diversity

MDPI

Article

Biodiversity and Abundance of Angiosperms and Environmental Resilience in the Tidal Range of Yuanjiang Dry–Hot Valley, Southwestern China

Fengchun Yang [1,2], Qiong He [1,2], Huaping Huang [2], Yanmei Cui [2], Jianyong Gou [3,*], Chaya Sarathchandra [4,*], Kritana Prueksakorn [5], Kiyota Hashimoto [6] and Li Liu [1]

1 School of Modern Agriculture, Yibin Vocational and Technological College, Yibin 644000, China; yangfengchun@gdpu.edu.cn (F.Y.); heqiong3344@163.com (Q.H.); 19881150986@163.com (L.L.)
2 Environment and Plant Protection Research Institute, Chinese Academy of Tropical Agricultural Sciences, Haikou 570100, China; hhp18@163.com (H.H.); cym2000000@163.com (Y.C.)
3 Honghe Meteorological Bureau, Honghe 661100, China
4 Department of Biological Science, Faculty of Applied Sciences, Rajarata University of Sri Lanka, Mihintale 50300, Sri Lanka
5 Faculty of Environment and Resource Studies, Mahidol University, Nakhon Phathom 73170, Thailand; kritana.pru@mahidol.ac.th
6 Faculty of Technology and Environment, Prince of Songkla University, Phuket 83000, Thailand; hash@reasoning.jp
* Correspondence: 18111142022@163.com (J.G.); chayasarathchandra@gmail.com (C.S.)

Abstract: Yuanjiang dry–hot valley is located in the southwest of mainland China. It is a sparsely vegetated area with a fragile arid ecosystem. Although the valley previously had forest cover, it has become a tropical montane savannah in recent decades. Mechanisms controlling plant species distribution in such dry–hot valleys are unclear. Clarifying this will be beneficial to sustainable ecosystem management in dry–hot valleys. This study explored the relationship between diversity patterns of plant species and their environments in the lowland of this dry–hot valley. To achieve this, transects and plots were arranged along the river channel. Alpha and beta diversity indices were calculated to quantify biodiversity changes between species and environments. Estimated species, rarity, and abundance indices were also utilized to examine the correlation among species, their population size, and their environment: *Species_estimated* (expected number of species in *t* pooled plots), *Singletons* (the number of species with only one individual in *t* pooled plots), *Uniques* (the number of species living in one plot in *t* pooled plots), *ACE* (species richness estimator with coverage-based abundance), *ICE* (species richness estimator with coverage-based incidence), and *Chao2* (species richness estimator extrapolated from *Singletons*). Fifty years of meteorological records, including temperature and precipitation, were utilized as climate variables. The results indicated the following findings: (1) alpha diversity was higher closer to the river, whereas the beta diversity was higher towards the lower sections of the river (Bray–Curtis < 0.5), but this trend was reversed in the perpendicular transects; (2) total phosphorous (TP) and total potassium (TK) were higher on flatter ground, tending to be associated with raised nitrogen (TN) and organic matter (OM); (3) soil nutrients were higher towards the lower sections of the river, corresponding to an increased number of species; (4) water supply determined plant distribution, with soil condition determining water retention; (5) the estimated species and their rarity and abundance indices were associated with proximity to the river, indicating heterogeneity of habitats and soil condition; and (6) fern species could be used as indicators representing the xeric environment of Yuanjiang dry–hot valley. Plant cover was reduced at low altitudes, with high temperatures and a low water supply. These results draw attention to the need for specific policy formation to protect the microhabitats and manage the environment of the Yuanjiang valley.

Keywords: biodiversity; dry–hot valley; environment; indicator species; tidal range

check for updates

Citation: Yang, F.; He, Q.; Huang, H.; Cui, Y.; Gou, J.; Sarathchandra, C.; Prueksakorn, K.; Hashimoto, K.; Liu, L. Biodiversity and Abundance of Angiosperms and Environmental Resilience in the Tidal Range of Yuanjiang Dry–Hot Valley, Southwestern China. *Diversity* **2024**, *16*, 703. https://doi.org/10.3390/d16110703

Academic Editors: Michael Wink and Mario A. Pagnotta

Received: 28 July 2024
Revised: 7 September 2024
Accepted: 8 September 2024
Published: 18 November 2024

1. Introduction

Species distribution and diversity, as well as interactions between living organisms and their physical environment, are markedly affected by climate change [1]. Dry–hot valleys are examples of fragile arid and semi-arid ecosystems (Figure 1), which account for 40% of the earth's terrestrial ecosystems [2]. It has been projected that dry–hot valleys will experience profound vegetation shifts since they are especially susceptible to climatic conditions [2]. These ecosystems may also be limited in their ability to adapt or recover after destructive events [3]. The interrelationship between species and their physical environmental conditions in arid ecosystems could be used as the basis for preliminary interpretation of adaptation mechanisms. Therefore, it is crucial to explore and provide insights into the underlying ecological processes [4,5].

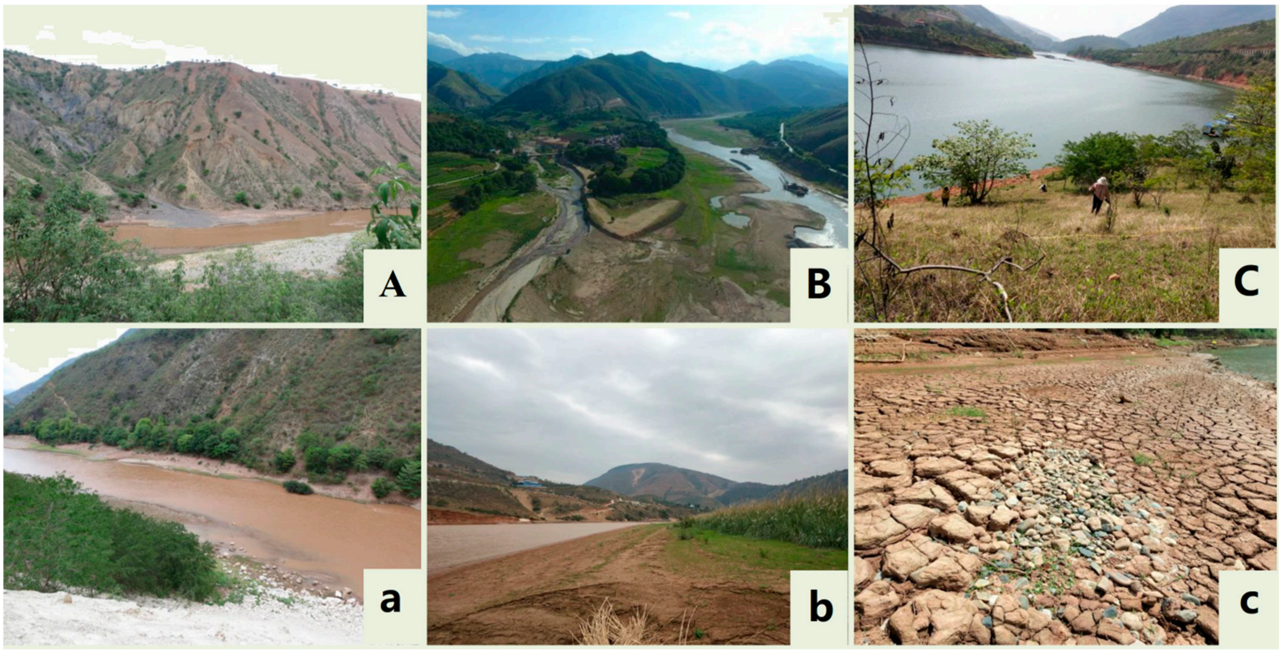


Figure 1. Vegetation and environment in the lower altitudinal range of Yuanjiang dry–hot valley, Southwestern China. (**A**,**a**) Upper; (**B**,**b**) middle; (**C**,**c**) lower; (**A**), (**B**) and (**C**) indicate rainy season, while a, b and c are in dry.

Yuanjiang dry–hot valley is located in the upper and middle watershed of the Yuanjiang Red River in Southwest China. It extends through tropical and subtropical areas, thus having high temperatures and dry air throughout the year [6]. Human colonization and low-land farming in these valleys has led to extreme degradation of the environment, which has been exacerbated by recent climatic change. Furthermore, the extant plant species and community have changed significantly compared to those present during the previous 500 yr B.P. [7]. Since the mid-17th century, the primary forest has been gradually replaced by a tropical montane savannah. Xerophytic components, mainly succulents, and annual therophytes have subsequently colonized the valley and flourished.

The environmental impacts on plants have mainly been caused by the environmental susceptibility of this fragile ecosystem [8]. It is also well known that plant diversity is determined by the living environment [9]. In the case of Yuanjiang dry–hot valley, however, it is not yet known how key diversity indexes correspond to environmental factors. Clarification of these relationships would contribute to our understanding of mechanisms underlying past vegetation shifts. A field investigation was conducted to investigate the relations between plants and the environment in Yuanjiang dry–hot valley. In this study, we tested the following hypotheses:

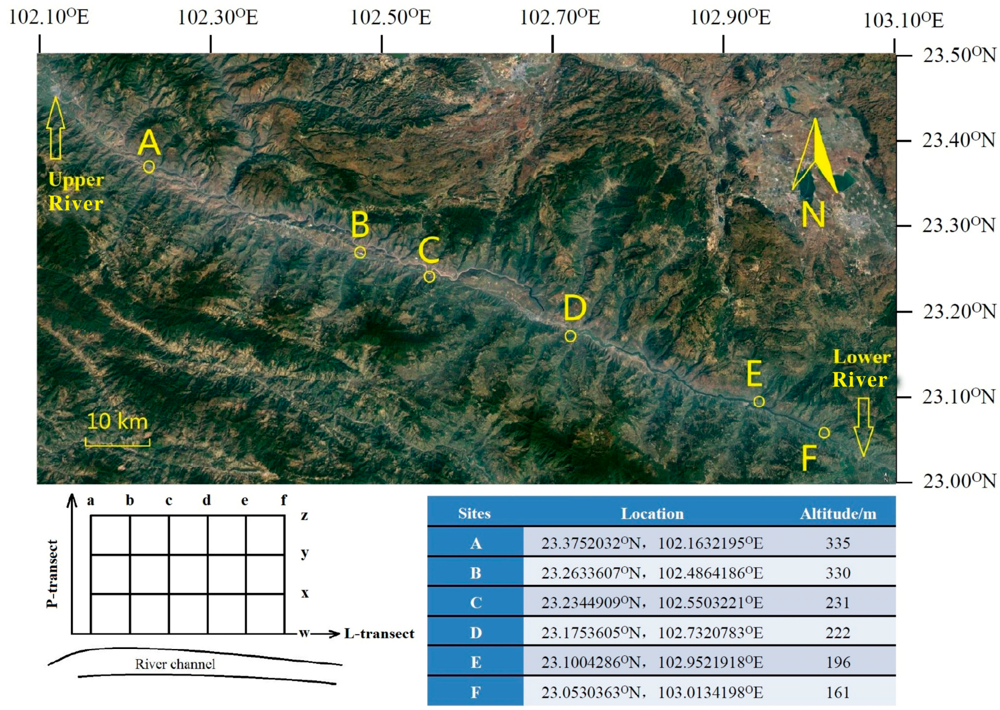
(1) Species diversity indices will vary with the environmental conditions along the valley.
(2) Changes in these indices will be closely related to water and soil conditions.

Due to limitations in baseline databases regarding regional ecological amplitude of tidal plants, assessments of environmental impacts on plant diversity patterns were conducted based on species habitat and distribution.

2. Materials and Methods

2.1. Field Transect and Plot Design

The Yuanjiang valley is oriented from northwest to southeast, with the altitude decreasing from 268 m to 227 m above sea level (*a.s.l.*). The ground surface comprises fragmented sandstone and shale. The soil mainly consists of purple sandstone or sandy shale derived from dry laterite [10]. Ten transects and twenty-four plots were set up and investigated in the core area, extending 105.26 km from the upper and the lower sections of the river (Figure 2). Two types of transects were established, perpendicular (P-transects) and parallel (L-transects). Each P-transect formed a line extending 70 m perpendicular to the river channel. Six P-transects designated as 'a–f' were set up, spaced between the upper and lower sites. To ensure random selection and a sufficient data source, four 10 m × 10 m plots were placed equidistantly along each transect. Each L-transect was set up by connecting those plots in a line parallel to the river. Plots with the same distance to the river channel were organized in one transect. Accordingly, four L-transects were designated as 'w to z' and established at equal distances paralleled to the river channel, with 20 m separating each transects. There were six plots in each L-transect. Plant species in the plots were identified following the Flora of China (http://www.iplant.cn/foc/, accessed on 21 April 2022).



Sites	Location	Altitude/m
A	23.3752032°N，102.1632195°E	335
B	23.2633607°N，102.4864186°E	330
C	23.2344909°N，102.5503221°E	231
D	23.1753605°N，102.7320783°E	222
E	23.1004286°N，102.9521918°E	196
F	23.0530363°N，103.0134198°E	161

Figure 2. Research sites A–F (**top**) and diagram (**bottom left**) of L-transect and P-transect (P-transect, transect perpendicular to river channel, a and b are in the upper river, c and d are middle, and e and f are lower; L-transect, transect parallel to river channel; transect w, at a distance of 5 m to river channel; transect x, at a distance of 25 m; transect y, at distance of 45 m; transect z, at a distance of 65 m). Site coordinates and elevation (**bottom right**).

2.2. Meteorological Records

Meteorological records from 1968 to 2018 were obtained from long-term meteorological stations at low altitudes in the Yuanjiang valley (312–576 m *a.s.l.*, https://data.cma.cn/, accessed on 12 April 2020). Temperature and precipitation were treated as the environmental factors to analyze relative to plant growth and distribution, because we expected these to be the major factors impacting ecosystem processes within dry–hot valleys.

2.3. Biodiversity Indices

Biodiversity was analyzed based on species and habitats; α-diversity, associated with species; β-diversity, associated with habitats [11]. Alpha diversity, denoting species diversity, was measured by the Shannon–Wiener (H) index. Evenness (J) and *Dominance* are aspects of Beta diversity (denoting habitat diversity), and were mainly represented by the *Bray–Curtis* index, which is a similarity index representing heterogeneity in sampling plots or transects along a multidisciplinary species matrix.

2.4. Estimated Species: Rarity and Richness Indices

The first stage of the data analysis process was conducted using Program EstimateS Version 9.1 [12], which offers diverse approaches for assessing the difference in plots and transects. The indices of the estimated species and their rarity and richness were the standard indices: *Species_estimated*, *Singletons*, and *Uniques* [13]. These parameters were calculated as *ACE*, *ICE*, and *Chao2*, respectively. Notes: (1) *Species_estimated*—expected number of species in t pooled plots; (2) *Singletons*—the number of species with only one individual in t pooled plots; (3) *Uniques*—the number of species living in one plot in t pooled plots (number of species in one plot regardless of their population size); (4) *ACE*—species richness estimator, with coverage-based abundance; (5) *ICE*—species richness estimator, with coverage-based incidence; and (6) *Chao2*—a species richness estimator extrapolated from *Singletons* [14]. *Singletons* and *Uniques* were associated with species rarity, while *ACE*, *ICE*, and *Chao2* were related to species richness.

All data matrices were computed 999 times in EstimateS. Then, the selected indices were analysed and displayed in R (version 3.6.1) and Rstudio (version 2023.06.1) using the following packages: *lme4* for generalized linear mixed models [15]; *vegan* for multivariate and diversity analyses [16]. All model inferences were based on the Chi-square (χ^2) test at a $p < 0.05$ significance level. Residuals were evaluated for normality using the Shapiro–Wilk test and for the homoscedasticity of variance using Levene's Test. Normality was assumed when $p \geq 0.05$ [17]. Multiple comparisons of the mean value were tested with Tukey's method at $p < 0.05$ significance level [18].

2.5. Indicators Screening

The species most strongly associated with their environment were treated as indicator species. They were screened using the indicator value function (*IndVal*) in R package *indicspecies* [19]. *IndVal* incorporated a random variable representing the value of "1" for visible and "0" for invisible. The multilevel pattern analysis was conducted at a significance level of $p < 0.05$ for the pooled species.

2.6. Physical and Chemical Properties of Surface Soil

Soil pH was measured using the potentiometry approach [20]. The potassium dichromate volumetric standard (CODcr) was used to measure the organic matter (OM) [21]. The total nitrogen (TN), following H_2SO_4–HClO digestion, was determined using the Kjeldahl method [22]. The ICP-AES method [23] was then used to measure the total phosphorus (TP) after $HClO_4$–HF digestion, and potassium (TK) after neutral CH_3COONH_4 (1 mol/L) extraction.

3. Results

According to long-term meteorological records, average annual temperature, precipitation, and evaporation were 23.95 °C, 814 mm, and 205 mm, respectively. These climatic conditions are similar to those of the Jinsha dry–hot valley [24]. Despite the proximity to the riverside, the temperature is still relatively high, with limited precipitation and high evaporation throughout the year.

Based on our sampling protocol at the research sites, we recorded 14,999 individual plants, belonging to 107 species, within 56 families (see Data). These records included multiple exotic species: 5496 individual exotic plants, belonging to 15 species within 11 families. We divided the plants into four categories: trees, bushes, herbs, and climbing plants. There were 973 individual trees belonging to 17 species within 12 families. There were 1259 individual bushes belonging to 19 species within 11 families. There were 12,650 individual herbs belonging to 65 species within 28 families. There were 117 individual climbing plants belonging to 6 species within 5 families.

3.1. Alpha-Biodiversity in P-Transect and L-Transect

The diversity index *H* in P-transects and L-transects displayed a slight gradient decline (Figure 3), indicating a decreased number of species along the course of the river. The decline began from the river channel and then outward (p = 0.2156) along the L-transects. The decline started from the upper river (p = 0.7204) and then went downstream along the P-transects. However, H_{max} decreased significantly ($p < 0.05$), from the river channel outward along the L-transect. Species diversity was highest in the plots closest to the river.

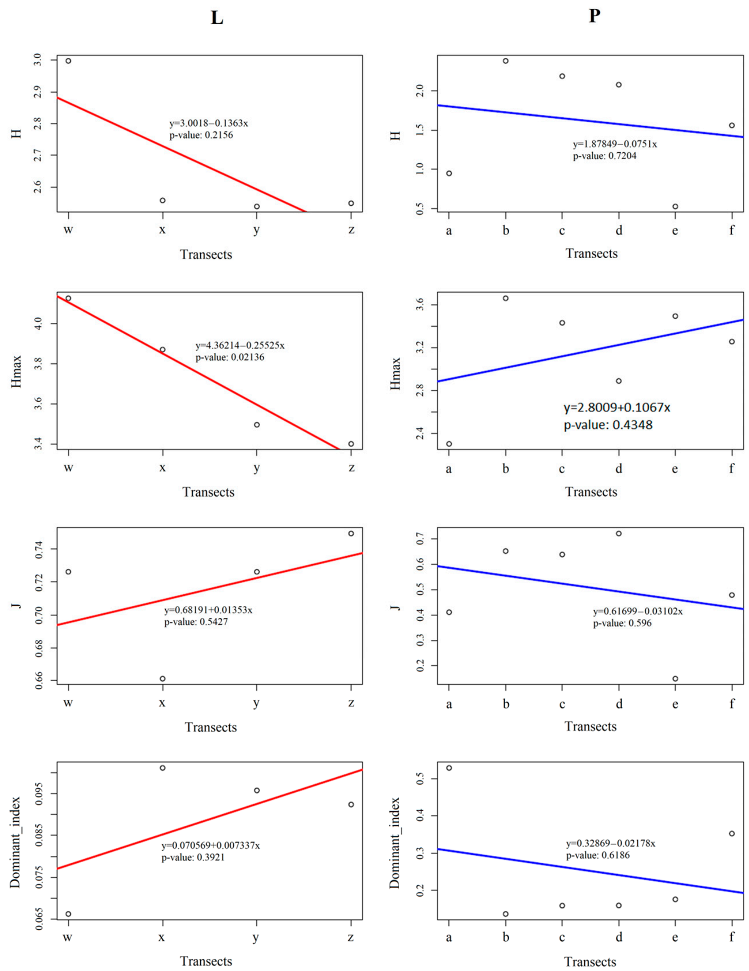


Figure 3. Shannon–Weiner index (H), maximum Shannon–Weiner value (Hmax), evenness index (J), and overall dominance index across P-transects and L-transects.

The number of species also displayed a significant decline along the L-transect (Figure 4). The greatest number of species was in transect_w, which is close to the riverbank. Species became progressively impoverished from transect_z outwards. Conversely, for the P-transects, the number of species slowly increased from the upper river transect_a to downstream transect_f. However, the results did not establish any underlying mechanism for diversity changes along the course of the river.

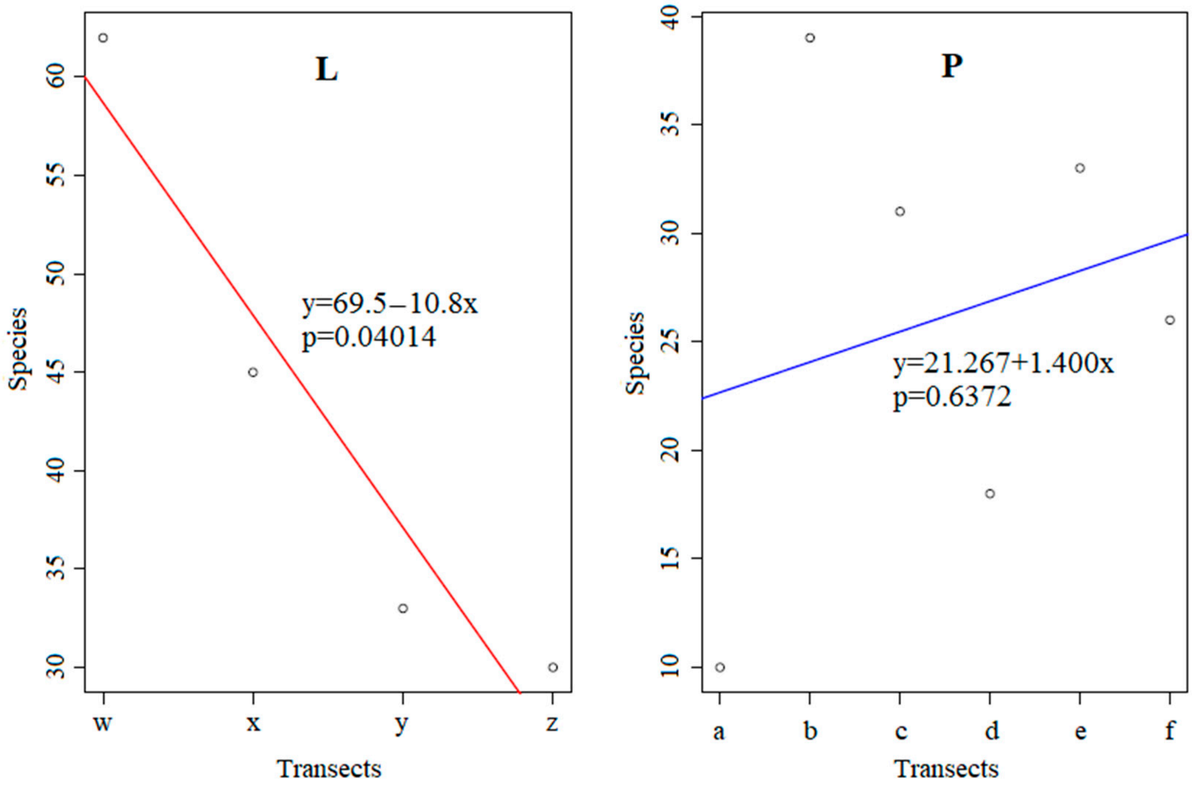


Figure 4. Overall change in species number along L- and P-transects.

Evenness (*J*) was highly variable between transects. There was no discernible spatial pattern in the maximum and minimum values of *J*, e.g., in the P-transect, the highest *J* was 0.72 in transect_d (18 species recorded), while the lowest was 0.15 in transect_e (33 species recorded). The regression results did not indicate a distinctive distribution. Spatial patterns did not relate to water resources (distance from river channel), but were associated with a diverse environment.

Likewise, the *Dominant_index* was highly variable between transects but was not significantly related to distance along the river or distance away from the river. Some species dominated the ecological community and constituted the largest share of the biomass. The *Dominant_index* was lower in the transect closest to the river channel, but was higher further from the river, along the L-transects. Along the P-transects, the dominance of a single plant species was higher in the upper sections than it was in the lower sections of the river. Exotic species such as *Ageratum conyzoides* L., and *Axonopus compressus* (Sw.) P. Beauv appear to have become invasive across the Yuanjiang river valley. They were distributed along whole transects with more than 600 seedlings in total. No species were recorded exclusively from any single plot in the lower section of the river.

3.2. Beta-Diversity and the Habitat Similarity in the Valley

Along the P-transects (Table 1), the index β was generally high (>0.500) in plots 3 and 4 in each transect, with the maximum value reported also away from the river channel. The habitat of these plots was similar and indicated a convergent habitat away from the river channel. Comparatively, in L-transect (Table 2), the index β was generally low (<0.500) in the plots from upper to lower stream, and the maximum value was distributed randomly. Therefore, the living habitat of plants was closely correlated to the environmental physical condition away from the river channel but did not vary considerably along the course of the river.

Table 1. Habitat similarities between the plots of P-transect. Six transects were designation 'a–f', extending from the upper to the lower river through the Yuanjiang dry hot valley.

Transect_a					**Transect_b**				
	1	2	3	4		1	2	3	4
1		0.06	0.03	0	1		0	0	0
2			0.60	0.02	2			1.00	0.18
3				0.02	3				0.18
4					4				
Transect_c					**Transect_d**				
	1	2	3	4		1	2	3	4
1		0.39	0.06	0.04	1		0	0.33	0
2			0.22	0.19	2			0.29	0.42
3				0.67	3				0.65
4					4				
Transect_e					**Transect_f**				
	1	2	3	4		1	2	3	4
1		0.43	0.43	0.21	1		0.01	0	0
2			0.77	0.42	2			0.07	0.02
3				0.73	3				0.92
4					4				

Table 2. Habitat similarities between the plots of L-transect.

Transect_w							**Transect_x**						
	1	2	3	4	5	6		1	2	3	4	5	6
1		0	0.01	0.01	0.02	0	1		0	0.05	0.02	0.41	0.02
2			0.03	0.04	0.02	0	2			0	0	0	0
3				0.03	0.01	0.01	3				0.18	0	0
4					0.22	0	4					0.39	0.09
5						0	5						0
6							6						
Transect_y							**Transect_z**						
	1	2	3	4	5	6		1	2	3	4	5	6
1		0	0.05	0	0.27	0.38	1		0	0.04	0.01	0.03	0
2			0	0	0	0	2			0	0	0	0
3				0	0.02	0.04	3				0	0	0
4					0.53	0.02	4					0.01	0
5						0.03	5						0
6							6						

3.3. L-Transect and the Variance of Expected Species, Rarity, and Abundance Indices

Species_estimated differed from plot 1 in the upper river to plot 6 in the lower river (Figure 5). Additional species occurrences were reported in the plots extending down the length of the river; they were apparently associated with corresponding heterogeneous habitats along the watershed. Significant alteration in species composition from the upper to lower river was supported by the field collections. The upper river plots were dominated by grass and herbs, including the following: *Arthraxon hispidus* (Thunb.) Makino, *Saccharum spontaneum* L., *Neyraudia reynaudiana* (Kunth.) Keng ex Hitchc., *Achyranthes aspera* L., *Praxelis clematidea* (Hieron. ex Kuntze) R. M. King and H. Rob. (exotic), *Solanum violaceum* Ortega, *Persicaria lapathifolia* (L.) Delarbre., *Calotropis gigantea* (L.) W. T. Aiton, and *Cajanus scarabaeoides* (L.) Thouars. In the plots besides the lower sections of the river, the flora shifted to bushes and trees, including the following: *Broussonetia papyrifera* (L.) L'Heritier ex Vent, *Pleurolobus gangeticus* (L.) J.St.-Hil. ex H. Ohashi and K. Ohashi., *Phyllanthus myrtifolius* (Wight) Müll. Arg., *Pistacia weinmanniifolia* J. Poisson ex Franch., *Grewia biloba* var. *parviflora* (Bunge) Hand.-Mazz., and *Streblus asper* Lour. Ferns and their associates were also reported, including the following: *Thelypteris parasitica* (L.) Tardieu, *Tectaria fuscipes* (Wall. Ex Bedd) C. Chr, and *Selaginella kurzii* Baker. The total number of recorded species were 62, 45, 33, and 30 in transects w, x, y, and z, respectively. The number of ferns declined from riverine transects to slopes.

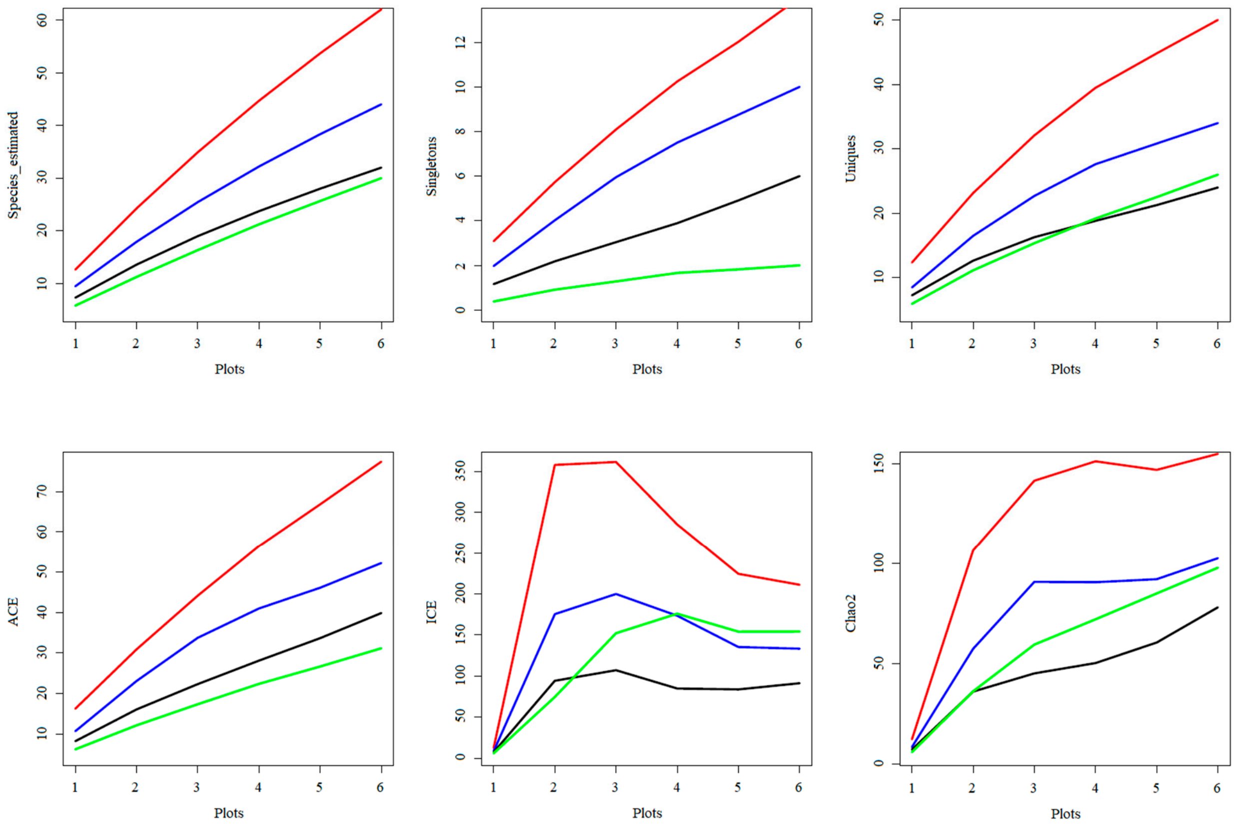


Figure 5. The variance of estimated species, rarity, and richness in plots 1–6 of L_transect. Red = transect w at a distance of 5 m to river channel; blue = transect x at a distance of 25 m; black = transect y at a distance of 45 m; and green = transect z at a distance of 65 m.

Singletons were more frequent close to the river channel but decreased with distance away from the river (Figure 5). Along transect_z the greatest number of *Singletons* was 65 m away from the river. However, this pattern was primarily due to the presence of only one species, namely *Clausena excavata* Burm. f. All other *Singletons* were more frequent at distances of 45 m, 25 m, and 5 m, without a distinct turning point. The maximum frequency of *Singletons* occurred in transect_w, which supported thirteen singleton species: *Trema tomentosum* (Roxb.) H. Hara, *Ipomoea nil* (L.) Roth (exotic), *Senna siamea* (Lam.) H. S. Irwin and Barneby, *Lotus corniculatus* L., *Lecanthus peduncularis* (Royle) Wedd., *Ficus religiosa* L., *Centella asiatica* (L.) Urb, *Alternanthera philoxeroides* (Mart.) Griseb. (exotic), *Phyla nodiflora* (L.) Greene, *Hylodesmum podocarpum* (DC.) H. Ohashi and R. R. Mill, *Macaranga denticulata* (Blume.) Müll. Arg., *Grewia biloba* G. Don, and *T. parasitica*. More species were also distributed in the transects close to the river channel, where individuals were small and rare. Ground substrates were critical to the growing and regeneration processes of most terrestrial plants. Conversely, irregular river tides, e.g., seasonal floods, removed riverbank substances, and organic fertilizer. Only a few plant species could tolerate the tidal range conditions, including the following: *Cynodon dactylon* (L.) Pers, *A. hispidus*, *Bidens pilosa* L. (exotic), *Eleusine indica* (L.) Gaertn., *Parthenium hysterophorus* L. (exotic), and *Cyperus rotundus* L. These species tolerate tidal conditions due to their annual regeneration of underground roots.

Uniques increased along all four transects, indicating that species were preferentially situated further down the course of the river (Figure 5). Transect_w, which was located closer to the river channel, was adequately irrigated. The impacts of river scouring on the habitats in transect_w differed according to the physical conditions: ground substance, flow speed, runoff, etc. Nutrients in the water were deposited randomly along the river channel. These unpredictable factors were associated with the living habitats along the river channel. Therefore, flood-tolerant species in various river segments also differed. Additional species co-habited or co-occurred in plots with other species along the course of the river, e.g., *Commelina communis* L. and *Euphorbia thymifolia* L. in the upper river, *Leucaena leucocephala* (Lam.) de Wit and *Calotropis gigantea* (L.) W. T. Aiton in the middle, and *Melia azedarach* L. and *Markhamia stipulate* (Wall) Seem in the lower river.

ACE, *ICE*, and *Chao2* had differing distributions. The *ACE* curve deviated considerably from *ICE* and *Chao2*, which may indicate that the models were incompatible (Figure 5). In contrast, ICE and *Chao2* appeared reliable. Turning points occurred within plots 3 and 4, while species richness was significantly lower in the outer transects than in the riverine transects.

3.4. P-Transect and the Variance of Expected Species, Rarity, and Abundance Indices

Species_estimated increased without an asymptote approximation, except for along transect_a. This indicated that newly reported species in the sampling plots were expected from riverine plot 1 to plot 4, at the bank slope (Figure 6). Habitat heterogeneity also increased along the transect, with shifting species composition. The riverine plots were dominated by hydrophilic species, e.g., *Centella asiatica* (L.) Urb, *Colocasia* esculenta (L.) Schott, *Phyla nodiflora* (L.) Greene, *Lindernia procumbens* (Krock.) Philcox, *Eclipta prostrate* (L.) L., *Juncus prismatocarpus* R. Br, *Commelina communis* L., *P. lapathifolia*, *Polygonum plebeium* R. Br., and seedlings of *Phragmites australis* (Cav.) Trin. ex Steud. The slope plots further from the river were more strongly colonized by xerophytic species, e.g., *P. gangeticus*, *Flemingia macrophylla* (Willd.) Kuntze ex Merr, *Pistacia weinmanniifolia* J. Poisson ex Franch., *Barleria cristata* L., *Senna siamea* (Lam.) H. S. Irwin and Barneby, *Cipadessa baccifera* (Roxb. ex Roth) Miq., *Calotropis gigantea* (L.) W. T. Aiton, and *Dodonaea viscosa* Jacq. In general, the number of species close to the river channel was higher than in plots that were further away. However, the increase in species in the tidal range did not correspond to denser vegetation, because tidal species were ephemeral and small. In the plots further away from the riverbank, there was minimal soil erosion and increasing vegetative cover with distance up the slope (Figure 6). Extensive plant colonization of the riverbanks will also have facilitated ecosystem resilience to irregular river flow.

Overall, *Singletons* were more frequently observed in the lower river transects in comparison with the upper. The lines of transect_a and transect_d progressively increased towards an asymptote of 1 (Figure 6). This pattern was large due to a sole species with only one individual in the pooled plots of each transect. According to field results, *Ixeris polycephala* Cass. and *Allium chinense* G. Don. were observed separately in the plots in these two transects. Trends were clearer in transects b, c, e, and f.

Uniques increased along transects b, e, and f, which indicated that more additional species were found, within exclusive habitats (Figure 6). However, the trends sloped down gradually in transects a, c, and d, with earlier turning points, reflecting habitat homogeneity.

Indices *ACE, ICE,* and *Chao2* all relate to species richness, thus are expected to show similar trends. However, the plots indicate that *ACE* deviated considerably from *ICE* and *Chao2* (Figure 6), meaning that the coverage-based estimates of abundance were not comparable with the other two indices. For all transects, *ICE* and *Chao2* increased from plot 1 to plot 2, then reached a turning point thereafter. These turning points indicate declining species richness according to tidal range and water supply shortage. Irregular river tides offered a homogeneous habitat to all species and rapidly removed large plants from their habitats (Figure 7). Several species grew primarily apart from the river channel: *Cynodon dactylon* (L.) Pers., *Helicteres angustifolia* L., *Barleria cristata* L., *Phragmites australis* (Cav.) Trin. ex Steud., and exotic species *Leucaena leucocephala* (Lam.) de Wit.

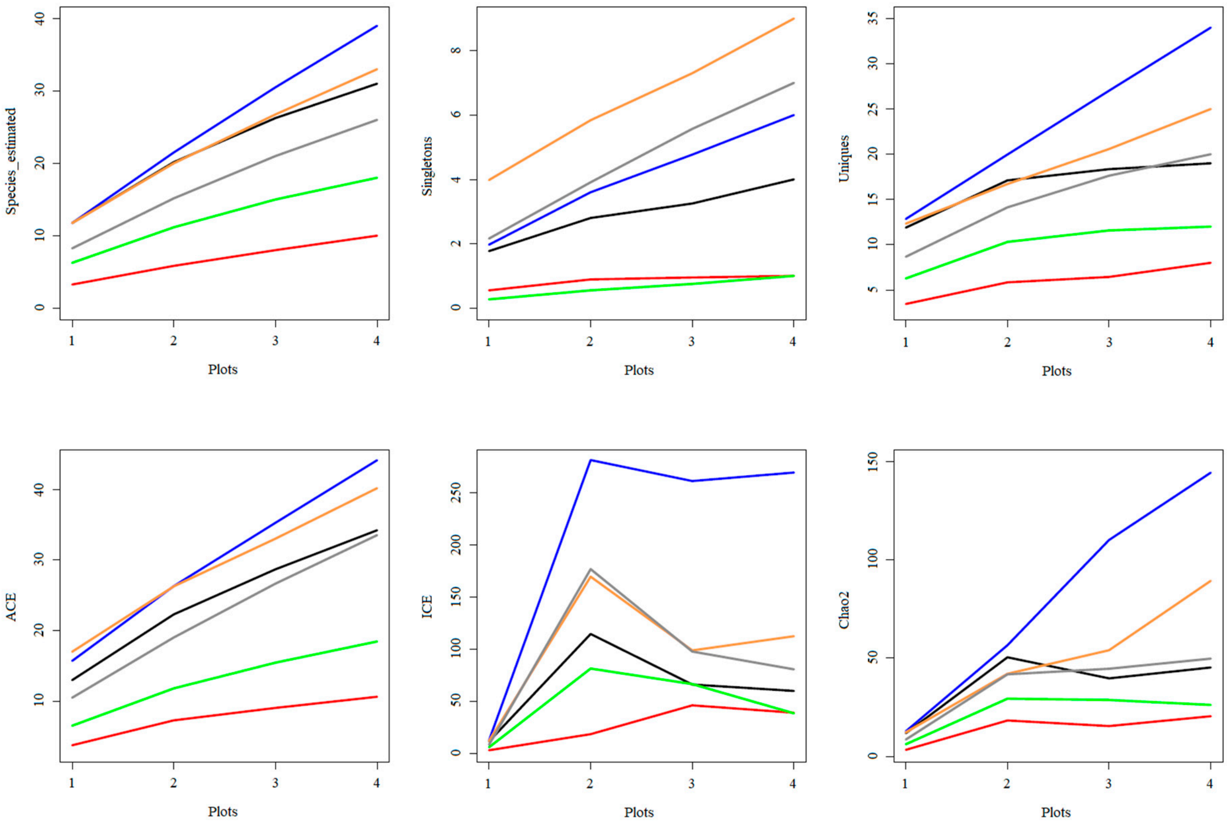


Figure 6. The variance of estimated species, rarity, and richness indices in plots 1–4 of P_transect. Red, blue, black, green, yellow, and gray lines indicate transects a–f, respectively.

Figure 7. Tidal range in Yuanjiang dry–hot valley. (**A**) River channel in low flow; (**B**) *Solanum virginianum*.

3.5. Indicator Species

Six species were potential environmental indicator species, based on the closeness of their habitat associations. These were *Leucaena leucocephala* (Lam.) de Wit (p = 0.002 **, exotic and worldwide), *Phragmites australis* (Cav.) Trin. ex Steud. (p = 0.015 *, native and worldwide), *Solanum virginianum* L. (p = 0.019 *, native and regional), *Axonopus compressus* (Sw.) Beauv (p = 0.019 *, exotic and worldwide), *Hylodesmum podocarpum* (DC.) H. Ohashi and R. R. Mill (p = 0.018 *, native and worldwide), and *Ageratum conyzoides* L. (p = 0.011 *, exotic and worldwide), * Means significant level while ** means extremely significant. Five of these species were distributed worldwide and so are considered unsuitable environmental indicators. The most suitable indicator species was *Solanum virginianum* L., which was recorded as typically colonizing sandy riverbanks at altitudes of 100–1300 m *a.s.l.*, with only native and regional distribution (Figure 7B).

3.6. Physical and Chemical Conditions of Surface Soil

Base rocks were mainly composed of dolomite, limestone, sandstone, shale, limestone, and conglomerate. Rock types were poorly integrated due to frequent thermal expansion and contraction. The surface soil was rich in chemical elements (except for phosphorus) but with relative nutrient distribution varying along the transects (Figure 8). Along the L-transects, total phosphorous (TP) and total potassium (TK) were higher on flatter ground, whereas total nitrogen (TN) and organic matter (OM) were higher on steeper slopes. For TN and OM there was a similar pattern for the Shannon–Weiner index (Figure 3 L) and species (Figure 4 L). Across P-transects all measured nutrients were aggregated towards the lower sections of the river, corresponding to an increased number of species (Figure 4 P).

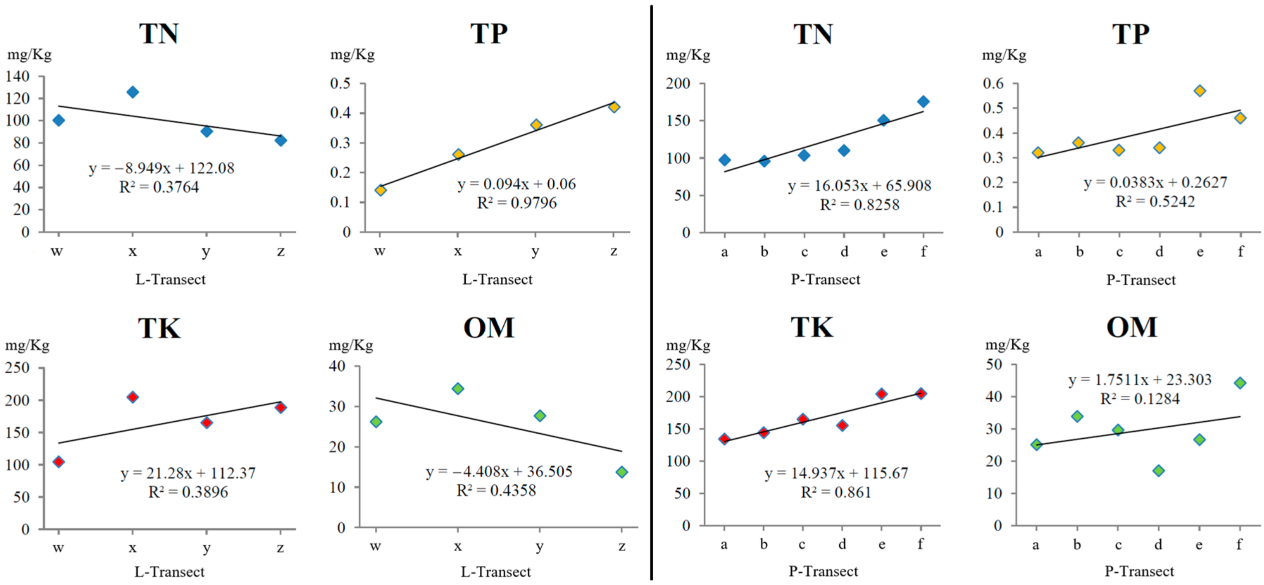


Figure 8. Nutrients in ground surface soil in the studied transects.

4. Discussion

4.1. Water Condition and Plant Distribution

Overall, a sufficient water supply was required to maintain the growth of plants and optimal population size. In this study, the variance of estimated species, rarity, and richness in the P-transects revealed the relationship between water supply and plants in Yuanjiang dry–hot valley. First, the distributions of *Singletons* and *Uniques* differed according to the distance to the riverbank. The indices in the lower river transects were stronger than those in the upper, while more new species and unitary habitats were accessed. Second, richness (*ACE*, *ICE*, and *Chao2*) revealed that more species appeared in the tidal range, with a declining number of species with increasing distance away from the river. Therefore, plants at low altitudes in the valley were strongly influenced by the water supply in soil and air. Nonetheless, atmospheric moisture in the valley was too low to support more plant species, and thus, epiphytic plants were absent. With inadequate precipitation, the plants in the Yuanjiang valley will rely on ground water supplies. We consider that water supply was a decisive factor in determining the distribution of living plants [25]. Therefore, species richness was interpreted as a reflection of environmental humidity or an optimal combination of humidity and mild temperature. The subsurface filtration from the river channel was the primary water supply for plants. Tidal vegetation is likely to reduce the erosion of channels in the fluvial and tidal zones [26]. The results of this study showed that tidal plants noticeably differed on a contrasting larger scale. Tidal vegetation was rich in species but poor in biomass. Therefore, the population could not flourish because of irregular expansion or shrinking due to the tides.

4.2. Soil Condition and Plant Distribution

Among the environmental processes that determined the diversity in ecological communities, species-dependent mechanisms were mediated by soil variability. Higher variability in soil conditions can increase niche partitioning but also increase the risk of species extinctions [27]. The dry red sandy loam in Yuanjiang dry–hot valley was a thin layer of topsoil with low nutrients and water retention. Moreover, soil leaching in the rainy season also exacerbated the degradation and nutrient losses on a relatively steep mountain slope (>20°). The ground vegetation closely corresponded to soil fertility [28]. The species number declined significantly ($p < 0.05$) from transect_w to transect_z of this study (Figure 4 L). The physical traits of surface soil also influence distribution patterns of plants in Yuanjiang dry–hot valley, which were strongly associated with the diversity index. It was reported that dry open woodland with a complex community has the highest soil fertility [9]. This forest type was found in narrow strips along the river channel.

4.3. Heterogeneous Habitats in the Valley

Xeric plants comprise a high proportion of the species in the research sites. Their distribution in the plots was ascribed to frequent hot and dry air coupled with habitat deterioration, such as substance rock fragmentation and surface soil erosion. Such processes have worsened in recent decades, which has resulted in dramatically declining environmental quality. Plant growth was associated with habitat characteristics, which depended on diverse environmental factors. The habitat heterogeneity hypothesis [29] assumes that continuous regeneration requirements include growing substances, water supply, temperature, nutrition, etc. These requirements differed for different species. Environmental processes classified their habitat requirements accordingly [30]. For an arid ecosystem, environmental processes with varying temperatures and precipitation changes were responsible for habitat patterns [31]. Diversity also increased in heterogeneous habitats [32]. Complex and diverse habitats typically support more species than a unitary habitat. In Yuanjiang dry–hot valley, statistical analysis revealed that unitary habitats were present in P- and L-transects, indicating ecosystem decline. Disturbances with differing intensities and spatial scales have previously been considered responsible for the decline and degradation of the dry–hot valley ecosystem [33]. This study demonstrated that dry and hot conditions in the valley accelerated such disturbances and would be exacerbated under current and future global change. In Yuanjiang dry–hot valley, values for the *Bray–Curtis* index varied along the L-transect and P-transect. The differences between environmental and physical conditions were closely related to the distance to the river in L-transect. There was comparatively minor variation along the P-transect. Topographic variation in gradients of L-transect and P-transect generated a mosaic microclimate across the valley.

4.4. Environmental Indicators

Indicator species were closely correlated to one or more environmental factors. The existence or absence of species, expansion, or reduction in the population responded to the dynamic change of the environmental factors. They were optimal to indicate the environmental evolution process regarding the diversity of habitat requirements in species. Most plant indicators were strictly limited to their habitats because of their sensitivity to environmental conditions [34]. Indicator analysis in this study was based on the species matrix of all transects and plots. The chosen candidate indicators were typically xeric, although most of them had a global distribution. Eight fern species were regarded as representing diverse habitats in this valley [35].

5. Conclusions

There was a unique thermal and moisture distribution pattern in the Yuanjiang dry–hot valley, with irregular water and temperature patterns. The valley was hot and dry at a low altitude. The habitat of plants was closely correlated to environmental factors. These factors were determined by distance from the river channel and position between the upper and lower sections of the river. Heterogeneous habitats developed in the valley, which also contributed considerably to increasing plant diversity. Soil, water, and thermal conditions were associated with the formation of heterogeneous habitats. Water supply was the determinant factor for plant distribution while soil condition was the key decisive factor for water retention. Generally, plant biodiversity was low. *Solanum virginianum* L. was selected as a suitable environmental indicator for Yuanjiang dry–hot valley. Attention should be given to microhabitat protection in regional environmental management.

Author Contributions: Conceptualization, F.Y. and J.G.; methodology, F.Y. and C.S.; software, F.Y. and Q.H.; validation, F.Y., H.H. and Y.C.; formal analysis, K.P.; investigation, F.Y. and J.G.; resources, J.G.; data curation, C.S.; writing—original draft preparation, F.Y.; writing—review and editing, C.S., K.P. and K.H.; visualization, C.S. and L.L.; supervision, F.Y.; project administration, F.Y.; funding acquisition, F.Y. and L.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Research Foundation for Advanced Talents of Yibin Vocational and Technical College (grant number: ybzysc20bk03), Research Platform of Yibin Vocational and Technical College (grant number: ybzy21kypt05), Project of Science and Technology Innovation Team (grant number: ybzy21cxtd-04), Yi Mi-nority Culture Research Center of the Key Research Base of Philosophy and Social Sciences of Sichuan Province (grant number: YZWH2101), and Sichuan Province Key Lab for Bamboo Pest Control and Resource Development (grant number: ZLKF20-02). And The APC was funded by the Project of Science and Technology Innovation Team (grant number: ybzy21cxtd-04).

Institutional Review Board Statement: Not applicable.

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

Acknowledgments: We thank Fiona R. Worthy for language editing.

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

References

1. Hea, Z.; Dua, J.; Chena, L.; Zhua, X.; Lina, P.; Zhao, M.; Fan, S. Impacts of recent climate extremes on spring phenology in arid-mountain ecosystems in China. *Agric. For. Meteorol.* **2018**, *260–261*, 31–40. [CrossRef]
2. Jina, J.; Wang, Q.; Wanga, J.; Otienoc, D. Tracing water and energy fluxes and reflectance in an arid ecosystem using the integrated model SCOPE. *J. Environ. Manag.* **2018**, *231*, 1082–1090. [CrossRef] [PubMed]
3. Srivastava, P.; Singh, R.; Tripathi, S.; Singh, H.; Raghubanshi, A. Understanding the complex interaction between soil N availability and soil C dynamics under changing climate conditions. *Soil Manag. Clim. Chang.* **2018**, *20*, 337–348. [CrossRef]
4. Ochoa-Hueso, R.; Delgado-Baquerizo, M.; Risch, A.C.; Schrama, M.; Morriën, E.; Barmentlo, S.H.; Geisen, S.; Hannula, S.E.; Resch, M.C.; Snoek, B.L.; et al. Ecosystem coupling: A unifying framework to understand the functioning and recovery of ecosystems. *One Earth* **2021**, *4*, 951–966. [CrossRef]
5. Tang, B.; Clark, J.S.; Marra, P.P. Modeling Community Dynamics Through Environmental Effects, Species Interactions and Movement. *J. Agric. Biol. Environ. Stat.* **2023**, *28*, 178–195. [CrossRef]
6. Dong, Y.; Xiong, D.; Su, Z.A.; Li, J.; Yang, D.; Shi, L.; Liu, G. The distribution of and factors influencing the vegetation in a gully in the Dry-hot Valley of southwest China. *Catena* **2014**, *116*, 60–67. [CrossRef]
7. Wang, X.; Zhao, L.; Yan, B.; Shi, L.; Liu, G.; He, Y. Morphological and physiological responses of Heteropogon contortus to drought stress in a dry-hot valley. *Bot. Stud.* **2016**, *57*, 17. [CrossRef]

8. Abotsi, K.E.; Bose, R.; Adjossou, K.; Deblauwe, V.; Rouhan, G.; Segla, K.N.; Atsri, K.H.; Kokou, K. Ecological drivers of pteridophyte diversity and distribution in Togo (West Africa). *Ecol. Indic.* **2020**, *108*, 105741. [CrossRef]
9. Ding, J.; Delgado-Baquerizo, M.; Wang, J.-T.; Eldridge, D.J. Ecosystem functions are related to tree diversity in forests but soil biodiversity in open woodlands and shrublands. *J. Ecol.* **2021**, *109*, 4158–4170. [CrossRef]
10. Schoenbohm, L.M.; Burchfiel, B.C.; Liangzhong, C.; Jiyun, Y. Exhumation of the Ailao Shan shear zone recorded by Cenozoic sedimentary rocks, Yunnan Province, China. *Tectonics* **2005**, *24*, TC6015. [CrossRef]
11. Jost, L. Partitioning diversity into independent alpha and beta components. *Ecology* **2007**, *88*, 2427–2439. [CrossRef]
12. Colwell, R.K. EstimateS: Statistical Estimation of Species Richness and Shared Species from Samples. Version 9.1. 2012 User's Guide and Application Published at 2016. Available online: http://viceroy.eeb.uconn.edu/estimates/EstimateSPages/AboutEstimateS.htm (accessed on 14 July 2016).
13. Colwell, R.K.; Chao, A.; Gotelli, N.J.; Lin, S.Y.; Mao, C.X.; Chazdon, R.L.; Longino, J.T. Models and estimators linking individual-based and sample-based rarefaction, extrapolation and comparison of assemblages. *J. Plant Ecol.* **2012**, *5*, 3–21. [CrossRef]
14. Budka, A.; Łacka, A.; Szoszkiewicz, K. Estimation of river ecosystem biodiversity based on the Chao estimator. *Biodivers. Conserv.* **2018**, *27*, 205–216. [CrossRef]
15. Xia, Y.; Sun, J. Introduction to Generalized Linear Mixed Models. In *Bioinformatic and Statistical Analysis of Microbiome Data*; Springer: Cham, Switzerland, 2023. [CrossRef]
16. Oksanen, J.; Simpson, G.; Blanchet, F.G.; Kindt, R.; Legendre, P.; Minchin, P.; O'hara, R.; Solymos, P.; Stevens, H.; Szöcs, E.; et al. Package 'Vegan' Community Ecology Package Version 2.6-8. Available online: https://cran.r-project.org/web/packages/vegan/vegan.pdf (accessed on 28 August 2024).
17. Shapiro, S.S.; Wilk, M.B. An analysis of variance test for normality (complete samples). *Biometrika* **1965**, *52*, 591–611. Available online: https://www.jstor.org/stable/2333709 (accessed on 16 April 2022). [CrossRef]
18. Lee, S.; Lee, D.K. What is the proper way to apply the multiple comparison test? *Korean J. Anesthesiol.* **2020**, *73*, 572. [CrossRef] [PubMed]
19. Cáceres, M.; Legendre, P. Associations between species and groups of sites: Indices and statistical inference. *Ecology* **2009**, *90*, 3566–3574. [CrossRef] [PubMed]
20. Zeitoun, R.; Biswas, A. Review—Potentiometric Determination of Phosphate Using Cobalt: A Review. *J. Electrochem. Soc.* **2020**, *167*, 127507. [CrossRef]
21. Xia, X.; Li, M.; Liu, H.; Zhu, Q.; Huang, D. Soil Organic Matter Detection Based on Pyrolysis and Electronic Nose Combined with Multi-Feature Data Fusion Optimization. *Agriculture* **2022**, *12*, 1540. [CrossRef]
22. Aguirre, J. The Kjeldahl Method. In *The Kjeldahl Method: 140 Years*; Springer: Cham, Switzerland, 2023. [CrossRef]
23. Yang, J.; Bai, J.W.; Liu, M.Y.; Chen, Y.; Wang, S.T.; Yang, Q.Y. Determination of Phosphorus in Soil by ICP-OES Using an Improved Standard Addition Method. *J. Anal. Methods Chem.* **2018**, *2018*, 1324751. [CrossRef]
24. He, Y.L.; Zhang, Y.P.; Wu, Z.J. Analysis of climate variability in the Jinsha river valley. *J. Trop. Meteorol.* **2016**, *22*, 243–251.
25. Dubbert, M.; Couvreur, V.; Kübert, A.; Werner, C. Plant water uptake modelling: Added value of cross-disciplinary approaches. *Plant Biol.* **2023**, *25*, 32–42. [CrossRef] [PubMed]
26. Temmerman, S.; Bouma, T.J.; Van de Koppel, J.; Van der Wal, D.; De Vries, M.B.; Herman, P.M.J. Vegetation causes channel erosion in a tidal landscape. *Geology* **2007**, *35*, 631–634. [CrossRef]
27. Fung, T.; Chisholm, R.A.; Anderson-Teixeira, K.; Bourg, N.; Brockelman, W.Y.; Bunyavejchewin, S.; Chang-Yang, C.; Chitra-Tarak, R.; Chuyong, G.; Condit, R.; et al. Temporal population variability in local forest communities has mixed effects on tree species richness across a latitudinal gradient. *Ecol. Lett.* **2019**, *23*, 160–171. [CrossRef]
28. Heydari, M.; Zeynali, N.; Bazgir, M.; Omidipour, R.; Kohzadian, M.; Sagar, R.; Prevosto, B. Rapid recovery of the vegetation diversity and soil fertility after cropland abandonment in a semiarid oak ecosystem: An approach based on plant functional groups. *Ecol. Eng.* **2020**, *155*, 105963. [CrossRef]
29. Heidrich, L.; Bae, S.; Levick, S. Heterogeneity–diversity relationships differ between and within trophic levels in temperate forests. *Nat. Ecol. Evol.* **2020**, *4*, 1204–1212. [CrossRef]
30. Sarathchandra, C.; Abebe, Y.A.; Worthy, F.R.; Wijerathne, I.L.; Ma, H.; Yingfeng, B.; Jiayu, G.; Chen, H.; Yan, Q.; Geng, Y.; et al. Impact of land use and land cover changes on carbon storage in rubber dominated tropical Xishuangbanna, South West China. *Ecosyst. Health Sustain.* **2021**, *7*, 1915183. [CrossRef]
31. Ganguly, T.; Arya, D.S.; Paul, P.K. Spatio-temporal patterns of precipitation in arid and semi-arid regions in western India. *J. Earth Syst. Sci.* **2023**, *132*, 71. [CrossRef]
32. Deák, B.; Kovács, B.; Rádai, Z.; Apostolova, I.; Kelemen, A.; Kiss, R.; Lukács, K.; Palpurina, S.; Sopotlieva, D.; Báthori, F.; et al. Linking environmental heterogeneity and plant diversity: The ecological role of small natural features in homogeneous landscapes. *Sci. Total Environ.* **2021**, *763*, 144199. [CrossRef]
33. Chen, M.; Tan, Y.; Xu, X.; Lin, Y. Identifying ecological degradation and restoration zone based on ecosystem quality: A case study of Yangtze River Delta. *Appl. Geogr.* **2024**, *162*, 103149. [CrossRef]

34. Scharwies, J.D.; Dinneny, J.R. Water transport, perception, and response in plants. *J. Plant Res.* **2019**, *132*, 311–324. [CrossRef]
35. Yang, F.C.; Mao, X.Y.; Liu, J.X.; Huang, H.P.; Li, Y.; Gou, J.Y.; Wen, H.T. Variation of Major Environmental Factors (Temperature and Precipitation) in Yuanjiang Dry-hot Valley and the Response of Pteridophytes. *J. Trop. Subtrop. Bot.* **2020**, *28*, 537–546. (In Chinese with English Abstract) [CrossRef]