.022
	Erigeron annuus (IAS)	0.013
	Cyperus rotundus	0.024
	Gaura parviflora (IAS)	0.024
	Cynodon dactylon	0.008
	Carex neurocarpa	0.047
	Amaranthus retroflexus (IAS)	0.023
	Artemisia argyi	0.033
	Elymus kamoji	0.042
Henan Xinxiang Yellow River wetland birds national nature reserve (XXG)	*Chenopodium ficifolium (IAS)*	0.043
	Cyperus difformis	0.046
	Potamogeton crispus	0.028
Henan Puyang Yellow River wetland provincial nature reserve (PYS)	*Miscanthus sacchariflorus*	0.012
	Eclipta prostrata (IAS)	0.023

$p \leq 0.05$ level of significance. IAS—invasive alien species.

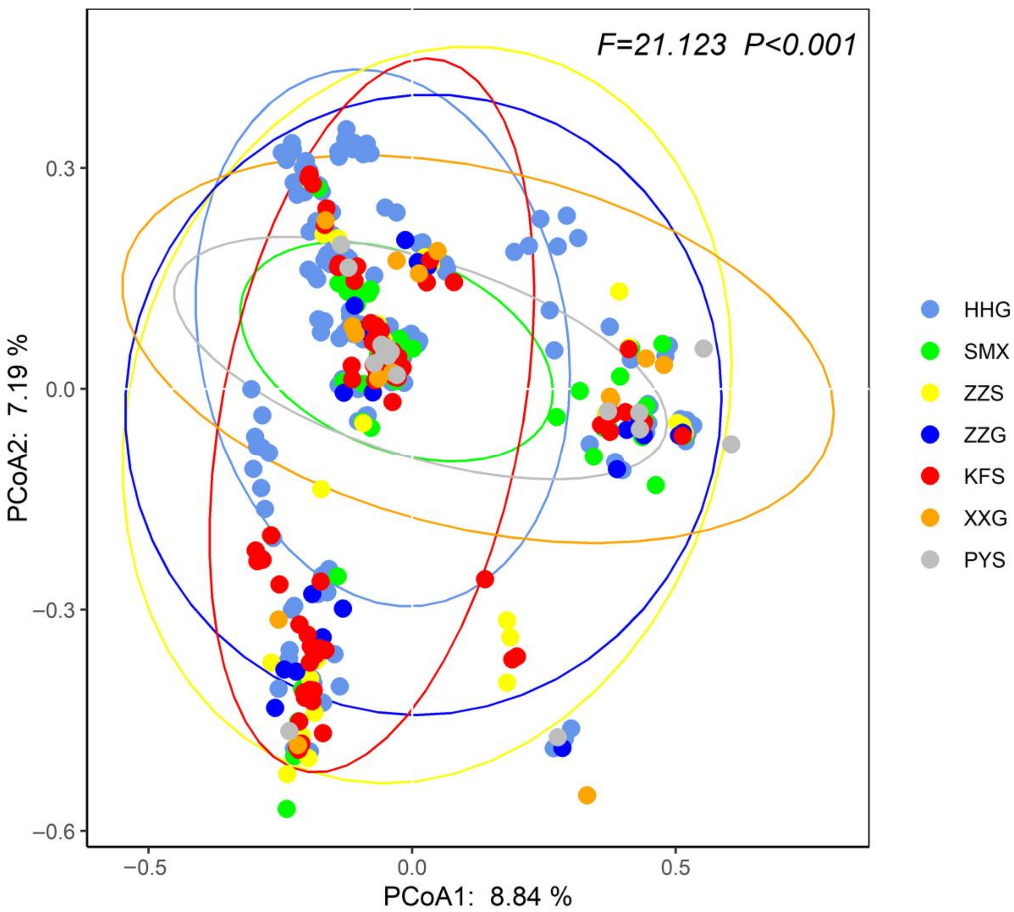

Figure 5. Effect of different nature reserves on the beta diversity of wetland plants determined with the betadisper function. ANOVA is applied to test how these distances differed among different nature reserves. Different colors represent different nature reserves. HHG, Henan Yellow River wetland national nature reserve. SMX, Sanmenxia reservoir area wetland. ZZS, Henan Zhengzhou Yellow River wetland provincial nature reserve. ZZG, Henan Zhengzhou Yellow River national wetland park. KFS, Henan Kaifeng Liuyuankou wetland provincial nature reserve. XXN, Henan Xinxiang Yellow River wetland birds national nature reserve. PYS, Henan Puyang Yellow River wetland provincial nature reserve.

The analysis of variation partitioning indicated that the effects of pure environmental factors (elevation, precipitation, evaporation, and temperature) on the beta diversity of the wetland plants in the nature reserves was the strongest (15.45% and 17.08%, respectively), followed by the effects of pure human disturbance factors (population density, industrial output value, and agricultural output value) (15.13% and 16.71%, respectively). The pure spatial factors, namely, longitude and latitude, had the lowest explanation rate for the beta diversity (βj and βs) of the wetland plants in the nature reserves; the values were 13.05% and 13.71%, respectively (Figure 7A,B).

3.4. Invasive Alien Species

A total of 28 invasive alien species belonging to 12 families and 21 genera were found in the seven nature reserves (Supplementary Table S3) and accounted for 14.97% of the total species. HHG had the most invasive alien species, with 18 invasive alien species. XXG had the fewest invasive alien species, with 2 invasive alien species. Eight invasive alien species were found in only one community in HHG. Furthermore, one invasive alien species, namely, *Eclipta prostrata*, was shared by the seven nature reserves and accounted for 3.57% of the total invasive alien species (Figure 8A). The box plot in Figure 8B shows that the differences in species richness among the seven nature reserves are not significant.

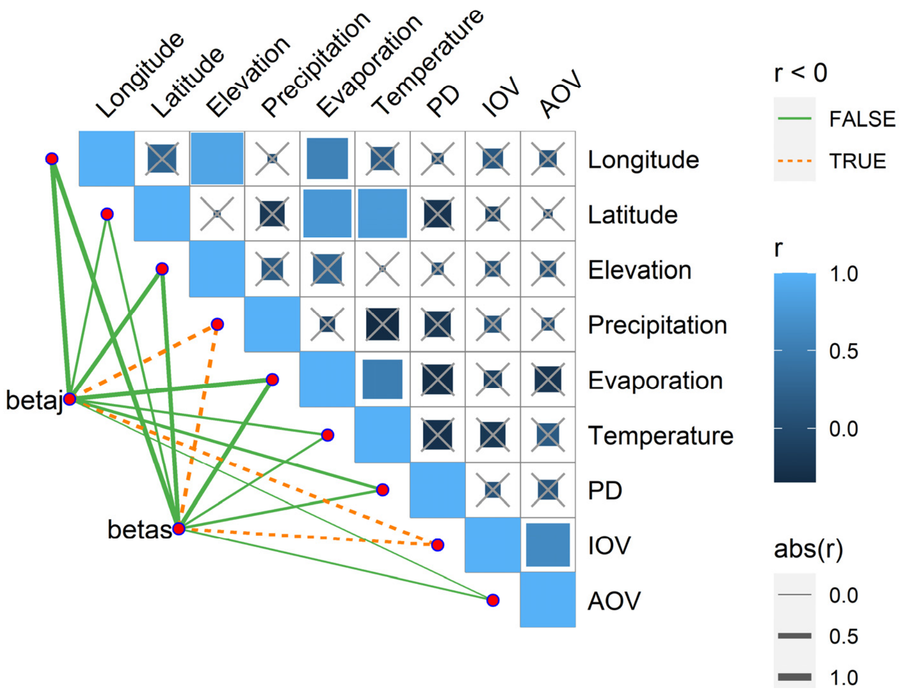

Figure 6. Relationship between natural and human environment variables and beta diversity of wetland plants. The color gradient represents the correlation coefficient. The thickness of the line indicates the correlation. The thicker the line, the stronger the correlation; the thinner the line, the weaker the correlation. PD, population density. IOV, industrial output value. AOV, agricultural output value.

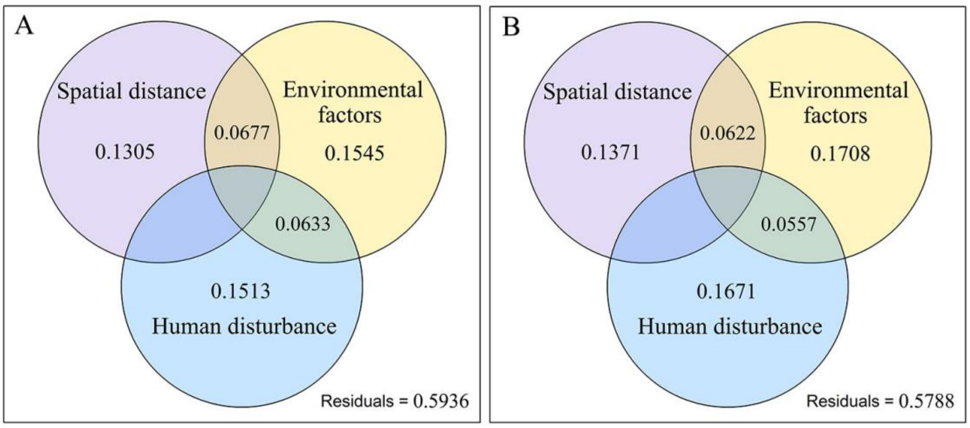

Figure 7. Main drivers of plant diversity in the seven nature reserves of the Yellow River in Henan Province, China. (**A**,**B**) Variance partitioning for the effects of spatial distance, environmental factors, and human disturbance on the beta diversity (βj and βs) of wetland plants in the nature reserves. Values less than zero are not shown. Spatial distance: longitude, latitude. Environmental factors: elevation, precipitation, evaporation, temperature. Human disturbance: population density, industrial output value, agricultural output value.

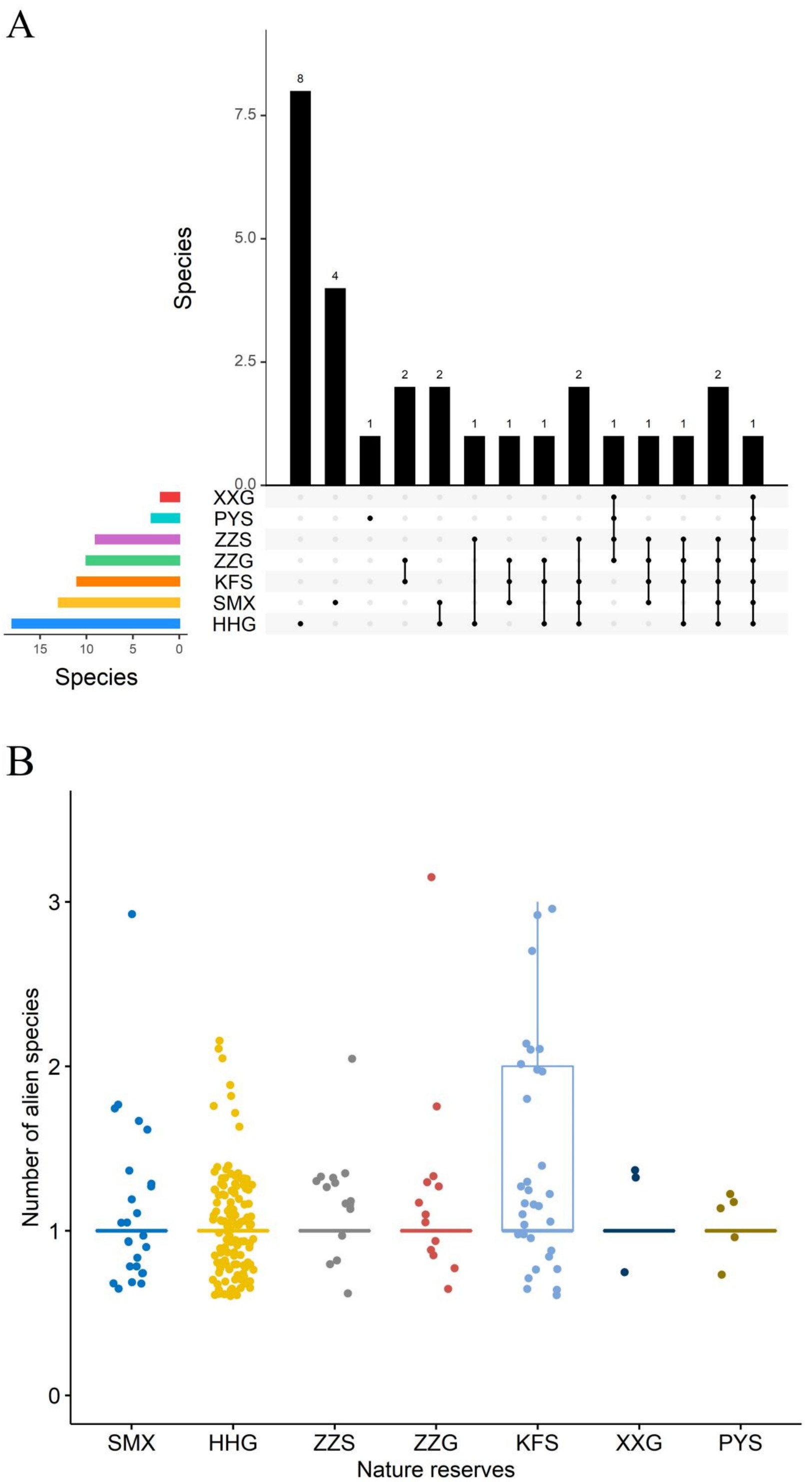

Figure 8. Composition of invasive alien species in the seven nature reserves of the Yellow River in Henan Province, China. (**A**) Venn diagram of invasive alien species in the seven nature reserves; (**B**) Number of invasive alien species in the seven nature reserves. HHG, Henan Yellow River wetland national nature reserve. SMX, Sanmenxia reservoir area wetland. ZZS, Henan Zhengzhou Yellow River wetland provincial nature reserve. ZZG, Henan Zhengzhou Yellow River national wetland park. KFS, Henan Kaifeng Liuyuankou wetland provincial nature reserve. XXN, Henan Xinxiang Yellow River wetland birds national nature reserve. PYS, Henan Puyang Yellow River wetland provincial nature reserve.

4. Discussion

4.1. Spatial Distribution of Plant Diversity

Our results revealed variations in the assemblage characteristics of the wetland plants in the different Yellow River wetland nature reserves ($F = 21.123$, $p < 0.001$). Plant diversity gradually decreases from west to east in the Yellow River wetland in Henan Province [45]. This phenomenon is mainly due to the fact that the middle and lower reaches of the Yellow River have the landform characteristics of western mountainous areas, central hills, and eastern plains [46]. The mountains have a large elevation difference and cover diverse topographic and climatic gradients, whereas the habitats in the plain areas are relatively simple, which may be an important reason for the gradually decreasing pattern of plant diversity from west to east [47,48]. HHG located in the western mountainous area is a national-level nature reserve with a large area and diverse habitats. It is a synthesis of multiple ecosystems, which may also be one of the reasons for the large diversity in the western mountainous area.

Our study found that ZZG had the highest plant diversity. This may be because ZZG located at the boundary of the middle and lower reaches of the Yellow River. Its unique geographical location makes the development of agriculture, forestry, and animal husbandry here faster, the annual average industrial output value and agricultural output value were 395.23 million yuan and 171.83 million yuan, respectively. ZZG is also the only characteristic area of National wetland park, which is a wetland landscape with special ecological and biological diversity values. Therefore, the plant diversity of ZZG was the highest in the studied wetland reserve.

Our network analysis suggests that a strong connection exists between the wetland plants and reserves (connectance index: 0.3018). The habitats of the different reserves vary greatly. For example, HHG reserve has a mountainous terrain, ZZG reserve is hilly, and KFS reserve is a plain. In addition, some differences exist in the precipitation and average temperature of the different reserves [49]. The indicator species of the different nature reserves are also different. For example, *Aster altaicus* and *Setaria viridis* are the main indicator species for HHG, whereas *Calamagrostis pseudophragmites* and *Paspalum distichum* are the main indicator species for ZZS. These findings are consistent with the discussion of Chen (2018), who reported that plants choose specific areas on the basis of their habitat traits. Therefore, wetland species have strong associations with reserves in the Yellow River wetland in Henan Province.

4.2. Determinants of Plant Diversity

In this study, elevation, precipitation, evaporation, and longitude were determined to be the main factors driving wetland species distribution in the Yellow River wetland in Henan Province. Elevation gradually decreases from the mountains in the west to the plains in the east in Henan Province [25]. Precipitation is an important factor that affects the spatial distribution and diversity of plants [50]. Influenced by the southeast monsoon and seaway location, the precipitation of the Yellow River wetland gradually decreases from east to west in Henan Province [51]. Studies have shown that 81.6% of the annual precipitation in the Yellow River basin evaporates [52]. Therefore, elevation, longitude, precipitation, and evaporation are important factors that affect the diversity of wetland plants in the middle and lower reaches of the Yellow River in China.

4.3. Effects of Human Disturbance on Plant Diversity

Aside from topography and climate playing a major role in plant diversity in the Yellow River in Henan Province, this study also found that human disturbance is an important factor that influences plant species diversity in the wetland. The explanation rates of pure human disturbance factors for the wetland plant beta diversity in the nature reserves were 15.13% and 16.71%, respectively. The wetland in the lower reaches of the Yellow River in Henan is a plain grain-producing area that is densely populated [53]. For historical reasons, the Loess Plateau in the middle reaches of the Yellow River and the

North China Plain in the lower reaches have a wide distribution of cultivated land [54]. According to national census data released in 2020, the permanent population of Henan Province is about 99.366 million, showing an increase of 5.68% compared with the figure for 2010. Additionally, agricultural irrigation influences wetland plant diversity. The vast river floodplain in this section has been developed into grazing sites and cultivated land for planting corn, wheat, and other field crops [55,56]. Previous results have indicated that frequent human activities, to some extent, adversely affect the wetland plant diversity of the middle and lower reaches of the Yellow River in China [57–59].

In our study, we also found that population density had a positive effect on the beta diversity of the wetland plants. A high population density indicates the possibility of strong human interference. Human disturbance results in landscape fragmentation and diverse habitats in the studied wetlands. The plant composition of different habitats exhibits great differences [60]. Therefore, population density has an important impact on plant diversity in wetlands along the Yellow River.

4.4. Invasive Alien Species Diversity

High population densities mean great human disturbance, which results in high beta diversity [60]. Another possible reason may be the inclusion of alien species, which are often positively correlated with high population densities or large settlements [61]. The invasive alien species of the Yellow River wetland in Henan Province invaded the local area early and have already adapted to the local habitat. They have a wide distribution in the local area. For example, *Eclipta prostrata* are distributed in all seven nature reserves, and according to historical data, *Eclipta prostrata* may have been introduced to China from abroad during the Tang dynasty (618–907). Therefore, the diversity of invasive alien species among the seven nature reserves in Henan province does not differ considerably. According to our field investigation and relevant literature, invasive plants do not affect the Yellow River ecosystem on a large scale in Henan Province. However, future research should pay careful attention to the impact of invasive alien species on the local ecological environment. The risks posed by invasive alien species should be evaluated thoroughly, monitored, and managed. In addition, preventive and protective measures must be implemented in advance.

5. Conclusions and Implications

From the perspectives of the natural environment and human disturbance, this study analyzed the characteristics of the plant community distribution in the middle and lower reaches of the Yellow River in China. It revealed the distribution of plant species in the middle and lower reaches of the Yellow River wetland in China and its driving factors.

Our results showed variations in the assemblage characteristics of wetland plants in the different Yellow River wetland nature reserves. The wetland species exhibited strong associations with the reserves in the Yellow River wetland in Henan Province. Elevation, longitude, precipitation, and evaporation were important factors that affected the diversity of wetland plants in the middle and lower reaches of the Yellow River in China. Human disturbance was another important factor that influenced plant species diversity in the wetland.

Wetland plants were strongly associated with the nature reserves in our study. Therefore, different conservation strategies should be adopted for different reserves and plants. Some protected-area endemic species require more attention than relatively common species during biodiversity conservation. Common wetland plants are widely distributed and have strong adaptability, so they can be used for wetland restoration. Reducing the farmland area and human activities is also an important measure for wetland restoration. This work is expected to provide a theoretical basis and possible data support for the high-quality development of ecological protection in the Yellow River basin.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/d14060470/s1. Table S1: The detailed description of the seven nature reserves; Table S2: The list of plant species names and plant stand data; Table S3: List of Invasive Alien Species Information.

Author Contributions: Data curation, Z.Y. and Y.C.; Investigation, M.X., Z.Z. and W.W.; Methodology, Y.C.; Project administration, Z.Y.; Software, M.X. and R.Q.; Supervision, Z.Y. and W.W.; Visualization, M.X., X.S., Y.L. and H.Z. (Huiping Zhang); Writing—original draft, M.X.; Writing—review & editing, Z.Y., H.Z. (He Zhao) and Y.C. All authors have read and agreed to the published version of the manuscript.

Funding: Project funded by China Postdoctoral Science Foundation (2021M693400); Youth Foundation of Natural Science Foundation of Henan Province (212300410153); Young Talents project funded by Henan Agricultural University (111/30500744); Natural Science Foundation of Henan Province (No. 212300410166).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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

References

1. Engelhardt, K.A.; Ritchie, M.E. Effects of macrophyte species richness on wetland ecosystem functioning and services. *Nature* **2001**, *411*, 687–689. [CrossRef] [PubMed]
2. Tilman, D.; Lehman, C.L.; Thomson, K.T. Plant diversity and ecosystem productivity: Theoretical considerations. *Proc. Natl. Acad. Sci. USA* **1997**, *94*, 1857–1861. [CrossRef] [PubMed]
3. Meng, W.; He, M.; Hu, B.; Mo, X.; Li, H.; Liu, B.; Wang, Z. Status of wetlands in China: A review of extent, degradation, issues and recommendations for improvement. *Ocean. Coast. Manag.* **2017**, *146*, 50–59. [CrossRef]
4. Yu, X.; Ding, S.; Zou, Y.; Xue, Z.; Lyu, X.; Wang, G. Review of rapid transformation of floodplain wetlands in northeast China: Roles of human development and global environmental change. *Chin. Geogr. Sci.* **2018**, *28*, 654–664. [CrossRef]
5. Fang, L.; Wang, L.; Chen, W.; Sun, J.; Cao, Q.; Wang, S.; Wang, L. Identifying the impacts of natural and human factors on ecosystem service in the Yangtze and Yellow River Basins. *J. Clean. Prod.* **2021**, *314*, 127995. [CrossRef]
6. Jiang, W.; Yuan, L.; Wang, W.; Cao, R.; Zhang, Y.; Shen, W. Spatio-temporal analysis of vegetation variation in the Yellow River Basin. *Ecol. Indic.* **2015**, *51*, 117–126. [CrossRef]
7. Zhang, W.; Wang, L.; Xiang, F.; Qin, W.; Jiang, W. Vegetation dynamics and the relations with climate change at multiple time scales in the Yangtze River and Yellow River Basin, China. *Ecol. Indic.* **2020**, *110*, 105892. [CrossRef]
8. Shi, F.; Liu, S.; Sun, Y.; An, Y.; Zhao, S.; Liu, Y.; Li, M. Ecological network construction of the heterogeneous agro-pastoral areas in the upper Yellow River basin. *Agric. Ecosyst. Environ.* **2020**, *302*, 107069. [CrossRef]
9. Li, H.; Liu, G.; Fu, B. Response of vegetation to climate change and human activity based on NDVI in the Three-River Headwaters region. *Acta Ecol. Sin.* **2011**, *31*, 5495–5504.
10. Li, F.; Xie, Y.; Chen, X.; Deng, Z.; Li, X. Composition of aquatic plants and their niche characteristics in wetlands of the Yellow River Delta. *Acta Ecol. Sin.* **2009**, *29*, 6257–6265.
11. Liu, Y.; Han, M.; Pan, B.; Liu, Y. The Spatial Distribution of Vegetation Biomass and Soil Salinity in New-born Wetlands of the Yellow River Delta. *Wetl. Sci.* **2017**, *15*, 364–368. [CrossRef]
12. Wang, Y.; Zhang, J.; Lv, Q.; Lv, Z.; Wang, Y.; Gao, Y.; Ren, Z. Effects of water and sediment regulation scheme on phytoplankton community and abundance in the Yellow River Estuary. *Mar. Environ. Sci.* **2021**, *40*, 369–378. [CrossRef]
13. Guofu, L.; Shengyan, D.; Zhiheng, L. Regional agricultural landscape pattern changes along the Yellow River in Henan Province from 1987 to 2002. *J. Geogr. Sci.* **2005**, *15*, 415–422. [CrossRef]
14. Guofu, L.; Shengyan, D. Impacts of human activity and natural change on the wetland landscape pattern along the Yellow River in Henan Province. *J. Geogr. Sci.* **2004**, *14*, 339–348. [CrossRef]
15. Liu, L.; Wei, J.; Ma, Y.; Luo, Q.; Wang, Z. Temporal and spacial changes for ecological environment of Yellow River in Henan Province. *Environ. Sci. Manag.* **2021**, *46*, 169–173.
16. Liang, S.; Li, C.; Li, C.; Ren, J.; Song, L.; Qiao, X. Distribution and Change of Wetlands in Henan Province in 1990, 2000 and 2007. *Wetl. Sci.* **2011**, *9*, 94–96. [CrossRef]
17. Yu, J.; Chen, X.; Sun, Z.; Xie, W.; Mao, P.; Wu, C.; Dong, H.; Mou, X.; Li, Y.; Guan, B.; et al. The spatial distribution characteristics of soil nutrients in new-born coastal wetland in the Yellow River delta. *Acta Sci. Circumstantiae* **2010**, *30*, 855–861. [CrossRef]

18. Lin, M.; Liu, R.; Wang, Y.; Luo, X.; Zhou, F. Spatial Heterogeneity of Soil Nutrients and The Relationship between Soil Nutrients and Plant Community in *Tamarix chinensis* Forest Farm Wetland of Yellow River Delta Wetland. *Wetl. Sci.* **2010**, *8*, 92–97. [CrossRef]
19. Zhao, Y. Potentialities and Countermeasures of Forestry Development in the Lower Reaches of the Yellow River in Henan. *Areal Res. Dev.* **2004**, *23*, 6l–65.
20. He, X.; Zheng, D.; Guo, H.; Ma, G. The Vegetation Species Diversity and Its Response to the Human Activities in Zhengzhou Yellow River Wetland Reserve. *Wetl. Sci.* **2014**, *12*, 459–463. [CrossRef]
21. Wohlfart, C.; Kuenzer, C.; Chen, C.; Liu, G. Social–ecological challenges in the Yellow River basin (China): A review. *Environ. Earth Sci.* **2016**, *75*, 1066. [CrossRef]
22. Hao, F.; Zhang, X.; Ouyang, W.; Skidmore, A.K.; Toxopeus, A.G. Vegetation NDVI linked to temperature and precipitation in the upper catchments of Yellow River. *Environ. Modeling Assess.* **2012**, *17*, 389–398. [CrossRef]
23. Chen, Y.; Syvitski, J.P.; Gao, S.; Overeem, I.; Kettner, A.J. Socio-economic impacts on flooding: A 4000-year history of the Yellow River, China. *Ambio* **2012**, *41*, 682–698. [CrossRef] [PubMed]
24. Ge, J.; Hu, Y. The Yellow River and the Yellow River Civilization. In *A Historical Survey of the Yellow River and the River Civilizations*; Springer: Singapore, 2021; pp. 1–48.
25. Zhang, J.; Zhu, W.; Zhu, L.; Cui, Y.; He, S.; Ren, H. Topographical relief characteristics and its impact on population and economy: A case study of the mountainous area in western Henan, China. *J. Geogr. Sci.* **2019**, *29*, 598–612. [CrossRef]
26. Liao, B. Research on Plant Diversity and It's Dynamics along the Environmental Gradient in Henan Province Section of the Yellow River Basin. Ph.D. Thesis, Henan University, Kaifeng, China, 2013.
27. Guo, J. Research on the Species Diversity of Compositae along the Different Gradient to Henan Section of the Yellow River Watershed. Master's Thesis, Henan University, Kaifeng, China, 2011.
28. Zuo, Q.; Wu, Z. Risk-Based Evaluation Index of Water Resource Renewability in the Yellow River Basi. Ph.D. Thesis, Zhengzhou University, Zhengzhou, China, 2003.
29. Benayas, R.; José, M.; Scheiner, S.M. Plant diversity, biogeography and environment in Iberia: Patterns and possible causal factors. *J. Veg. Sci.* **2002**, *13*, 245–258. [CrossRef]
30. Chesson, P. Mechanisms of maintenance of species diversity. *Annu. Rev. Ecol. Syst.* **2000**, *31*, 343–366. [CrossRef]
31. Jaccard, P. The distribution of the flora in the alpine zone. 1. *New Phytol.* **1912**, *11*, 37–50. [CrossRef]
32. Sorensen, T.A. A method of establishing groups of equal amplitude in plant sociology based on similarity of species content and its application to analyses of the vegetation on Danish commons. *Biol. Skar.* **1948**, *5*, 1–34.
33. Jost, L. Partitioning diversity into independent alpha and beta components. *Ecology* **2007**, *88*, 2427–2439. [CrossRef]
34. Dixon, P. VEGAN, a package of R functions for community ecology. *Journal of Vegetation Science* **2003**, *14*, 927–930. [CrossRef]
35. Conway, J.R.; Lex, A.; Gehlenborg, N. UpSetR: An R package for the visualization of intersecting sets and their properties. *Bioinformatics* **2017**, *33*, 2938–2940. [CrossRef] [PubMed]
36. Blüthgen, N.; Menzel, F.; Hovestadt, T.; Fiala, B.; Blüthgen, N. Specialization, constraints, and conflicting interests in mutualistic networks. *Curr. Biol.* **2007**, *17*, 341–346. [CrossRef] [PubMed]
37. Bastian, M.; Heymann, S.; Jacomy, M. Gephi: An open source software for exploring and manipulating networks. In Proceedings of the Third International Conference on Weblogs and Social Media, San Jose, CA, USA, 17–20 May 2009; Volume 3, pp. 361–362.
38. De Caceres, M.; Jansen, F.; De Caceres, M.M. Package 'Indicspecies'. *Indicators*. 2016, 8. Available online: https://emf-creaf.github.io/indicspecies/ (accessed on 8 June 2022).
39. Chen, Y.; Yuan, Z.; Bi, S.; Wang, X.; Ye, Y.; Svenning, J.C. Macrofungal species distributions depend on habitat partitioning of topography, light, and vegetation in a temperate mountain forest. *Sci. Rep.* **2018**, *8*, 13589. [CrossRef]
40. Oksanen, J. Vegan: Community Ecology Package. R Package Version 1.17-9. 2011. Available online: http://cran.r-project.org/package=vegan (accessed on 8 June 2022).
41. Hollister, E.B.; Engledow, A.S.; Hammett, A.J.M.; Provin, T.L.; Wilkinson, H.H.; Gentry, T.J. Shifts in microbial community structure along an ecological gradient of hypersaline soils and sediments. *ISME J.* **2010**, *4*, 829–838. [CrossRef]
42. Legendre, P.; Mi, X.; Ren, H.; Ma, K.; Yu, M.; Sun, I.F.; He, F. Partitioning beta diversity in a subtropical broad-leaved forest of China. *Ecology* **2009**, *90*, 663–674. [CrossRef]
43. Oksanen, J.; Kindt, R.; Legendre, P.; O'Hara, B.; Stevens, M.H.H.; Oksanen, M.J.; Suggests, M.A.S.S. The vegan package. *Community ecology package.* **2007**, *10*, 719.
44. Kassambara, A.; Kassambara, M.A. Package 'Ggpubr'. In R Package Version 0.1. 2020, Volume 6. Available online: https://www.sthda.com/english/rpkgs/ggpubr (accessed on 8 June 2022).
45. Xu, H.; Cao, M.; Wu, Y.; Cai, L.; Cao, Y.; Wu, J.; Lei, J.; Le, Z.; Ding, H.; Cui, P. Disentangling the determinants of species richness of vascular plants and mammals from national to regional scales. *Sci. Rep.* **2016**, *6*, 21988. [CrossRef]
46. Eryong, Z.; Yingchun, S.; Cunrong, G.; Xinwei, H.; Zhantao, H.; Hongmei, Z.; Qianqing, D.; Xingchun, L.; Baogui, L.; Runlian, Z.; et al. Regional geology and hydrogeology of the Yellow River basin. *Bull. Geol. Surv. Jpn.* **2009**, *60*, 19–32. [CrossRef]
47. Becker, A.; Körner, C.; Brun, J.J.; Guisan, A.; Tappeiner, U. Ecological and land use studies along elevational gradients. *Mt. Res. Dev.* **2007**, *27*, 58–65. [CrossRef]
48. Moeslund, J.E.; Arge, L.; Bøcher, P.K.; Dalgaard, T.; Svenning, J.C. Topography as a driver of local terrestrial vascular plant diversity patterns. *Nord. J. Bot.* **2013**, *31*, 129–144. [CrossRef]

49. Zhao, Q.; Ma, L.; Liu, Q.; Ding, S.; Tang, Q.; Lu, X. Plant species diversity and its response to environmental factors in typical river riparian zone in the middle and lower reaches of Yellow River. *Chin. J. Ecol.* **2015**, *34*, 1325–1331. [CrossRef]
50. Stella, J.C.; Rodríguez-González, P.M.; Dufour, S.; Bendix, J. Riparian vegetation research in Mediterranean-climate regions: Common patterns, ecological processes, and considerations for management. *Hydrobiologia* **2013**, *719*, 291–315. [CrossRef]
51. Shi, B.; Zhu, X.; Hu, Y.; Yang, Y. Drought characteristics of Henan province in 1961-2013 based on Standardized Precipitation Evapotranspiration Index. *J. Geogr. Sci.* **2017**, *27*, 311–325. [CrossRef]
52. Liu, C.; Wang, S.; Liang, Y. Analysis of pan evaporation change and the influence factors in the Yellow River Basin in 1961–2010. *Progress. Inquisitiones DE Mutat. Clim.* **2013**, *9*, 327. [CrossRef]
53. Li, H.; Wang, J.; Zhang, J.; Qin, F.; Hu, J.; Zhou, Z. Analysis of characteristics and driving factors of wetland landscape pattern change in Henan Province from 1980 to 2015. *Land* **2021**, *10*, 564. [CrossRef]
54. Sun, Y.; Hu, W.; Yao, S.; Sun, Y.; Deng, J. Geographic patterns and environmental determinants of angiosperm and terrestrial vertebrate species richness in the Yellow River basin. *Biodivers. Sci.* **2020**, *28*, 1523. [CrossRef]
55. Liang, S.; Luo, X.; Meng, X.; Sun, R. Characteristics of herbaceous plant community diversity along the Yellow River wetland of Henan. *Pearl River* **2018**, *39*, 9–13. [CrossRef]
56. Zhao, X.; Zhao, Y. Current Situation, Protection and Management of Wetlands along the Yellow River in Henan. *Wetl. Sci. Manag.* **2016**, *12*, 27–29.
57. Cousins, S.A.; Eriksson, O. The influence of management history and habitat on plant species richness in a rural hemiboreal landscape, Sweden. *Landsc. Ecol.* **2002**, *17*, 517–529. [CrossRef]
58. Chen, Y.; Xu, N.; Yu, Q.; Guo, L. Ecosystem service response to human disturbance in the Yangtze River economic belt: A case of Western Hunan, China. *Sustainability* **2020**, *12*, 465. [CrossRef]
59. Arias, M.E.; Cochrane, T.A.; Norton, D.; Killeen, T.J.; Khon, P. The flood pulse as the underlying driver of vegetation in the largest wetland and fishery of the Mekong Basin. *Ambio* **2013**, *42*, 864–876. [CrossRef] [PubMed]
60. Chen, J.; Guo, Y.; Lu, X.; Ding, S.; Su, S.; Guo, J.; Li, Q. Species diversity of herbaceous communities in the Yiluo River Basin. *Acta Ecol. Sin.* **2012**, *32*, 3021–3030. [CrossRef]
61. Wu, X.; Luo, J.; Chen, J.; Li, B. Spatial patterns of invasive alien plants in China and its relationship with environmental and anthropological factors. *J. Plant Ecol.* **2006**, *30*, 576–584.