Responses to the Editor and the Reviewer:

We thank the editor and the reviewer for the time they spent evaluating our manuscript and providing constructive comments. Their detailed comments helped us to further improve the quality of this manuscript. We have gone through all the comments and modified the original manuscript based on the suggestions and comments. In the following pages we provide point-by-point responses to the editor's and the reviewer's comments. Please refer to the attached manuscript with track-changes mode for further details.

Responses to the Editor:

Editor: Referee number 4 has provided a set of comments that can further improve the manuscript. While I have essentially recommended publication, I urge the authors to make use of referee #4 ́s comments as a minor revision.

Authors: We thank the editor for giving us a valuable chance to further improve this manuscript and thank the reviewer#4 for giving detailed comments and suggestions for this manuscript. We have gone through all the comments and amended the original manuscript based on the suggestions and comments.

Responses to the Reviwer#4:

Major issues:

Reviewer: While this manuscript (MS) is interesting and at this stage pretty well written, there are still several ambiguities and shortcomings. After I read the MS I went back to the first round of reviews to see what comments other referees had, and to my surprise I recognized some of my own comments there. That is, some comments from the first round are still valid and have not been properly addressed.

Authors: We thank the reviewer for giving us constructive suggestions and detailed comments to improve the quality of this manuscript. Following the reviewer's comment on the unaddressed comments during the first round of review in this manuscript, we have carefully checked the comments and amended these unaddressed comments in the manuscript (e.g., the definition of variables and the description of data collection; please see refer to the responses to comments below). We have further revised the language throughout the manuscript and the supplementary material to avoid the ambiguities in expression.

Reviewer: All in all, the language in the main text of the MS is fine now (though I found some wordings that sound strange to me, especially in the Introduction, and the language of the Supplementary, especially S4, needs improvement), but the presentation is still unclear in certain parts of the MS. For instance, in the Discussion it was at times not clear to me what are results/conclusions of this work and what is conclusions from the literature (this comment also applies to parts of the Introduction). This may be a language issue, since past tense is used throughout, even for previously published results. This usage gives the impression that the authors are talking about their results although they are actually discussing results from the literature. An example: “Bulk density accounted for 13.51% of the total explanation of the vegetation variance and was negatively correlated with the annual average NDVI (NDVI_a) and the annual variability of NDVI (NDVI_c). In the hyperarid zone, soils with high bulk density were often characterized as having a high proportion of coarse soil particles but low clay content” (P21, lines 18-22). I guess the first sentence here refers to results from this study whereas the second sentence refers to the literature. However, the usage of “were” instead of “are” in the second sentence give the impression that this is a result of the present study (though this has not been shown in the MS). This kind of wording is very confusing, but common throughout the Discussion (see also e.g. P19, lines 12-19) and Introduction.

Authors: We thank the reviewer for pointing out the language issues in the manuscript and the supplementary material. We have carefully revised language throughout the manuscript and the supplementary material, especially the Introduction and Discussion section in the manuscript and S4 in the supplementary material.

Based on the reviewer’s comments on the unclear presentation in Introduction and Discussion section, we use the present tense when depicting the results from literature and we added the depiction such as “Study shows that” when refer to the literature throughout the manuscript and the supplementary material. As to the example “P21 lines 18-22” put by the reviewer, please see the revised sentences in the manuscript at Page 24 Line 16-21: “Bulk density accounted for 13.51% of the total explanation of the vegetation variance and was negatively correlated with the annual average of NDVI (NDVI_a) and the annual variability of NDVI (NDVI_c). Study shows that, in the hyperarid zone, soils with high bulk density are often characterized by a high proportion of coarse soil particles but low clay content (Ravi et al., 2009).” As to the example “P19, lines 12-19” put by the reviewer, please see the revised sentences in the manuscript at Page 21 Line 28- Page 22 Line 10: “At the same time, other study find that the presence of the deep-rooted tree, *Populus euphratica*, can redistribute deep soil water to the shallow layer as a strategy of mutualism, benefiting the growth of shallow-rooted herbaceous species (Hao et al., 2013). Similar mechanism also occurs at further distance (i.e., 3000 m) from the river. Although situated in the transition region (from riparian forest to desert shrubs), soils at the distance of 3000 m from river channel were still rich in fine particles (clay and silt; 35.6%) (Table S3), brought by the interaction between wind erosion and shrubs (Ravi et al., 2009). The presence of fine soil particles can increase the soil water holding capacity and soil nutrients around the shrub patches (‘fertile islands’) (Ravi et al., 2010), allowing the growth of some xerophytic herbs and increasing the community diversity in arid region (Stavi et al., 2008)”.

Reviewer: Some of the sampling procedures and monitoring require better descriptions (and this was one of the comments from the first round of reviews). For instance, how were the vegetation quadrats chosen? Randomly? How does the groundwater monitoring transect look like (e.g. how many wells, how deep were the wells, what was the precision and accuracy of the HOBOs and at what distances from the river were the wells located)? Same thing with soil moisture monitoring – where was this done? At how many sites? And where were the sites located? Adding the locations of these monitoring sites to the map would be helpful.

Authors: Following the reviewer's suggestion, we added all the descriptions of the sampling procedures and monitoring data in the Methods section. The vegetation quadrats were chosen randomly. We added the description in the Method section. Please see Page 8 Line 8-9 in the manuscript: "Three tree quadrats (30 m × 30 m) and shrub quadrats (10 m × 10 m) were established randomly at each site." In addition, we also added the detailed information on the acquisition of soil properties. Please see Page 8 Line 20-30 in the manuscript: "Soil samples were collected every 20 cm at a depth of 100 cm in each site to determine the soil composition and chemical properties. Surface soil samples (from a depth of 0–20 cm) were subsequently analyzed in the laboratory to determine their clay (<0.002 mm), silt (0.002–0.05 mm), sand (0.05–2 mm), and gravel (>2 mm) content using a Malvern Mastersizer 2000. Soil organic matter (SOM) was measured using the $K_2Cr_2O_7$ method (Liu, 1996). Total nitrogen (TN) was determined using the Kjeldahl procedure (ISSCAS, 1978). Total phosphorus (TP) was determined using a UT–1810PC spectrophotometer (PERSEE, Beijing, China), after H_2SO_4–$HClO_4$ digestion (ISSCAS, 1978). Total salt content (TS) was determined by oven method (Liu, 1996)".

The detailed information of the groundwater monitoring points (including the locations of wells and accuracy of HOBOs) was added in the Methods section. Please see Page 9 Line 17-23 in the manuscript: "The spatial variation of groundwater table was obtained from groundwater monitoring data recorded by seven wells (i.e., 7.62–9.66 m deep) in the Ejina oasis, located at 50 m, 300 m, 2200 m, 2700 m, 3200 m, and 3700 m from the river center (Fig. 1). These monitoring data of the groundwater table were recorded as 18-hour averages with a three decimal places accuracy using a HOBO automatic groundwater table gauge from October 2010 to December 2014 (Fu et al., 2014)".

We also added the following description of soil moisture monitoring point. Please see Page 9 Line 23-28 in the manuscript: "The diurnal and annual variations of soil moisture were obtained from the monitoring data of soil moisture, recorded at 0.5 Hz, as a 10-min average from 2013–2015 using a suite of micrometeorological sensors (CR800, CR23X, CR23XTD, Campbell Scientific Inc.) installed at a site that is located within Heihe riparian forest, about 1500 m from the Heihe river channel (Fig. 1) (doi:10.3972/hiwater.241.2015.db; doi:10.3972/hiwater.318.2016.db) (Liu et al., 2011)".

In addition, we added locations of these monitoring points in the map of study area (Fig. 1B). Please see Page 7 Figure 1 in the manuscript.

Reviewer: I am not familiar with all the indices used in the manuscript but I found the description of some of them incomplete. For example, how are the variables/parameters in equations 1 and 2 defined? Also, could you please cite a source for this method? What does A and Ai stand for in equation 4? What do you mean by "importance value" (P. 10, line 26)? The variables TN, TP and TS are never defined – what do they stand for (again, this was a comment by one of the first referees)? How is riparian zone defined? Based on distance, geomorphology, soil properties, topography or something else?

Authors: We thank the reviewer for pointing out the incomplete presentation. We have carefully revised these problems and checked the similar issues throughout the whole manuscript.

Following the reviewers' suggestion, we added the explanation and reference resource on the variables in equation1 and 2. Please see Page 10 Line 10-11 in the manuscript: "where P_{Tree} is the importance value in the tree layer. $P_{\text{Shrub or Grass}}$ is the importance value in the shrub or grass layer". A reference for the method (i.e. Zhang, 2011) was also added in the manuscript (Page 10 Line 7).

A is the total diversity index of the community; A_i is the diversity index of the i^{th} growth type. We added the explanation in the manuscript. Please see Page 10 Line 27- Page 11 Line 1 in the manuscript: "where A is the total diversity index of the community; $i = 1$ for the tree layer, 2 for the shrub layer and 3 for the herb layer; W_i is the weighted parameters of the diversity index for the i^{th} growth type; A_i is the diversity index of the i^{th} growth type". In addition, we also revised the definition of variables in equation 5-8. Please see Page 11 Line 12-13 in the manuscript: "where P_i is the relative importance value of the i^{th} species, and S is the total number of species in each growth type at each sampling site".

The importance value is an index that depicts the relative importance of plant species in the community. We added the explanation in the manuscript. Please see Page 10 Line 4-7 in the manuscript: "The importance value (P), an index that characterizes the relative importance of plant species in the community (Zhang and Dong, 2010) was calculated for each species at each tree shrub and herb layer in every sampling site using the following formulas (Zhang, 2011)".

We apologize for not defining the variables TN, TP and TS in the main text of the manuscript. We added the definition of these variables when it first appeared in the manuscript. Please see Page 8 Line 26-30 in the manuscript: "Soil organic matter (SOM) was measured using the $K_2Cr_2O_7$ method (Liu, 1996). Total nitrogen (TN) was determined using the Kjeldahl procedure (ISSCAS, 1978). Total phosphorus (TP) was determined using a UT–1810PC spectrophotometer (PERSEE, Beijing, China), after H_2SO_4–$HClO_4$ digestion (ISSCAS, 1978). Total salt content (TS) was determined by oven method (Liu, 1996)." We carefully checked the similar issues throughout the manuscript. We revised the variables in the note of table. Please see Page 21 Line 1-7 in the manuscript: "a: spatial distribution factors, including 0–30 cm soil moisture (SWC1), 30–100 cm soil moisture (SWC2), 100–200 cm soil moisture (SWC3), bulk density (BD), clay, silt, sand, gravel, soil organic matter (SOM), total nitrogen (TN), total phosphorus (TP), total salt content (TS); b: temporal factors, including annual average of groundwater table (GWT_a), annual average of 2 cm soil moisture (SWC2cm_a), annual average of 100 cm soil moisture (SWC100cm_a), annual variability of groundwater table (GWT_c), annual variability of 2 cm soil moisture (SWC2cm_c), annual variability of 100 cm soil moisture (SWC100cm_c)". We also added the definition of the diversity indices when they first appeared in the manuscript. Please see Page 11 Line 3-10 in the manuscript: "Species diversity indices were calculated (Liu et al., 1997), including the Shannon-Wiener diversity index (H); Simpson dominance index (D) was calculated as; and Pielou evenness index (J_{sw}) was calculated as; Finally, Patrick richness index (R) was calculated as". In addition, we revised the definition of variables in the Supplementary

Material S5. Please see Page 6 Line 13-16 in the Supplementary Material: "SOM (soil organic matter), TN (total nitrogen) and TP (total phosphorus) generally decreased along the distance from river channel and reached a relatively high value at the distances of 500 m and 2000–2500 m. TS (total salt content) peaked at the distance of 1000 m (2.57%) (Table S3) and dropped gradually".

We added the definition of the riparian zone in the Introduction section. Please see Page 2 Line 23-27 in the manuscript: "Riparian zone is the linkage between terrestrial and aquatic ecosystems (Naiman and Décamps, 1997), which is usually defined as the stream channel between the low- and the high-water marks, in addition to the terrestrial landscape above the high-water mark. Consequently, vegetation in the riparian zone is likely to be influenced by elevated water tables or extreme flooding and by the ability of soils to hold water (Nilsson and Berggren 2000)." We also completed the explanation on how we choose the sampling range of the riparian zone in the downstream Heihe. Please see Page 7 Line 8-14 in the manuscript: "However, the spatial extent of the riparian zone is difficult to precisely delineate due to the heterogeneity of the landforms (Décamps et al., 2004). Although previous studies indicates that the forests are distributed between 0 m and 2000 m from the river channel, corresponding to the influence range of ecological water conveyance (Si et al., 2005), our study extended beyond that range (i.e., up to 3000 m from the river channel) to fully cover the distribution pattern of the desert riparian forests in downstream Heihe River".

Reviewer: Not all data are reported. The soil characteristics, which are key to the paper, are never reported. Why not add a table with those data?

Authors: We thank the reviewer for this suggestion. We added the Table S3 to depict the characteristics of environmental factors (including soil characteristics and groundwater) at different distances from the river channel. Please see Page 8 Table S3 in the Supplementary Material: "The characteristics of environmental factors at different distances from river channel".

Reviewer: Some of the supplementary material is not referred to in the main text. If it is essential for the MS, it should be referred to.

Authors: We thank the reviewer for the suggestion. We have carefully checked and added the reference of each supplementary material. We added the reference of Figure S2 in the manuscript. Please see Page 11 Line 17-19: "The monitoring data of soil moisture in desert riparian forest showed that soil moisture under 20 cm was relatively stable and could represent water condition at the sampling site (Fig. S1)." We added the reference of Table S2 in the manuscript. Please see Page 11 Line 14-15: "The least significant difference (LSD) test was used to determine the significance of the variability in vegetation characteristics among five transects (Supplementary Material S3, Table S2)." We added the reference of Table S3 in the manuscript. Please see Page 22 Line 4-7: "Although situated in the transition region (from riparian forest to desert shrubs), soils at the distance of 3000 m from river channel were still rich in fine particles (clay and silt; 35.6%) (Table S3), brought by the interaction between wind erosion and shrubs (Ravi et al., 2009)." We added the reference of Figure S7 in the manuscript. Please see Page 20 Line 5-7: "When combined, these factors explained 15.2% of the community characteristics variation, accounting for 34.3% of the total explanation that was explained by all the investigated environmental factors (Fig. S7)".

Reviewer: Based on the history of this MS I perhaps should recommend rejection, especially since not all previous comments have been addressed. However, the main story is interesting (though I have to admit that the topic is far beyond my own competence, not being a desert ecologist). I therefore suggest major revisions of the MS before the editor should consider it for publication.

Authors: We thank the reviewer for giving us a valuable chance to further improve this manuscript. We have amended the original manuscript based on all the suggestions and comments. Following the reviewer's comment on the unclear presentation, we have carefully checked and revised the similar issues throughout the manuscript and the supplementary material. In addition, we have carefully checked the comments and amended these unaddressed comments in the manuscript and the supplementary material (e.g., the definition of variables and the description of data collection; please refer to the responses to the major issues above).

Minor issues:

Reviewer: Detailed comments (these are only the most important minor comments I found)

Authors: We thank the reviewer for giving us these valuable and detailed comments, we have carefully revised them and checked the similar issues throughout the whole manuscript.

Reviewer: P3, line 2: what do you mean by "diversity level"? Biodiversity?

Authors: We replaced the "diversity level" with "biodiversity". Please see Page 3 Line 5-7 in the manuscript: "However, due to their low biodiversity and weak resilience, desert riparian forests are sensitive to disturbance and likely to be threatened by climate change and human disturbance (Li et al., 2013)".

Reviewer: P3, line 13: What oasis area? Do you refer to a specific oasis or oases in general?

Authors: It referred to the oasis area in the downstream Heihe. To make it clear, we revised this sentence. Please see Page 3 Line 17-21 in the manuscript: "While most of vegetation in the downstream Heihe River has been restored (Lü et al., 2015), nearly 20% of its oasis area covered by desert riparian forests remains degraded despite better downstream water conditions and the rising of groundwater table (Zhang et al., 2011a)".

Reviewer: P3, lines 18-29: I found this section confusing. You start off with general statements but then suddenly you refer to specific results. It was not clear to me what refers to desert forests in general and what is specific info about desert forests in the Heihe Basin.

Authors: We thank the reviewer for pointing this out. To make it clear, we carefully rewrote this section. Please see Page 3 Line 29- Page 4 Line 15 in the manuscript: “In hyperarid zone, groundwater is regarded the major driving factor of vegetation distributions and groundwater table should be between 2 m and 4 m deep to support vegetation growth (Zheng et al., 2005). Study in Tarim River, for example, shows that species diversity peaks where groundwater depth is around 2–4 m. Once groundwater tables falls beyond 4.5 m, a deficiency in soil moisture occurs, followed by degradation of vegetation communities (Li et al., 2013). While groundwater drops rapidly away from the river bank to approximately 6 m deep at a distance of 1000 m from Tarim River channel, (Aishan et al., 2013), groundwater table in downstream Heihe River, where most of the desert riparian forest are distributed, remains above 4 m even at the distance of 3800 m from the river channel (Wang et al., 2011; Fu et al., 2014). Yet some sites have not been completely restored in the Heihe riparian zones, and its downstream vegetation community is still dominated by shrubs instead of multiple layers of tree (He and Zhao, 2006; Zhang et al., 2011a).”

Reviewer: P4, line 5-6: Does soil moisture affect hydrological processes? Or are hydrological processes affecting soil moisture?

Authors: We apologize for the confusion of this sentence. To make it clear, we revised this sentence. Please see Page 4 Line 20-22 in the manuscript: “Apart from groundwater, soil properties, such as soil moisture, soil physical and chemical properties also shape the community characteristics and species vitality (Stirzaker et al. 1996; Salter and Williams, 1965)”.

Reviewer: P4, line 9: Are you talking about diversity or abundance? Most of the MS is about diversity so I find it strange that you talk about abundance here.

Authors: Species abundance is actually only one of the indices to depict the diversity of the community. To make the sentence easier to understand, we replaced the “abundance” with “diversity” and revised the whole sentence. Please see Page 4 Line 24-28 in the manuscript “As different depths of soil moisture affect species diversity in each community layer (D'Odorico et al., 2007; Fang et al., 2016), a decline in soil moisture may reduce the diversity of drought-sensitive species (e.g., herbs), resulting in a community shift towards drought-tolerant vegetation types with distance from the river channel (Zhu et al., 2014)”.

Reviewer: P4, line 12: Changes due to what?

Authors: In this sentence we cited the result of a research conducted in the hyperarid zone in the Tarim River to illustrate the role of soil nutrient in influencing the community dynamics. Based on grey correlation analysis, the research found that there exist significant relationship of plant species diversity with soil nutrient which suggesting that changing in soil nutrient could accounted for the changes in species diversity in the lower reaches of Tarim River. This research mainly focused on investigating the driving forces for the changes in species diversity and the reasons for changes in soil nutrient were not addressed in this research.

Reviewer: P5, line 6-8: I do not think you ever address the second part of this objective, and I do not think that you should either. I suggest you remove it; you do not present any results related to this objective ("appropriate restoration and protection measures … under a changing environment").

Authors: Following the reviewers' suggestion, we deleted this part of objectives. Please see Page 5 Line 23-25 in the manuscript.

Reviewer: P5, line 8: I suggest you use "studied" or "sampled" instead of "used".

Authors: Following the reviewer's suggestion, we replaced the word "sampled" with "studied". Please see Page 5 Line 25-28 in the manuscript: "We studied 3000 m transects running perpendicular to the river channel to include different distances from the river channel and to depict the spatial distribution of vegetation (e.g., changes in floristic composition, community structure and diversity) at each distance from the river channel".

Reviewer: P5, line 11: What sampling? You have not described any sampling thus far.

Authors: According to the reviewer's comments, we revised this sentence and deleted the "field sampling". Please see Page 5 Line 28-30 in the manuscript: "We used NDVI variations at different distances from the river channel, derived from high resolution images (e.g., 30 m resolution) from 2000–2014, to depict the temporal variation of the vegetation".

Reviewer: P6, line 5: Roads are used for transport and travel – remove this sentence, it is a tautology

Authors: Following the reviewer's suggestion, we deleted this sentence. Please see Page 6 Line 20 in the manuscript.

Reviewer: P6, line 11: I don't think these are formal soil types according to common soil classification schemes (e.g. FAO)

Authors: According to the reviewer's comments, we replaced these soil types with formal soil types. As the soil types in the downstream Heihe are intensely regional, we used formal soil types according to the Chinese soil taxonomic classification scheme referred from the book of Chinese soil geography (Gong, 2014). Please see Page 6 Line 25- Page 7 Line 1 in the manuscript: "The main soil types in the area are Gypsi Sali–Orthic Aridosols and Calcaric Aridi–Orthic Primosols. Para–alkalic Aqui–Orthic Halosols and Calcaric Ochri–Aquic Cambosols also exist in the lake basins and lowlands (Chen et al., 2014; Gong., 2014)".

Reviewer: P6, Figure 1. The second sentence is repetition from the main text – is it necessary?

Authors: Following the reviewer's suggestion, we deleted this sentence. Please see Page 7 Line 4 in the manuscript.

Reviewer: P8, line 8: 1000 m sound pretty coarse to me – what is the cause of this resolution?

Authors: In this study, temporal variation of soil moisture and groundwater were used to investigate the impact of water variability on the desert riparian forest. As there was lack of the long-term field monitoring data during 2000-2014, we used the remotely sensed dataset with 1000 m resolution to derive the temporal variation of 2 cm soil moisture, 100 cm soil moisture and groundwater at each site during the research period. The retrieved remote sensing data was generated by the land model CLM4.5 using the high-resolution ASTER DEM dataset and the multi-source integrated Chinese land cover map (MICLCover). As the resolution of Chinese land cover map (MICLCover) was 1000m, the whole retrieved remote sensing dataset was in 1000m resolution. Although the resolution of this dataset was quite coarse compared to the field sampling data, it was characterized with high temporal resolution and its temporal variation pattern could well depict the water variability during the research period. Thus we used this dataset to depict the temporal variation of water variability and its influence on the desert riparian forest. As to the accuracy of this remote sensing dataset, please see "S4 Validation of the retrieved remote sensing data" in the supplementary material.

Reviewer: P 11, line 1: what is a "contribution rate"?

Authors: To make it easier to understand, we rewrote this sentence and replaced the "contribution rate of each factor" with "the percentage of vegetation variance explained by each factor". Please see Page 12 Line 13-16 in the manuscript: "To further separate the key influencing factors of the 18 environmental variables, the marginal and conditional effects of the various variables were calculated through Monte Carlo forward selection in RDA (redundancy analysis), which directly showed the significance and the percentage of vegetation variance explained by each factor".

Reviewer: P15, lines 18-19: this is really methods description

Authors: According to the reviewer's comments, we deleted these methods description and revised the sentence. Please see Page 17 Line 16-19 in the manuscript: "The correlation coefficient between NDVI and runoff was measured to examine the relationship between runoff and NDVI (Fig. 6)".

Reviewer: P17, lines 11-13: this is really methods description

Authors: According to the reviewer's comments, we deleted these methods description and revised the sentence. Please see Page 19 Line 12-13 in the manuscript.

Reviewer: P17, lines 13-17: I do not understand all these percentages – could you clarify? Also, I guess you should refer to Fig S7 here.

Authors: These percentages represented the percentage of community characteristics variation explained by different groups of factors and the percentage they account for in the total explanation that explained by all the investigated environmental factors. To make this section easier understand, we rewrote these sentences and clarify the meaning of these percentages. Please see Page 19 Line 13- Page 20 Line 7 in the manuscript: "Spatial heterogeneity factors explained 43.5% of the variation of community characteristics and accounted for 98.4% of the variance explanation explained by all the investigated environmental factors (Table 3). This result indicated that spatial heterogeneity of environmental factors was the major driving force of the spatio-temporal variation in this desert riparian forest. In contrast, temporal variation factors only explained 15.9% of the variation of community characteristics, accounting for 35.9% of the total explanation that was explained by all the investigated environmental factors (Table 3). This result suggested that temporal variation of the environmental factors exerted less impact on community characteristics compared to spatial heterogeneity of environmental factors in this desert riparian forest. While each factor group affected community characteristics separately, the spatial heterogeneity factors and temporal variation factors also jointly shaped the variation of community characteristics in downstream Heihe riparian forest. When combined, these factors explained 15.2% of the community characteristics variation, accounting for 34.3% of the total explanation that was explained by all the investigated environmental factors (Fig. S7)".

Reviewer: P19, line 10: what does "this region" and "They" refer to?

Authors: To make it clear, we revised these sentences. Please see Page 21 Line 24-28 in the manuscript: "We attributed fine-textured soils found in the upper soil layer to the high species diversity at sites located about 1000 m from the river channel. Previous study shows that fine-textured soils increase the soil water holding capacity and improve the gravimetric moisture content in the upper soil layer, which provide suitable habitat for the growth of diverse herb species with shallow rooting systems (Liu et al., 2008)".

Reviewer: P19, line 12-19: Are these conclusions based on this study? I do not think it is possible to draw these conclusions based on the data from this study. The wording is confusing.

Authors: These conclusions were drawn based on literature study. To make it clear, we used present tense and added "study finds that" when referring to the results from literatures. Please see the revised sentences in the manuscript at Page 21 Line 28-Page22 Line10: "At the same time, other study finds that the presence of the deep-rooted tree, *Populus euphratica*, can redistribute deep soil water to the shallow layer as a strategy of mutualism, benefiting the growth of shallow-rooted herbaceous species (Hao et al., 2013). Similar mechanism also occurs at further distance (i.e., 3000 m) from the river. Although situated in the transition region (from riparian forest to desert shrubs), soils at the distance of 3000 m from river channel were still rich in fine particles (clay and silt; 35.6%) (Table S3), brought by the interaction between wind erosion and shrubs (Ravi et al., 2009). The presence of fine soil particles can increase the soil water holding capacity and soil nutrients around the shrub patches ('fertile islands') (Ravi et al., 2010), allowing the growth of some xerophytic herbs and increasing the community diversity in arid region (Stavi et al., 2008)" .

Reviewer: P20, line 4: No results presented to show this

Authors: This conclusion was drawn based on a literature study. To make it clear, we revised this sentence. Please see Page 22 Line 22-26 in the manuscript: "As the fine roots of most herb species are mainly distributed within the top 30 cm of the surface soils (Fu et al., 2014), surface soil moisture (0–30 cm soil moisture; SWC1) likely became the main water source for the herb layers and contributed to a high coverage of dominant herb species, such as *S. alopecuroides* and *K. caspica*".

Reviewer: P20, line 14: No results presented to show this

Authors: This conclusion was drawn based on a literature study. To make it clear, we revised this sentence. Please see Page 23 Line 6-9 in the manuscript: "Bulk density and soil composition (clay, silt, gravel), which are critical for water and nutrient holding capacity (Stirzaker et al., 1996; Meskinivishkaee et al., 2014), mainly influenced community density, community coverage, shrub coverage and diversity indices (Table 1)".

Reviewer: P23, lines 15-19: I do not think this paragraph is necessary and suggest that you remove it.

Authors: We thank for the reviewer's suggestion. However, we consider this paragraph necessary as it provides the reason for conducting this study. Since water availability and soil physical properties were the key factors influencing community structure in this desert riparian forest, we proposed to better protect soil conditions under climate change and intensive human activities. To illustrate the necessity of this paragraph, we revised these sentences. Please see Page 26 Line 22-29 in the manuscript: "Our study showed that water availability and spatial heterogeneity of soil properties were the main driving forces for the spatial distribution and temporal variation of restored desert riparian forest at Heihe River Basin. To halt degradation in this critical zone, we suggested to build natural channels perpendicular to the river to fully extend the influencing scope of the ecological water conveyance and benefit the regions far from the river bank (Zhang et al., 2011b). At the same time, multiple conservation measures such as establishing critical fenced areas for ecological protection and constructing artificial shields or establishing straw checker boards on the bare land to prevent erosion, were recommended around the periphery of the river".

Reviewer: P23, lines 26-27: This has not been mentioned before. I guess you could describe the ecological water conveyance better in the Introduction

Authors: Following the reviewer’s suggestion, we added the influencing range of ecological water conveyance to the Introduction section. Please see Page 3 Line 16-17 in the manuscript: “The influence of ecological water conveyance may reach as far as 2000 m from the river (Si et al., 2005; Zeng et al., 2016)”.

Reviewer: P24, lines 1-5: I do not think this paragraph is necessary and suggest that you remove it.

Authors: We thank the reviewer’s suggestion. However, we consider this sentence necessary as it provides some suggestions to improve the current restoration efforts in this desert riparian forest. To make it clear, we rewrote these sentences. To make it clear, we shorted these sentences. Please see Page 27 Line 10-13 in the manuscript: “In addition, multiple conservation measures that protect the soil structure (e.g., artificial soil cover and livestock grazing exclusion) were recommended for regions close to the river to reduce the adverse effects of grazing on soil properties”.

Reference:

Gong, Z. T., Chinese soil geography. Science Press, Beijing, Pp. 523–524, 2014.

The spatial distribution and temporal variation of desert riparian forests and their influencing factors in the downstream Heihe River Basin, China

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Abstract. Desert riparian forests are the main restored vegetation community in ~~the~~ Heihe River Basin. They provide critical habitats and a variety of ecosystem services in this arid environment. Since they are also sensitive to disturbance, examining the spatial distribution and temporal variation of desert riparian forests and their influencing factors is important for determining the limiting factors of vegetation recovery after long-term restoration. In this study, field experiment and remote sensing data were used to determine the spatial distribution and temporal variation of desert riparian forests and their relationship with the environmental factors. We classified five types of vegetation communities at different distances from the river channel. Community coverage and diversity formed a bimodal pattern, peaking at the distances of 1000 m and 3000 m from the river channel. In general, the temporal NDVI trend from 2000 to 2014 was positive at different distances from the river channel, except for the region closest to the river bank (i.e., within 500 m from the river channel), which had been undergoing degradation since 2011. The spatial distribution of desert riparian forest was mainly influenced by the spatial heterogeneity of soil properties (e.g., soil moisture and soil physical properties), while the temporal variation of vegetation was affected by both the spatial heterogeneity of soil properties (e.g., soil moisture and soil particle composition) and to a lesser extent, the temporal variation of water availability (e.g., annual average and variability of groundwater, soil moisture and runoff). Since surface (0~~-~~–30 cm) and deep (100~~-~~–200 cm) soil moisture~~ and ~~, bulk density and the annual average of soil moisture at 100 cm obtained from the remote sensing data were regarded as major determining factors of community distribution and temporal variation, conservation measures that protect the soil structure and prevent soil moisture depletion (e.g., artificial soil cover and water conveyance channels) were suggested to better protect desert riparian forests under climate change and intensive human disturbance.

1 Introduction

Riparian zone is the linkage between terrestrial and aquatic ecosystems (Naiman and Décamps, 1997), which is usually defined as the stream channel between the low- and the high-water marks, in addition to the terrestrial landscape above the high-water mark. Consequently, vegetation in the riparian zone is likely to be influenced by elevated water tables or extreme flooding and by the ability of soils to hold water (Nilsson and Berggren 2000). Riparian zone~~which~~ plays an important role in numerous ecological processes and provides a variety of ecosystem services, such as sand stabilization and carbon sequestration (Décamps et al., 2004). Desert riparian forests, also known as 'Tugai forests', are mainly located in the floodplains of the major Central Asian rivers~~,~~. They are considered ~~to be~~ the core of ~~the~~ riparian zone in hyperarid areas (Gärtner et al., 2014)~~.~~ ~~They~~ by ~~provide~~ providing critical habitats for various species and functioning as an 'ecological shelter' against desertification ~~in hyperarid areas~~ (Ding et al., 2016). However, due to their low ~~diversity level~~biodiversity and weak resilience, desert riparian forests are sensitive to disturbance and likely to be threatened by ~~desertification under a changing environment~~ climate change and human disturbance (Li et al., 2013).

Desert riparian forests are the main communities in ~~the~~ Heihe River Basin, ~~with the Heihe River being~~ the second largest inland river in China (Feng et al., 2015). During the past century, an increase ~~in~~ of the human population and overexploitation of the upstream water resources have led to a significant degradation ~~of~~ in the downstream desert riparian forests (Wang et al., 2014). Since 2000, the ecological water conveyance project (EWCP), a restoration project ~~aimed~~ aiming to deliver water downstream, has been implemented to restore the ecosystems of ~~the~~ Heihe River Basin (Wang et al., 2011). Every year, approximately 300 billion m^3 of water ~~have been~~is delivered using concrete channels, which were built perpendicular to the river to expand the range of the river impact and to deliver water for irrigation. The influence of ecological water conveyance may reach as far as 2000 m from the river (Si et al., 2005; Zeng et al., 2016). While most of ~~the downstream~~ vegetation in the downstream Heihe River has been restored (Lü et al., 2015), nearly 20% of ~~the~~ its oasis area covered by desert riparian forests remains degraded despite better downstream water conditions and ~~still underwent major degradation in spite of~~ the rising of groundwater ~~level~~ table~~and better downstream water conditions~~ (Zhang et al., 2011a). To understand what may cause such variations in this desert riparian forest, we need to examine the spatial distribution of community characteristics along an ecological gradient, which can reflect how the spatial distribution of vegetation has been shaped by multiple environmental factors (Goebel et al., 2012; Li et al., 2013)~~To conserve and restore this fragile ecosystem more effectively, studies that address the variation in desert riparian forests and their relationships with environmental factors need to be conducted~~.

~~The spatial distribution of community characteristics along an ecological gradient can reflect how the spatial distribution of vegetation was shaped by multiple environmental factors (Goebel et al., 2012; Li et al., 2013).~~ In ~~the~~ hyperarid zone, groundwater ~~has been~~is regarded ~~as~~ the major driving factor of vegetation distributions~~.~~ and ~~the appropriate~~ groundwater table should be between 2 m and 4 m deep to support vegetation growth (Zheng et al., 2005). Study in Tarim River, for example, shows that species diversity peaks where groundwater depth is around 2–4 m. Once groundwater tables falls beyond 4.5 m, a deficiency in soil moisture occurs, followed by degradation of vegetation communities~~Previous studies showed that species diversity peaked where the groundwater depth was approximately 2-4 m before it started to decrease when groundwater dropped below 4-4.5 m and soil moisture limitation occurred~~ (Li et al., 2013). While groundwater drops rapidly away from the river bank to approximately 6 m deep at a distance of 1000 m from Tarim River channel, ~~While this could be the case for some hyperarid zones (e.g., the Tarim River) where the groundwater drops rapidly away from the river bank to approximately 6 m deep at a distance of 1000 m from the river channel~~ (Aishan et al., 2013), groundwater table in downstream Heihe River, where most of the desert riparian forest are distributed, remains above 4 m even at the distance of 3800 m from the river channel ~~, the groundwater table remains above 4 m at a distance of 3800 m from the Heihe River channel~~ (Wang et al., 2011; Fu et al., 2014). ~~However,~~ Yet some sites have not been completely restored in the Heihe riparian zones, and ~~the~~ its downstream vegetation community is still dominated by shrubs instead of multiple layers of tree (He and Zhao, 2006; Zhang et al., 2011a). A ~~previous~~ study by Zhu et al. (2013) ~~showed~~ shows that Patrick's richness index and the Shannon-Wiener diversity index for the downstream vegetation ~~formed~~ form a bimodal pattern instead of a unimodal pattern with groundwater depth in the Heihe River Basin, indicating that there ~~could~~ may be other factors affecting the spatial distribution of desert riparian forests.

Apart from groundwater, soil properties, such as soil moisture, soil physical and chemical properties also shape the community characteristics and species vitality ~~by influencing the ecological and hydrological processes~~ (Stirzaker et al. 1996; Salter and Williams, 1965). Soil moisture, influenced by precipitation and groundwater, is the direct water source for desert riparian forests (Wang et al., 2012). As different depths of soil moisture ~~exert different impacts on~~affect ~~vegetation~~ species diversity in each community layer (D'Odorico et al., 2007; Fang et al., 2016), a decline in soil moisture ~~would~~ may reduce the ~~abundance~~ diversity of drought-sensitive species (e.g., ~~tree and~~ herbs~~ species~~), resulting in a community shift towards drought-tolerant vegetation types with distance from the river channel (Zhu et al., 2014). ~~Some s~~Stud~~ies~~y ~~have~~ also ~~found~~ find that variation in soil properties explains the evolution of dominant species in arid areas and the changes in soil nutrients contribute greatly to species diversity (Yang et al. 2008).

The temporal variation in vegetation can reflect how communities respond to the changing environment during ecological restoration (Bakker et al., 1996; Scott et al., 1996). Due to the lack of long-term field-based observational data, long-term~~time~~ series of remote sensing data (e.g., MODIS-NDVI, SPOT-NDVI) have been widely used to explore vegetation changes and to evaluate the effectiveness of ecological restoration (Wang et al., 2014; Geng et al., 2014). Since the implementation of ecological restoration, the Normalized Difference Vegetation Index (NDVI) in the downstream Heihe River Basin has significantly increased and the temporal variation in environmental factors, especially water availability (e.g., runoff and groundwater) has been reported as the major driving factor in vegetation recovery (Jia et al., 2011; Zeng et al., 2016). While large-scale remote sensing data (e.g., MODIS-NDVI, SPOT-NDVI) ~~could~~ can capture the general trend of the whole study area, they fail to accurately delineate the temporal variation of desert riparian forest vegetation at the fine scale (i.e., <100 m). However, community variation is a result of long-term interactive effects between vegetation and the environment, influenced by both spatial heterogeneity and temporal variation factors during ecological restoration (Zhu et al., 2013; Xi et al., 2016). Until recently, very few studies have incorporated both spatial and temporal variation of desert riparian forests into a single study due to the inconsistency in scale between fine field sampling and coarse remote sensing analysis. As desert riparian forest is the main community that maintains ecosystem functions under hyperarid conditions, comprehensive research that simultaneously examines the spatial and temporal variation of vegetation is crucial for the restoration of degraded riparian zones.

In this study, we aim to (i) explore both the spatial distribution and temporal variation of Heihe desert riparian forest at different distances from the river channel~~,~~ and (ii) disentangle the impacts of spatial heterogeneity in soil properties and temporal variation in water availability on the vegetation community~~, and (iii) understand the resilience of the vegetation community in order to suggest the appropriate restoration and protection measures for desert riparian forests under a changing environment~~. We ~~used~~ studied 3000 m transects running perpendicular to the river channel to include different distances from the river channel and to depict the spatial distribution of vegetation (e.g., changes in floristic composition, community structure and diversity) at each distance from the river channel. ~~Consistent with this field sampling, w~~We used ~~the variation of the~~ NDVI variations at different~~each~~ distances from the river channel, derived from high resolution images (e.g., 30 m resolution) from 2000~~-~~–2014, to depict the temporal variation of the vegetation. Spatial heterogeneity of soil properties (e.g., soil moisture, soil physical properties and soil nutrition) and temporal variation of water availability (e.g., annual average and annual variability of groundwater, soil moisture and runoff) were used to explain the vegetation community variance.

2 Data and methods

2.1 Study area

The study was conducted in the downstream Heihe River (40°20′–42°30′N; 99°30′–102°00′E) in the Ejina Oasis, Inner Mongolia, northwest China. The oasis covers an area of 3×10^4 km^2, with declining surface elevation (i.e., 1127 m to 820 m above sea level) from the southwest to the northeast. This region has a typical continental arid climate with a mean annual temperature of 8.77 ℃. Its maximum and minimum temperatures usually occur in July (41°C) and January (−36 ℃) (Wen et al., 2005). The mean annual precipitation is <39 mm, 84% of which occurs during the growing season (May to September), while the mean annual potential evaporation is >3,390 mm (Chen et al., 2014).

The Heihe River originates from rainfall and snow melt in the Qilian Mountains. It branches into the Donghe River and the Xihe River at Langxinshan Mountain and ultimately flows into East Juyan Lake and West Juyan Lake in Ejina. The population of the Ejina Oasis is 32,410 (Ejina statistical office, 2012). The local economy mainly depends on cantaloupe farming and animal husbandry (e.g., sheep, cattle and camels). The Ejina Oasis is one of China’s most important tourist attractions with respect to desert riparian forests, attracting almost 200,000 visitors per year during September to October (Hochmuth et al., 2014). One primary road is built parallel to the river channel, and another runs across the south of the oasis. ~~These roads are used mainly for transportation and travel.~~

The desert riparian forests are the main components of the Ejina Oasis. They mainly grow along the river banks and spread across the fluvial plain, with the dominant vegetation including *Populus euphratica*, *Tamarix ramosissima*, *Lycium ruthenicum*, *Sophora alopecuroides*, *Karelinia caspica*, and *Peganum harmala*. Sparse and drought-tolerant desert species, such as *Reaumuria soongarica*, *Zygophyllum xanthoxylon* and *Calligonum mongolicum* are mainly distributed in the Gobi Desert. The main soil types in the area are Gypsi Sali-Orthic Aridosols~~shrubby meadow soil, aeolian soil~~ and Calcaric Aridi-Orthic Primosols~~grey-brown desert soils~~. Para-alkalic Aqui-Orthic Halosols~~Saline-alkaline soils~~ and Calcaric Ochri-Aquic Cambosols~~swamp soils~~ also exist in the lake basins and lowlands (Chen et al., 2014; Gong., 2014).

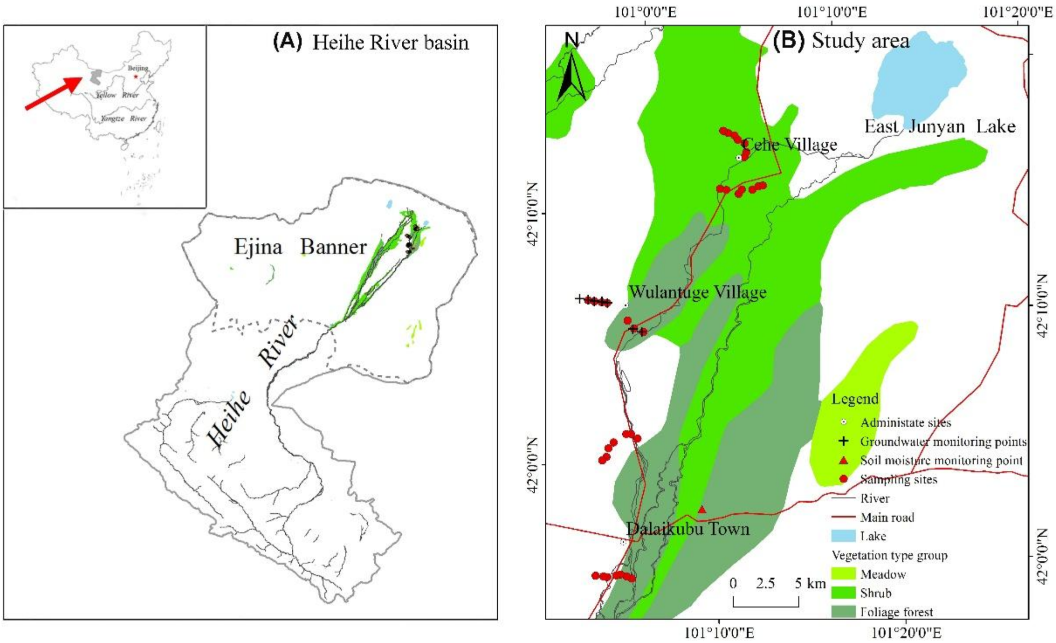

Figure 1. The Heihe River Basin in China (A) and the location of sampling points in the study area (B). ~~One primary roads is built parallel to the river channel, and another runs across the south of the oasis.~~

2.2 Spatial field survey and experimental design

In the downstream Heihe River Basin, desert riparian forests make up the core of the desert oasis, mainly composed of tree, shrub and grass communities. ~~The forests are distributed along the Heihe River from 0 m to approximately 2000 m from the river channel (Si et al., 2005).~~ However, the spatial extent of the riparian zone is difficult to precisely delineate due to the heterogeneity of the landforms (Décamps et al., 2004). Although previous studies indicates that ~~T~~the forests are distributed ~~along the Heihe River from~~ between 0 m ~~to~~and ~~approximately~~ 2000 m from the river channel, corresponding to the influence range of ecological water conveyance (Si et al., 2005)~~.s Therefore~~, our study extended beyond that range (i.e., ~~covered distances~~ up to 3000 m from the river channel) to fully cover the distribution pattern of the desert riparian forests in ~~the~~ downstream Heihe River.

Our field survey was conducted in July 2015 after the ecological water conveyance was delivered. Ecological water conveyance is implemented according to the water dispatching scheme and is conducted in April, July, August, September and November with a scheduled discharge (Feng et al., 2015). Due to the regulated water discharge, the ~~ecological water conveyance~~flooding only affects the sites near the river bank (within a 100-m radius) (Liu et al., 2008). We conducted vegetation and soil sampling perpendicular to the river channel and sampled at distances of 100 m, 500 m, 1000 m, 1500 m, 2000 m, 2500 m, and 3000 m from the river channel. Five replicates were sampled at each distance from the river channel and a total of 35 sampling sites were established. These sites were far from farmlands, irrigated channels and reservoirs to minimize the impact of human disturbance and other water resources. Although there is a main road extending across the oasis and almost parallel to the river channel (Fig. 1), the vegetation community growing near the road is considered to be undisturbed by the road, as the road is separated from the surroundings by iron wire.

Three tree quadrats (30 m × 30 m) and shrub quadrats (10 m × 10 m) were established randomly at each site. The number of each species (tree and shrub), plant height, coverage and the diameter at breast height (DBH) of the trees (≥ 2 m) were recorded individually. Four (2 m × 2 m) herb quadrats were established at each corner of the tree or shrub quadrat to collect data on the number of herb species, vegetation cover and height.

At each site, soil samples ~~and~~ for soil moisture measurement ~~samples~~ were randomly collected in three replicates using an auger (5 cm in diameter) ~~. Soil gravimetric water content (SWC) was collected~~ at ~~depths of~~ 5, 10, 15, 20, 30, 40, 50, 60, 70, 80, 100, 120, 140, 160, 180 and 200 cm deep. The soil samples were sealed in a freezer and the gravimetric soil water content (SWC) was determined via oven drying at 105 ℃ to a constant weight.~~and weighed at the time of sampling as well as after oven drying at 105 ℃ for 48 hours~~~~until constant~~. Bulk density (BD) was measured by collecting undisturbed soil cores from the surface layer using a stainless-steel cutting ring (100 cm^3 in volume) with three replicates at each site, which were then oven dried at 105 ℃ to a constant weight. Soil samples were collected every 20 cm at a depth of 100 cm in each site to determine the soil composition and chemical properties. ~~The soil particle size distribution and soil chemical properties (soil organic matter, total nitrogen, total phosphorus and total salt content) were analysed in the laboratory using 0-100 cm soil samples that were collected separately at each site.~~Surface soil samples (from a depth of 0–20 cm) were subsequently analyzed in the laboratory to determine their clay (<0.002 mm), silt (0.002–0.05 mm), sand (0.05–2 mm), and gravel (>2 mm) content using a Malvern Mastersizer 2000. Soil organic matter (SOM) was measured using the $K_2Cr_2O_7$ method (Liu, 1996). Total nitrogen (TN) was determined using the Kjeldahl procedure (ISSCAS, 1978). Total phosphorus (TP) was determined using a UT–1810PC spectrophotometer (PERSEE, Beijing, China), after H_2SO_4–$HClO_4$ digestion (ISSCAS, 1978). Total salt content (TS) was determined by oven method (Liu, 1996).

2.3 Temporal data collection and processing

To understand the long-term vegetation variation since the implementation of ecological water conveyance, we analysed NDVI data from 2000 to 2014. As the NDVI measures the vegetation status, including coverage and vigour, we used the maximum NDVI during growing season as the indicator of vegetation community characteristics (Wang et al., 2014). NDVI data during 2000~~-~~–2014 were calculated using ENVI (5.0) based on the Landsat TM/ETM image (30 m) acquired from Geospatial Data Cloud (http://www.gscloud.cn/). We calculated the NDVI at each distance from the river channel based on the NDVI derived from the sampling sites. The variable environmental factors, such as 2 cm soil moisture, 100 cm soil moisture and groundwater at each site during the research period, were extracted from ~~the~~ remotely~~-~~ sensed data (~~with~~ 1000 m resolution) (doi:10.3972/heihe.0034.2016.db), ~~which was~~ generated by~~using~~ the land model CLM4.5 using~~based on the~~ high-resolution ASTER DEM dataset, the multi-source integrated Chinese land cover map (MICLCover), the Heihe watershed allied telemetry experimental research land cover map (HiWATER Land Cover Map), and the China soil characteristics dataset (Zeng et al., 2016). The validation of the retrieved remote sensing data is provided in the Supplementary Material S4. Land use change information from 2000~~-~~–2014 was extracted from land use data ~~at~~ with a scale of 1:100,000 (for 2000 and 2014) (doi:10.3972/heihe.020.2013.db; doi:10.3972/hiwater.155.2014.db) (Zhong et al., 2015). The spatial variation of groundwater table~~ with distance from the river~~ was obtained from groundwater monitoring data recorded by seven wells (i.e., 7.62–9.66 m deep) in the Ejina oasis, ~~along a transect~~ located at 50 m, 300 m, 2200 m, 2700 m, 3200 m, and 3700 m from the river center– (~~i.e., the Wulantuge transect~~Fig. 1). These monitoring data of the groundwater table were recorded as 18-hour averages with a three decimal places accuracy using a HOBO automatic groundwater table gauge from October 2010 to December 2014 (Fu et al., 2014). The diurnal and annual variations of soil moisture were obtained from the monitoring data of soil moisture, recorded at 0.5 Hz, as a 10-min average~~s~~ from 2013~~-~~–2015 using a suite of micrometeorological sensors (CR800, CR23X, CR23XTD, Campbell Scientific Inc.) installed ~~in~~ at ~~the~~ a site that is located within Heihe riparian forest, about 1500 m from the Heihe river channel ~~(101°8′1″E, 41°59′25″N)~~ (Fig. 1) (doi:10.3972/hiwater.241.2015.db; doi:10.3972/hiwater.318.2016.db) (Liu et al., 2011). The retrieved remote sensing data, monitoring data, land use data, groundwater monitoring data and runoff data at Donghe station (i.e., a hydrological station in the downstream Heihe) (doi:10.3972/heihe.1009.2013.db) were acquired from the Environmental & Ecological Science Data Center for West China, National Natural Science Foundation of China (http://westdc.westgis.ac.cn).

2.4 Statistical analysis

The importance value ~~P~~ (P~~importance value~~), an index that characterizes the relative importance of plant species in the community (Zhang and Dong, 2010)~~of each tree, shrub and herb~~ ~~at each sampling site~~ was calculated for each species at each tree shrub and herb layer in every sampling site using the following formulas ~~(Zhang and Dong, 2010)~~(Zhang, 2011):

$$P_{\text{Tree}} = (RDen + RDom + RH)/3 \qquad (1)$$

$$P_{\text{Shrub or Grass}} = (RDen + RDom + RC)/3 \qquad (2)$$

where P_{Tree} is the importance value in the tree layer. $P_{\text{Shrub or Grass}}$ is the importance value in the shrub or grass layer. *RDen* is the relative density, *RDom* is the relative dominance, *RH* is the relative height and *RC* is the relative coverage.

In our study, the total diversity index of the community was employed to depict the community diversity at each site. According to the characteristics of the community vertical structure, the total diversity index of the community is measured using the weights of indices for different growth types. The weight is the average of the relative coverage and thickness of the leaf layer (Fan et al., 2006). We applied the following formula (Gao et al., 1997):

$$W_i = (C_i/C + h_i/h)/2 \qquad (3)$$

where C is the total coverage of the community ($C = \sum C_i$); i = 1 for the tree layer, 2 for the shrub layer and 3 for the herb layer~~, and the meaning of *i* is same below~~; h is the thickness of the leaf layer of various growth types ($h = \sum h_i$); W_i is the weighted parameter of the diversity index for the i^{th} growth type; C_i is the coverage of the i^{th} growth type; and h_i is the average thickness of the leaf layer of the i^{th} growth type. Among the different growth types, the thickness of the tree leaf layer is calculated at 33.3% the height of the tree layer, the shrub layer at 50% and the herb layer at 100%.

The total diversity index of the community was calculated according to the following formula:

$$A = \sum W_i A_i \qquad (4)$$

where A is the total diversity index of the community; i = 1 for the tree layer, 2 for the shrub layer and 3 for the herb layer; W_i is the weighted parameters of the diversity index for the i^{th} growth type;~~the tree layer, shrub layer and herb layer. *A* is the total diversity index of the communitydiversity index of~~

~~the tree layer, shrub layer or herb layer,~~ A_j is the diversity index of the i^{th} growth type. ~~which can be calculated using the formulas listed below.~~

Species diversity indices were calculated (Liu et al., 1997), including the Shannon-Wiener diversity index ~~Shannon–Wiener's index of diversity~~ (H)

$$H = -\sum_{i=1}^{s}(P_i \ln P_i) \tag{5}$$

Simpson dominance index~~Simpson's index of dominance~~ (D) was calculated as

$$D = 1 - \sum_{i=1}^{s} P_i^2 \tag{6}$$

and Pielou evenness index~~Pielou's index of evenness~~ (J_{sw}) was calculated as

$$J_{sw} = H/(\ln(S)) \tag{7}$$

Finally, Patrick richness index~~Patrick's index of richness~~ (R) was calculated as

$$R = S \tag{8}$$

where P_i is the relative importance value of the i^{th} species ~~i~~, and S is the total number of species ~~at~~ in ~~the i^{th}~~ each growth type at each sampling site.

The least significant difference (LSD) test was used to determine the significance of the variability in vegetation characteristics among five transects (~~Supplement~~Supplementary Material S3, Table S2). For each distance from the river channel, vegetation community characteristics, soil moisture and soil properties of the five sites were calculated as the mean ± standard error (SE) of the mean. The monitoring data of soil moisture in desert riparian forest showed that soil moisture under 20 cm was relatively stable and could represent water condition at the sampling site (Fig. S1). Thus, to depict the water condition at the sampling sites and to illustrate~~To depict~~ the vertical structure of soil moisture, soil water content was divided into three layers: 0–30 cm soil moisture (SWC1), 30–100 cm soil moisture (SWC2), and 100–200 cm soil moisture (SWC3) in accordance with the distribution of fine roots herbs, trees and shrubs in this area (Fu et al., 2014). We averaged the soil moisture at each corresponding finer increment to obtain the value of SWC1, SWC2 and SWC3. The soil chemical properties, however, were analysed using the mean values of 0–100 cm due to the low vertical variation. The NDVI change rate was calculated based on the percentage change of NDVI from 2000 to 2014. The annual average value and annual variability were used to depict the temporal variation of community characteristics and environmental factors. The annual averages of NDVI (NDVI_a), groundwater (GWT_a), 2 cm soil moisture (SWC2cm_a) and 100 cm soil moisture (SWC100cm_a) were calculated using the mean values from 2000–2014. The annual variability of NDVI (NDVI_c), groundwater (GWT_c), 2 cm soil moisture (SWC2cm_c) and 100 cm soil moisture (SWC100cm_c) were calculated using the mean values of change rate for each year.

Regression analysis was used to examine the variation pattern. Exponential and polynomial regressions were fit to the data to ~~best~~ explain the statistical relationship between community characteristics and the distance from the river channel. Pearson correlation was used to determine the strengths of possible relationships between community characteristics and environmental factors. Significant differences were evaluated at the 0.05 and 0.01 levels. Statistical analysis was performed using SPSS (version~~.~~ 18.0).

Two-way indicator species analysis (TWINSPAN, in WinTWINSPAN, version 2.3), a method of community hierarchical classification (Hill, 1979), was used to classify the possible desert riparian forest community types. The importance value data for all plant species, obtained from the vegetation survey, were used in this analysis and the cutoff levels of the importance value for each class were set as: 0, 0.1, 0.2, 0.4, 0.6 and 0.9. To further separate the key influencing factors of the 18 environmental variables, the marginal and conditional effects of the various variables were calculated through Monte Carlo forward selection in RDA (redundancy analysis), which directly showed the significance and ~~contribution rate of~~ the percentage of vegetation variance explained by each factor. Marginal effects reflect~~ed~~ the effects of the environmental variables on the community characteristics, while conditional effects reflect~~ed~~ the effects of the environmental variables on the community characteristics after the anterior variable ~~was~~ is eliminated by the forward selection method. Since the redundant variables ~~were~~ are eliminated and a group of key environmental factors ~~was~~ is identified through forward selection, this method ~~allowed~~ allows key variables to be determined through the strength of their effects and significance. The variation of community characteristics explained by the different group of environmental factors was analysed using variation partitioning analysis. The significance of the resulting ordination was evaluated by 499 Monte Carlo permutations (Zhang and Dong, 2010). The Monte Carlo test and variation partitioning analysis were performed using the software program CANOCO (ver. 5.0) (Microcomputer Power, USA) (Braak et al., 2012).

3 Results

3.1 Vegetation community types and temporal changes in vegetation composition

The species composition at each site in the downstream Heihe River Basin is shown in Table S1 in the Supplementary Material, and the following five plant community types distributed across the 3000 m transect from the river channel were obtained based on the TWINSPAN classification (Fig. 2):

(i) Community I was an association of (Ass.) *Populus euphratica–Tamarix ramosissima* + herbs. Characterized by multiple layers of tree–shrub–herb, the community coverage was low (38.05%) and dominated by the tree species *Populus euphratica* with sparse understory vegetation. This community was mainly distributed near the river bank, mostly within 500 m from the river channel.

(ii) Community II was Ass. *Tamarix ramosissima–Lycium ruthenicum* + herbs. This community was composed of shrub and herb layers with high community coverage (81.43%). *Tamarix ramosissima* was the dominant shrub species of the shrub layer, while the herbs were dominated by both hygrophyte and xerophyte species, such as *Kochia scoparia* and *Peganum harmala*. This community was mainly distributed near the river bank (approximately 1000 m from the river channel).

(iii) Community III included *Tamarix ramosissima*. This community was mainly composed of shrub layers and dominated by *Tamarix ramosissima* with average community coverage of 75.93%. It was mainly distributed at the distance between 1000 m and 2000 m from the river channel.

(iv) Community IV was Ass. *Lycium ruthenicum–Tamarix ramosissima* + xerophyte herbs. This community was mainly composed of shrub and herb layers with average community coverage of 68.86%. *Lycium ruthenicum* was the dominant shrub species (importance value = 0.42–0.77), while the dominant xerophytic herb species were *Sophora alopecuroides* and *Suaeda salsa*. It was mainly distributed between 1500 m and 2500 m from the river channel.

(v) Community V was Ass. *Tamarix ramosissima–Lycium ruthenicum–Reaumuria soongarica*. This community was the transition community from desert riparian shrub forests to desert shrubs, indicated by the presence of *Reaumuria soongarica*, a typical desert shrub. *Tamarix ramosissima* was the dominant species of the shrub layer, mainly existing in the form of shrub dunes. This community was mainly distributed approximately 2500–3000 m from the river channel, with low community coverage (54.40%).

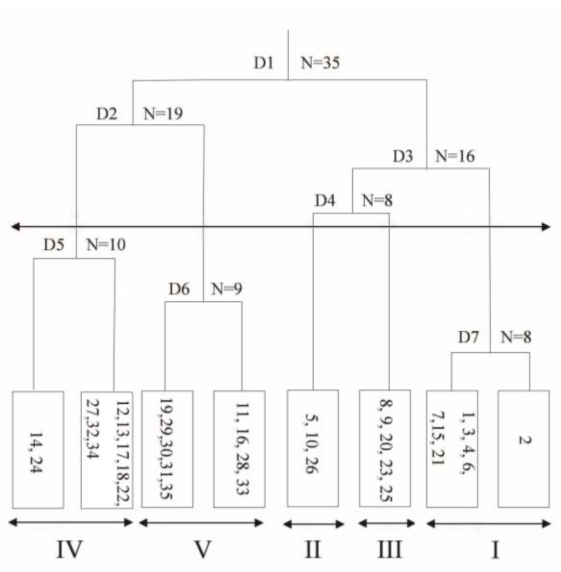

Figure 2. The dendrogram of the sampling sites based on the TWINSPAN classification.

Notes: Numbers 1–35 represent the site numbers of the sampling sites. D indicates the classification levels, and N indicates the number of sampling sites for the classification. I to V represent communities I to V. Arrows indicates that all the sites were divided into five major groups after the fourth classification.

Between 2000 and 2014, changes in the vegetation composition of each community type (I to V) (Fig. 3) were obtained from changes in the land use map (Fig. 3). Among the five community types, community V underwent the most changes, with 22.22% of the sites changing from sparse forest to grassland, 22.22% from grassland to shrubland and 22.22% from bareland to grassland. The majority (>60%) of the vegetation composition remained unchanged in communities I to IV, with the following exceptions: (i) 37.5% of the sites in community I changed from shrubland to sparse forest and from bareland to grassland, (ii) 33% and 20% of the sites in communities II and III changed from bareland to grassland and from sparse forest to grassland, respectively, and (iii) 20% of the sites in community IV changed from sparse forest to grassland and another 20% from grassland to shrubland (Fig. 3).

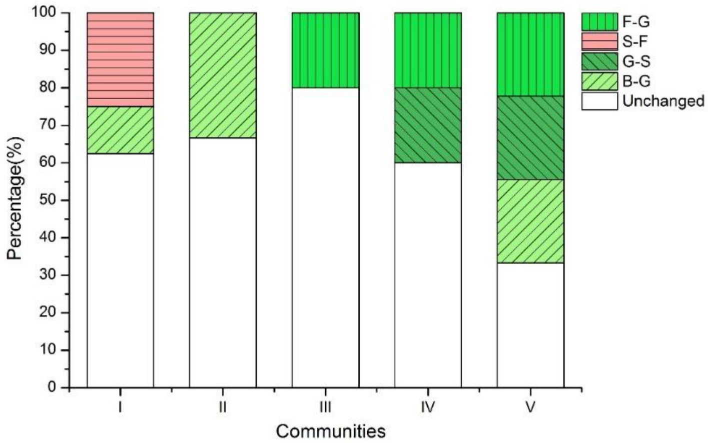

Figure 3. The percent changes in vegetation composition in each community from 2000–2014.

Notes: F–G: change from sparse forest to grassland; S–F: change from shrubland to sparse forest; G–S: change from grassland to shrubland; B–G: change from bareland to grassland.

3.2 The spatial distribution and temporal variation of community characteristics in desert riparian forest

Community characteristics varied with distance from the river channel (Fig. 4). Vegetation community height and density dropped rapidly after 500 m (Fig. 4a, b), while community coverage formed a bimodal pattern, peaking at the distances of 500–1000 m and 3000 m (Fig. 4c). The variation of vertical structure was depicted by the following hierarchical coverage (Fig. 4d): (i) the tree layer mainly existed within 1000 m, (ii) the shrub layer peaked at approximately 1500–2000 m, and (iii) the herb layer fluctuated with distance from the river channel, peaking at 500 m and 2500–3000 m from the river channel. All diversity indices showed a bimodal pattern with distance from the river channel. The Shannon-Wiener diversity index, Pielou evenness index and Patrick richness index peaked at 1000 m and 3000 m (Fig. 4e–g). Simpson dominance index, however, formed an opposite trend to the other three diversity indices, by peaking at 500 m and 2000 m, where the other indices were at their low level (Fig. 4h).

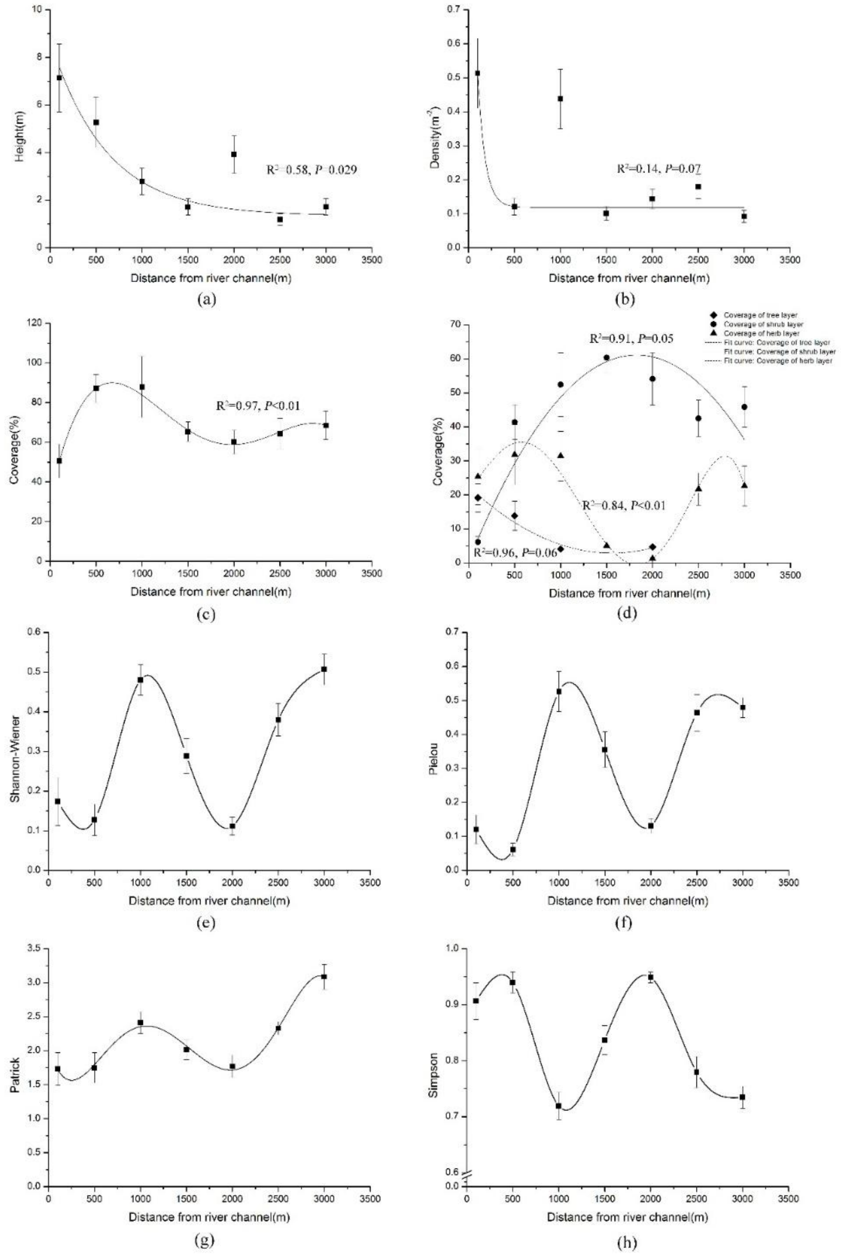

Figure 4. The variation of community structure and diversity with distance from the river channel.

The temporal variation in community characteristics was depicted by the variation in NDVI (Fig. 5). At different distances from the river channel, the NDVI showed an increasing trend throughout the research period except for a small decrease during the initial years (2000–2002). The NDVI decreased with distance from the river channel, peaked at 100 m and 500 m from the river channel, and reached the lowest values at the furthest distance from the river channel (3000 m) (Fig. 5a). The annual variability in the NDVI, however, showed a contrasting trend, increasing with distance from the river channel (Fig. 5b).

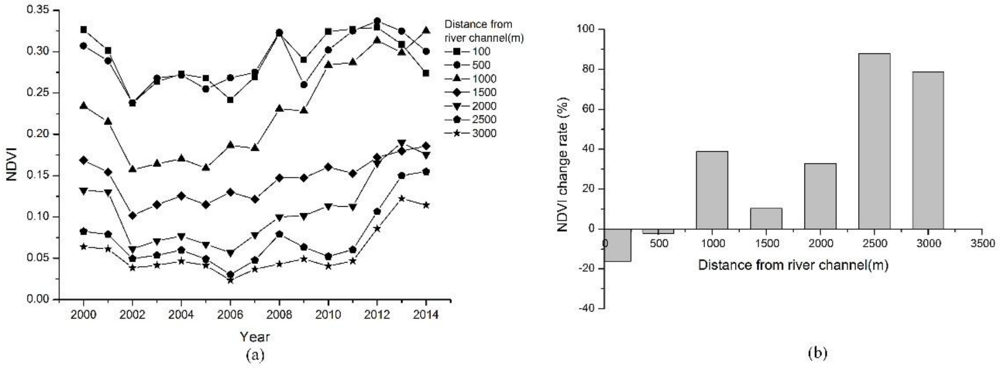

Figure 5. The temporal variations of NDVI (a) and annual variability of NDVI (b) from 2000 to 2014 at different distances from the river channel.

3.3 Pearson correlation between community characteristics and environmental factors

The result of the Pearson correlation analysis between community characteristics and environmental factors is shown in Table 1. The community density showed significant positive correlations with SWC2, SWC3, SWC2cm_a and SWC100cm_a, but negative correlations with BD and GWT_a. The community coverage was positively correlated with all the three soil moisture layers (P<0.0.1) but negatively correlated with BD. The tree and shrub layers were influenced by GWT_a and BD, respectively, while the herb layer was positively correlated with SWC1 and SCW3. Among the diversity indices, the Patrick richness index was significantly correlated with SOM and gravel, while Simpson ~~domination~~ dominance index was significantly correlated with sand and silt. For the temporal variation of community characteristics, NDVI_a was mainly influenced by soil moisture (SWC1, SWC2 and SWC3), soil particle composition (clay, gravel) and bulk density, while NDVI_c was significantly correlated with SWC3, gravel and TS.

The correlation coefficient between ~~the~~ NDVI and runoff was measured to examine the relationship between runoff and ~~the~~ NDVI ~~of the same year, while the correlation coefficient between the one-year lag NDVI and runoff was measured to examine the relationship between runoff and the NDVI of the following year~~ (Fig. 6). The relationship between runoff and the NDVI of the following year was significantly stronger than the relationship between runoff and the NDVI of the same year, indicated by the higher correlation coefficient and significance in the one-year lag NDVI~~-~~–runoff correlation compared to the NDVI~~-~~–runoff correlation.

Table 1. Pearson correlations between community characteristics and environmental factors.

	H	R	C	J_{sw}	Height	Density	Cover-a	Cover-t	Cover-s	Cover-h	NDVI_a	NDVI_c
SWC1	0.255	0.167	-0.286	0.182	-0.088	0.251	**0.545**	-0.017	0.168	**0.514**	**0.430**	0.188
SWC2	0.046	-0.072	-0.098	0.067	-0.114	**0.382**	**0.439**	0.007	0.280	0.263	**0.469**	0.254
SWC3	0.142	0.157	-0.147	0.111	-0.242	**0.362**	**0.448**	-0.142	0.175	**0.382**	**0.445**	**0.506**
Clay	0.112	0.005	-0.128	0.045	0.048	0.290	0.204	0.037	-0.093	0.272	**0.398**	0.125
Silt	0.308	0.117	**-0.344**	0.311	-0.121	0.111	0.321	-0.071	0.247	0.168	0.185	-0.115
Sand	-0.327	-0.148	**0.354**	-0.306	0.130	-0.165	-0.307	0.076	-0.166	-0.217	-0.212	0.125
Gravel	0.226	**0.350**	-0.155	0.179	-0.284	-0.081	-0.185	-0.173	-0.179	0.011	**-0.413**	**-0.396**
BD	0.174	0.282	-0.127	0.123	-0.041	**-0.353**	**-0.350**	0.049	**-0.465**	0.063	**-0.354**	-0.050
SOM	-0.256	**-0.398**	0.187	-0.102	0.193	0.058	-0.192	0.116	-0.121	-0.296	-0.025	-0.009
TN	-0.191	-0.333	0.138	-0.060	0.101	0.032	-0.278	0.112	-0.296	-0.223	-0.006	0.108
TP	-0.238	-0.303	0.198	-0.098	0.116	0.022	-0.181	0.084	-0.090	-0.288	-0.018	0.194
TS	-0.139	-0.125	0.111	-0.099	-0.184	0.271	0.011	-0.086	0.034	-0.131	-0.140	**0.382**
GWT_c	0.094	-0.028	-0.133	0.228	-0.074	0.001	-0.137	0.102	-0.060	-0.189	-0.286	0.040
SWC2cm_c	0.113	0.085	-0.117	0.084	-0.161	0.098	-0.027	-0.093	-0.029	-0.024	-0.177	0.119
SWC100cm_c	0.171	0.185	-0.165	0.109	-0.116	-0.080	0.073	-0.096	0.107	0.038	-0.198	0.141
GWT_a	-0.022	-0.226	-0.050	0.127	0.300	**-0.343**	-0.092	**0.352**	0.017	-0.131	0.042	0.004
SWC2cm_a	-0.169	-0.270	0.129	-0.096	0.013	**0.405**	-0.184	0.103	-0.224	-0.183	0.160	0.144
SWC100cm_a	-0.085	-0.194	0.047	-0.014	-0.094	**0.403**	-0.137	-0.046	-0.206	-0.150	0.090	0.140

Notes: Significant correlations with P<0.05 and P<0.01 are shown in bold and in bold with underline, respectively. H, Shannon-Wiener diversity index; R, Patrick richness index; C, Simpson dominance index; J_{sw}, Pielou evenness index; ~~H, Shannon- Wiener diversity index; C, Simpson domination index;~~ a, total plant community; t, tree layer; s, shrub layer; h, herb layer; NDVI_a, annual average of NDVI; NDVI_c, average annual variability of NDVI; SWC1, 0–30 cm soil moisture; SWC2, 30–100 cm soil moisture; SWC3, 100–200 cm soil moisture; BD, bulk density; SOM, soil organic matter; TN, total nitrogen; TP, total phosphorus; TS, total salt content. ~~0–20cm soil particle composition were analyzed in the laboratory for the clay (<0.02mm), silt (0.02–0.05 mm), sand (0.05–2 mm), and gravel (>2mm) contents by using Mastersizer 2000. Soil chemical properties at 0–20, 20–40, 40–60, 60–80 and 80–100 cm and the average value of 0–100cm were used in the analysis.~~ GWT_a, annual average of groundwater table; SWC2cm_a, annual average of 2 cm soil moisture; SWC100cm_a, annual average of 100 cm soil moisture; GWT_c, annual variability of groundwater table; SWC2cm_c, annual variability of 2 cm soil moisture; SWC100cm_c, annual variability of 100 cm soil moisture;

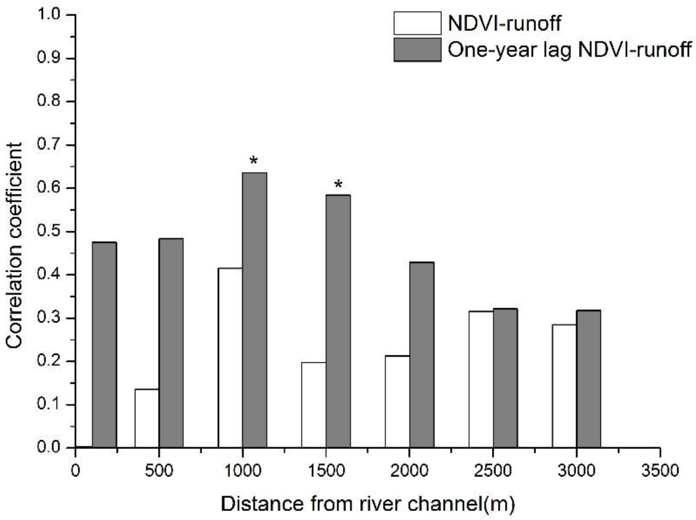

Figure 6. Pearson correlation coefficients of NDVI~~–~~-runoff and one-year lag NDVI~~–~~-runoff at different distance from the river channel.

Notes: * above the bar indicates significant correlations (P<0.05).

3.4 Key environmental factors that influenced community characteristics

To further examine the key environmental factors that controlled the variation in the vegetation indices, redundant variables were eliminated by a forward selection method. Table 2 shows the key influencing factors based on the marginal and conditional effects of 18 variables under the Monte Carlo test in the process of forward selection. All the environmental factors explained 74% of the total variance. In the Monte Carlo test of forward selection (*P*<0.05), SWC1, SWC3, BD and SWC100cm_a were regarded ~~as~~ the key environmental factors that ~~influencing~~ influenced the variation of community characteristics. ~~To further investigate the variation explained by spatial heterogeneity factors and temporal variation factors, we divided those 18 factors into two groups for partitioning analysis (Table 3).~~ Spatial heterogeneity factors explained 43.5% of the variation of community characteristics ~~vegetation variance~~ and accounted for 98.4% of the ~~total~~ variance explanation explained by all the investigated environmental factors (Table 3).~~,~~ This result indicated that spatial heterogeneity of environmental factors was the major driving force of the spatio-temporal variation in this desert riparian forest. In contrast, ~~while~~ temporal variation factors only explained 15.9% of the variation of community characteristics~~vegetation variance~~, accounting for 35.9% of the total ~~variance~~ explanation that was explained by all the investigated environmental factors (Table 3). This result suggested that temporal variation of the environmental factors exerted less impact on community characteristics compared to spatial heterogeneity of environmental factors in this desert riparian forest. While each factor group affected community characteristics separately, the spatial heterogeneity factors and temporal variation factors also jointly shaped the variation of community characteristics in downstream Heihe riparian forest. When combined, these factors~~These two groups of factors jointly~~ explained 15.2% of the community characteristics variation~~vegetation variance~~, accounting for 34.3% of the total ~~variance~~ explanation that was explained by all the investigated environmental factors (Fig. S7).

Table 2. The selection of the key influencing factors based on the marginal and conditional effects obtained from the forward selection of the Monte Carlo test.

Environmental factors	Marginal effects	Environmental factors	Conditional effects	*P* value	*R* value (%)
	Percentage of variance explained (%)		Percentage of variance explained (%)		
SWC1	20.2	SWC1	20	0.002	27.03
SWC3	18.8	SWC3	14	0.004	18.92
SWC2	12.3	BD	10	0.006	13.51
BD	11.4	SWC100cm_a	9	0.018	12.16
TN	7.1	GWT_a	4	0.078	——
Silt	7.0	GWT_c	3	0.096	——
Sand	6.1	TP	2	0.250	——
SOM	4.1	Clay	2	0.282	——
Clay	3.8	TN	2	0.296	——
SWC2cm_a	3.7	SWC2cm_a	2	0.308	——
TP	3.6	SWC100cm_c	1	0.444	——
Gravel	2.6	SWC2cm_c	3	0.112	——
SWC100cm_a	2.5	SWC2	1	0.620	——
GWT_c	1.8	Silt	1	0.636	——
GWT_a	1.4	TS	<0.1	0.788	——
SWC100cm_c	0.6	SOM	<0.1	0.932	——
TS	0.5	Sand	<0.1	0.992	——
SWC2cm_c	0.1	Gravel	<0.1	0.960	——
		Total	74	0.036	——

R value represents the relative proportion of individual explanation to the total variance explanation.

SWC1, 0–30 cm soil moisture; SWC2, 30–100 cm soil moisture; SWC3, 100–200 cm soil moisture; BD, bulk density; SOM, soil organic matter; TN, total nitrogen; TP, total phosphorus; TS, total salt content. GWT_a, annual average of groundwater table; SWC2cm_a, annual average of 2 cm soil moisture; SWC100cm_a, annual average of 100 cm soil moisture; GWT_c, annual variability of groundwater table; SWC2cm_c, annual variability of 2 cm soil moisture; SWC100cm_c, annual variability of 100 cm soil moisture.

Table 3. The percentage of community characteristic variation explained by different groups of environmental factors.

Fraction	Variation	% of all	% of explained	F	*P*
a	0.435	43.5	98.4	5.9	0.008
b	0.159	15.9	35.9	4.0	0.088
c	0.152	15.2	34.3	2.2	0.016
Total explained	0.442	44.2	100	5.9	——

a: spatial distribution factors, including 0–30 cm soil moisture (SWC1), 30–100 cm soil moisture (SWC2), 100–200 cm soil moisture (SWC3), bulk density (BD), ~~SWC1, SWC2, SWC3, BD, ~~clay, silt, sand, gravel, soil organic matter (SOM), total nitrogen (TN), total phosphorus (TP), total salt content (TS)~~SOM, TN, TP, TS~~; b: temporal factors, including~~–~~ annual average of groundwater table (GWT_a), annual average of 2 cm soil moisture (SWC2cm_a), annual average of 100 cm soil moisture (SWC100cm_a), annual variability of groundwater table (GWT_c), annual variability of 2 cm soil moisture (SWC2cm_c), annual variability of 100 cm soil moisture (SWC100cm_c)~~SWC2cm_a, SWC100cm_a, GWT_a , SWC2cm_c, SWC100cm_c, GWT_c~~; c: ~~the ~~variation that jointly explained by group a and b. Variation: the variance explained by different fraction when the total variance is 1; % of all: the proportion of variation explained by different fraction; % of explained: the relative proportion of individual explanation to the total explanation.

4 Discussion

4.1 The spatial distribution in Heihe desert riparian forest and its influencing factors

In the downstream Heihe River Basin, community height and density declined significantly as the dominant species changed from trees to riparian-desert shrubs with increasing distance from the river channel. Community coverage reached two local maxima at 1000 m and 3000 m from the river, with diverse shrub and herb layers. The spatial distribution of community diversity can illustrate how vegetation responds and interacts with numerous environmental factors along different ecological gradients (Oksanen and Minchin, 2002). ~~Our findings under these hyperarid conditions were different~~ Different from ~~those found ~~studies in the relatively humid regions (e.g., coastal regions or boreal forest), which suggest~~s~~ that riparian forest species diversity either decreases~~d~~ or forms~~ed~~ a unimodal pattern with increasing distance from the stream (Pabst and Spies, 2011; Macdonald et al., 2014), our findings in the downstream Heihe (i.e., hyperarid conditions) showed that community diversity formed a bimodal pattern along the distance from the river channel. ~~At the distance of 1000 m from the river channel, the~~We attributed fine-textured soils found in the upper soil layer~~ partly contributed~~ to the high species diversity ~~of this region~~at sites located about 1000 m ~~from river channel~~from the river channel. ~~They ~~Previous study shows that ~~These ~~fine-textured soils increase~~d~~ the soil water holding capacity and improve~~d~~ the gravimetric moisture content in the upper soil layer, which provide~~d~~ suitable habitat for the growth of diverse herb species with shallow rooting systems (Liu et al., 2008). At the same time, other study finds that the presence of the deep-rooted tree, *Populus euphratica*, can redistribute~~d the~~ deep soil water to the shallow layer as a strategy ~~for~~ of mutualism, benefiting the growth of shallow-rooted herbaceous species (Hao et al., 2013). Similar mechanism also ~~occurred~~ occurs at further distance (i.e., 3000 m) from the river. Although situated in the transition region (from riparian forest to desert shrubs), ~~the~~ soils at the distance of 3000 m from ~~the~~ river channel ~~was~~ were still rich in fine particles (clay and silt; 35.6%) (Table S3), brought by the interaction between wind erosion and shrubs (Ravi et al., 2009). The presence of fine soil particles can increase~~d~~ the soil water holding capacity and soil nutrients around the shrub patches (‘fertile islands’) (Ravi et al., 2010), allowing the growth of some xerophytic herbs and increasing the ~~level of~~ community diversity in ~~this~~ arid region (Stavi et al., 2008). By contrast, Simpson dominance index peaked at the distances of 500 m and 2000 m (Fig. 4 h), likely due to inter-species competition for water and nutrient resources reported by previous studies (Maestre et al., 2006). At these sites, ~~low community diversity dominated by a few species contributed greatly to the diversity index (Zhu et al., 2013). D~~dominant species with ~~a~~ high importance value (i.e., trees and shrubs at 500 m and 2000 m, respectively) often ~~had~~ has high competition for resources, thus, hindering the growth of other species (i.e., herbs) and increasing the dominance index of the community (Koerselman and Meuleman, 1996).

Among different environmental factors, changes in water availability associated with soil properties are considered to be the most important selective forces which ~~shaping~~ shape ecosystem stability in hyperarid zones (Rosenthal and Donovan, 2005, Ravi et al., 2010, Feng et al., 2015). Our study showed that spatial heterogeneity of soil properties was the major driving force for the spatial distribution of vegetation, with SWC1, SWC3 and BD contributing 59.46% of the total explanation of vegetation variance (Table 2). As the fine roots of most herb species are mainly distributed within the top 30 cm of the surface soils (Fu et al., 2014),~~The~~ surface soil moisture (0~~-~~–30 cm soil moisture; SWC1) likely became the main water source for the herb layers and contributed to ~~the~~ a high coverage of ~~the~~ dominant herb species~~layers, as it is the main water source for the dominant herb species~~, such as *S. alopecuroides* and *K. caspica*~~, whose fine roots were mainly distributed within the top 30 cm of the surface soils according to the previous study in Heihe desert riparian forest (Fu et al., 2014)~~. Meanwhile, deep soil moisture (SWC2 and SWC3) mainly influenced the community density and coverage. SWC2 (30~~-~~–100 cm soil moisture) ~~was~~ is the main water resource for shrubs such as *T. ramosissima*.~~ and~~ SWC3 (100–200 cm soil moisture), recharged by the flood-raised groundwater table

(Liu et al., 2015), ~~wa~~is the main water source for phreatophytes such as *P. euphratica* or desert shrubs (Yi et al., 2012). As trees and shrubs contributed greatly to ~~the~~ community composition, the increase in SWC2 and SWC3 could significantly promote vegetation growth~~, and increase~~ community density and coverage.

Apart from ~~the~~ soil moisture, ~~the~~ soil physical properties were also important in determining the spatial distribution of ~~the~~ vegetation community in our study. Bulk density and soil composition (clay, silt, gravel), which ~~were~~ are critical for water and nutrient holding capacity (Stirzaker et al., 1996; Meskinivishkaee et al., 2014), mainly influenced ~~the~~ community density, community coverage, shrub coverage and diversity indices (Table 1). Previous study shows that s~~S~~oil with ~~a~~ low bulk density usually ~~had~~ has high water and nutrient holding capacity associated with fine soil particles as opposed to soil with high bulk density ~~which is often consisted of coarse soil particles~~ (Ravi et al., 2010). Low water holding capacity associated with coarse soil particles ~~The latter could~~ can induce water stress and limit vegetation growth, especially for herb species, which contribute~~d~~ greatly to ~~the~~ community coverage, density and diversity (Stirzaker et al., 1996). Interestingly, we found that soil nutrients explained no more than 0.1% of the vegetation variance and that SOM (soil organic matter) was negatively correlated with the species richness (Table 1, Table2). ~~These~~ Our findings were different from the positive relationship commonly found between SOM and species richness in semiarid zones (e.g., the Loess Plateau) (Jiao et al., 2011; Yang et al., 2014). Although SOM determines soil nutrient storage and the supply of available nutrients, our sites in the hyperarid zone were ~~often~~ characterized by barren soil with less than 1% ~~soil organic matter~~SOM (Fig. S5d, Table S3). Such a low amount of SOM might not be able to boost the growth of various species in desert riparian forests. At the same time, the dominant species (i.e., *P. euphratica* and *T. ramosissima*), despite producing a high amount of litter, also ~~had~~ has high competition for resources, hindering the diversity and growth of other species (Su, 2003).

4.2 The temporal variation in Heihe desert riparian forest and its influencing factors

Our results showed that ~~the~~ NDVI ~~has~~ generally increased since the implementation of the ecological water conveyance project in 2000, except for an initial decrease between 2000 and 2002, likely due to the lagging effect and the relatively low amount of runoff during these years (Jin et al., 2008). With better water availability (e.g., increased surface soil moisture and ~~a higher~~ groundwater table)~~, even at~~

~~the furthest distance from the river (2000-3000 m)~~, the conversion of sparsely forested land or bareland to shrubland and grassland ~~at these distances~~ likely contributed to ~~this~~ the increase of NDVI, especially at the furthest distance from the river (2000–3000 m) (Fig. 3). ~~In~~ By contrast, ~~the~~ NDVI near the river bank underwent a slight decrease during some recent years (2012~~-~~–2014), likely due to the conversion of shrubland to sparse forest land (Fig. 3, Fig. 5 b).~~,~~ Other factors such as increasing grazing pressure and tourism pressures as reported by Hochmuth et al. (2014), may also contribute to the decrease in NDVI around the periphery of the river.~~in the periphery of the river (Todd., 2006), and high tourism pressure (Hochmuth et al., 2014) reported by previous studies in recent years.~~

Our results also indicated that the NDVI at different distances from the river channel was affected by the spatial heterogeneity of soil properties, particularly soil moisture and bulk density, explaining 45.95% and 13.51% of the vegetation variance respectively (Table 2). All three soil moisture layers (SWC1, SWC2 and SWC3) positively affected the annual average of NDVI (NDVI_a) by supplying water to both shallow- and deep-rooted riparian vegetation (Fu et al., 2014). ~~The d~~Deep soil moisture (SWC3), recharged by the increasing groundwater table, ~~wa~~is particularly important for the shrub and tree layers (e.g., *P. euphratica* and *T. ramosissima*) (Yi et al., 2012), which contributed largely to the increase rate of NDVI in ~~this~~ Heihe desert riparian forest. Bulk density accounted for 13.51% of the total explanation of the vegetation variance and was negatively correlated with the annual average of NDVI (NDVI_a) and the annual variability of NDVI (NDVI_c). Study shows that, i~~I~~n the hyperarid zone, soils with high bulk density ~~were~~ are often characterized ~~as having~~by a high proportion of coarse soil particles but low clay content~~(e.g., sites at distances of 2500 and 3000m from the river channel; Fig. S5b, c in the Supplement)~~ (Ravi et al., 2009). In general, ~~This resulted~~ results in low water holding capacity in the upper soil layer ~~and~~ may ~~constrained~~ constrains the growth of shallow-rooted vegetation, ~~thus~~ lower~~ing~~ the average NDVI and inhibit~~ing~~ the NDVI increase~~at each distance from the river channel~~.

Apart from soil, the temporal variation in runoff driven by the ecological water conveyance played an important role in ~~driving~~ influencing the annual variability of the NDVI in this desert riparian forest. ~~This The runoff significantly improved improves the water conditions by lifting the groundwater table and increasing the soil water content (Zeng et al., 2016).~~ However, ~~we found that~~ the correlation between runoff and NDVI was stronger with that of the following year than that of the same year (Fig. 6), consistent with previous findings (Jin et al., 2010) which indicate~~d~~ the lagging effects of runoff.

The~~se~~ lagging effects were unsurprising, considering that the increase in runoff needs to undergo a series of hydrological (e.g., seepage, interflow, groundwater movement) and ecological processes (e.g., vegetation water uptake and water utilization) to increase groundwater, soil moisture, and vegetation growth (Williams et al., 2006; Liu et al., 2012). Compared to the significant relationship between the spatial heterogeneity of soil moisture (e.g., SWC3) and the annual variability of NDVI (~~e~~i.~~g~~e., NDVI_c) (Table 1), there was weaker relationship between the annual variability in water availability (~~e~~i.~~g~~e., SWC2cm_c, SWC100cm_c, GWT_c) and the annual variability of NDVI (~~e~~i.~~g~~e., NDVI_c). We suggested that a~~A~~ combination of ~~those~~ hydrological and ecological~~aforementioned~~ processes in the Heihe riparian zone ~~also~~ may result~~ed~~ in ~~the~~ a more stable increase ~~growth rate~~ of groundwater and soil moisture during 2000~~-~~–2014 (Fig. S6a, b, c) compared to the amount of runoff that showed significant annual fluctuations (Fig. S6d), thus contribute less to the NDVI variability. ~~Therefore, there were weaker relationships between the annual variability in soil moisture and groundwater (e.g., SWC2cm_c, SWC100cm_c, GWT_c) and the annual variability of NDVI (e.g., NDVI_c) than between the spatial heterogeneity of soil moisture (e.g., SWC3) and the annual variability of NDVI (e.g., NDVI_c) (Table 1).~~ In addition, temporal variation of soil moisture and groundwater was derived from retrieved remote sensing dataset. T~~t~~he deviations between simulations and observations in temporal variation of soil moisture and groundwater could also partly account for its weak correlations with the community characteristics~~the weak correlations between the variability of soil moisture, groundwater and community characteristics, as the variation of soil moisture and groundwater was derived from the remote sensing dataset~~.

Compared to the spatial heterogeneity of the soil properties, the temporal variation factors only accounted for 35.9% of the total explanation (Table 3). Except for the possible influence of the accuracy of the retrieved remote sensing dataset, lack of data regarding the temporal variation of soil properties could also ~~have~~ partly accounted for the low explanatory power of temporal influencing factors. Although studies show that most of the physical and chemical properties of the soils remain~~ed~~ unchanged during the 15 years' ~~of~~ ecological restoration (Cao et al., 2010; Chen et al., 2014), some of those soil properties, such as soil organic matter, might change due to vegetation recovery during ecological restoration. Future studies that include the temporal variation in soil properties might therefore be required to comprehensively address how temporal variation in environmental factors impacts on vegetation variation.

4.3 Community resilience of desert riparian forests and implications for ecological restoration

Although community diversity was generally low at most sites in the downstream Heihe River Basin, our findings suggested that there were some sites with significantly higher community diversity, for example those at distances of 1000 m and 3000 m from the river channel (Fig 4). Consistent with other finding~~s~~ (Hao et al., 2013), high resistance to ~~drought~~ water stress was observed at these distances from the river channel, with trees and shrubs can lifting water up from the deeper to shallower layers as a strategy for mutualism. Different species contribute~~d~~ differently to the ecosystem functions (e.g., trees and shrubs with large crowns mainly contribute to sand fixation, while diverse herbs contribute~~d~~ to biodiversity), maintaining a stable habitat after drought stress and/or human disturbance (Krieger et al., 2001). Indeed, species-rich communities can maintain ecosystem functions during stress-based perturbations due to the complementary of functional traits and ecological redundancy (Luck et al., 2013; Isbell et al., 2015).

In contrast, communities at the other distances from the river channel could easily undergo degradations, such as that at the distance of 500 m from the river channel, indicated by the decreasing NDVI in recent years (Fig. 5a). ~~While e~~Exposure to human disturbance (e.g., tourism, grazing) ~~might~~ may exacerbate the effects of ~~potentially change soil physical properties and reduce ecosystem services such as water and soil conservation in this region (Zhao et al., 2012; Daryanto et al., 2013), the~~ projected rise in temperature and drought frequency ~~could lead to degradation~~ in regions that are far from the river channel and experience the limited influence of ecological water conveyance (Si et al., 2005; Zhang et al., 2015a~~Zeng et al., 2016~~) by~~potentially~~ changinge soil physical properties and reduceing ecosystem services such as water and soil conservation~~ in this region~~ (Zhao et al., 2012; Daryanto et al., 2013)~~,~~. Our study showed that water availability and spatial heterogeneity of soil properties were the main driving forces for the spatial distribution and temporal variation of restored desert riparian forest at Heihe River Basin. To halt degradation in this critical zone, ~~As conservation measures,~~ we suggested to build~~ing~~ natural channels perpendicular to the river to fully extend the influencing scope of the ecological water conveyance and benefit the regions far from the river bank (Zhang et al., 2011b). At the same time, multiple conservation measures such as establishing critical fenced areas for ecological protection and constructing artificial shields or establishing straw checker boards on the bare land to prevent erosion, ~~are~~ were recommended around the periphery of the river.

5 Conclusions

Through extensive field observations at multiple desert riparian forest locations and analyses of long-term remote sensing images, we found that community characteristics differed spatially and temporally with distance from the river channel. In locations with high diversity indices, high community resilience could be maintained by the multiple interactions between vegetation and soil properties. In contrast, regions with low diversity might face greater challenges under climate change and intensive human disturbance. Since the influence of ecological water conveyance is currently limited to a distance of 1000–2000 m from the river (Si et al., 2005; Zeng et al., 2016), extending the distance of ecological water conveyance ~~is~~ was recommended to recharge the surface soil moisture and benefit the growth of ground cover (i.e., herb species), which contribute greatly to species diversity. In addition, multiple conservation measures that protect the soil structure (e.g., artificial soil cover and livestock grazing exclusion) ~~are~~ were recommended for regions close to the river to reduce the adverse effects of grazing on soil properties. ~~Unless these necessary precautions are taken, desert riparian forests may become fragmented and experience significant community transition under projected climate change scenarios and more intensive human disturbance.~~

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