Responses to the Editor and Reviewers:

We thank the editor and reviewers very much 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 to meet the standard of HESS journal. We have gone through all the comments and amended the original manuscript based on the suggestions and comments. In the following pages we provide point-by-point responses to the editor's and reviewers' comments. Please refer to the attached manuscript with track-changes mode for further details.

Responses to the Editor:

Editor: Both of the reviewers found that there had been significant improvements in the manuscript, but that important work remained to be done concerning the quality of the presentation. I am therefore returning the manuscript for further revision so that this new round of comments can be used to bring the standard of the presentation in line with the expectations of the journal.

Authors: We thank the editor for giving us a valuable chance to further improve this manuscript and thank the reviewers for giving details comments and suggestions for this manuscript. We have gone through all the comments and amended the original manuscript based on the suggestions and comments. To improve the quality of presentation, we have carefully condensed and revised the language throughout the manuscript. In addition, the language in our manuscript has been polished by a native English speaker.

Editor: Reviewer #1 has particularly detailed comments that can be of help in addressing issues that detract from reader's ability to readily grasp and appreciate the points being made by the manuscript.

Authors: We thank the Reviewer #1 for giving detailed comments to help us improve the presentation quality of this manuscript. Based on the comments of Reviewer #1, we have carefully revised the manuscript. To improve the readability of this manuscript, the language in our manuscript has been polished by a native English speaker.

Editor: Reviewer #3 has more general comments that will require more work to address, but are still of great value. These include identifying how your work complements or changes the state of the science in relation to what earlier work has shown. And while it is a great step forward to have used remote sensing data to infer the temporal variability in soil moisture, the inferred soil moisture status should be compared to the direct observations of soil moisture and groundwater where available.

Authors: We thank the Reviewer #3 for giving valuable suggestions on this manuscript. We have carefully revised the manuscript according to the comments of Reviewer #3.

To figure out the gaps of studies and highlighted the novelty of our study, we rewrote the

Introduction section. The gaps of previous study were: 1) lack of study that accurately delineate the temporal variation of desert riparian forest; 2) lack of research that incorporates the spatial and temporal variation of desert riparian forest due to the scale inconsistent between spatial and temporal data. The novelty of this study were: 1) accurately delineate the temporal variation of Heihe desert riparian forest along different distances from river channel based on high resolution images; 2) explore both the spatial distribution and temporal variation of Heihe desert riparian forest as well as their influencing factors. Please see Page 5 Line 11-21 in the Introduction section for details: "While large-scale remote sensing data (e.g., MODIS-NDVI, SPOT-NDVI) could 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." We also illustrated the novelty of this study in the objectives part at the Introduction section. Please see Page 6 Line 1-4: "(i) explore both the spatial distribution and temporal variation of Heihe desert riparian forest at different distances from the river channel, (ii) disentangle the impacts of spatial heterogeneity in soil properties and temporal variation in water availability on the vegetation community"

The providers of the retrieved remote sensing data validated this dataset in the published paper (Zeng et al., Hydrology and Earth System Sciences, 2016). Comparisons of simulation outputs and observations from automatic weather station systems and water wells demonstrated that CLM_RIV showed considerable ability to reproduce the natural conditions along riverbanks. The soil moisture was well simulated, while the groundwater table was much deeper than the observation groundwater. Based on the validation by the providers, we further corrected the simulated groundwater table by using the monitoring groundwater data along a groundwater monitoring transect. We added the validation of the retrieved remote sensing data in the Supplement. Please see Please see Page 3-5: "S4 Validation of the retrieved remote sensing data" in the Supplement.

Responses to the Reviwer#1:

Major issues

Reviewer: I reviewed an earlier version of this MS and find this revision much improved. The authors implemented several of my suggestions, gathering a large amount of spatial and long-term data (NDVI and soil moisture) to support their conclusions. However, the manuscript remains in places inconsistent, incomplete, or unclear, and language must be improved (as of now, it is not up to the standards of HESS).

Authors: We thank the reviewer for giving us constructive suggestions to improve the quality of this manuscript during these two rounds of review. Following the reviewer's comment on the inconsistent, incomplete and unclear expression in this manuscript, we have carefully revised the language throughout the manuscript and invite a native English speaker to polish the whole manuscript.

Reviewer: The accuracy of the added remotely sensed soil moisture data needs to be stated to assess if patterns are significant. My comments are listed below (I did not report all the numerous language issues).

Authors: Following the reviewer's suggestion, we added the validation of remotely sensed soil moisture data in the Supplement. Please see Page 3 Line 21- Page 4 Line 9: "S4 Validation of the retrieved remote sensing data" in the Supplement: "1) Validation result of soil moisture. The provider of the retrieved remote sensing dataset used observation data from the automatic weather station (AWS) system of the Bajitan Gobi Desert station in the middle of Heihe River to validate the simulation of soil moisture. The result showed that the variation pattern of soil moisture was similar to the observation. Although surface soil moisture simulation had positive bias in spring and winter, the simulation could generally capture the peak value of soil moisture induced by rain events in summer. Please refer to Figure 6 (c) in the paper of Zeng et al (Zeng et al., Hydrology and Earth System Sciences, 2016; www.hydrol-earth-syst-sci.net/20/2333/2016/). In our manuscript, we mainly emphasized on the depiction of temporal variation of soil moisture and the vegetation growth was mainly affected by soil moisture condition in summer. Thus considering that the remote sensed soil moisture data could well reflect the temporal variation pattern and water condition across different distances from river channel in the vegetation growing season, we used this remote sensed soil moisture data to depict the temporal variation of soil moisture in this manuscript (Fig. S6 a, b)."

We added the relevant explanation of validation of data in the Method section, Please see Page 10 Line 8-9 in the manuscript: "The validation of the retrieved remote sensing data is provided in the Supplement S4". As there were still deviations between simulated data and observed data, we added the possible influence of the remotely sensed soil moisture data accuracy on the result of our study in the Discussion section. Please see Page 31 Line 5-8 in the manuscript: "In addition, the deviations between simulations and observations could also partly account for the weak correlations between variability of soil moisture, groundwater and community characteristics as the variation of soil moisture and groundwater was derived from retrieved remote sensing dataset."

We have carefully checked throughout the manuscript and revised the all language issues. And then, the language in our manuscript has been polished by a native English speaker. We hope the revised manuscript can up to the standards of HESS journal.

Minor issues:

Reviewer: P2, L15: I would report the 43.5% of the total variance explained, rather than the fraction of explained variance captured by spatial heterogeneity factors. The 43.5% figure better represents the overall explaining power.

Authors: As we analyze the influencing factors of vegetation distribution pattern and temporal variation separately, we rewrote this sentence. Please see Page 2 Line 15-20 in the manuscript: "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 the temporal variation of water availability (e.g., annual average and variability of groundwater, soil moisture and runoff)."

Reviewer: P2, L17: missing word "35.9% of the total…"

Authors: As we rewrote the abstract, we delete this sentence. Please see Page 2 Line 23 in the manuscript.

Reviewer: P2, L19: add that the 100 cm moisture is obtained from remote sensing products

Authors: We revised this sentence carefully according to the reviewer's suggestion. Please see Page 2 Line 24-29 in the manuscript: "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."

Reviewer: P3, L25: check verb tenses.

Authors: We checked the verb tenses of this sentence according to the reviewer's suggestion. Please see Page 4 Line 4-7 in the manuscript: "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)."

Reviewer: P4, L6: soil moisture is water, so writing "Apart from water… soil moisture…" seems contradictory.

Authors: We revised this contradictory expression. Please see Page 4 Line 18-20 in the manuscript: "Apart from groundwater, soil properties, such as soil moisture, soil physical and soil chemical properties also shape the community characteristics by influencing the ecological and hydrological processes"

Reviewer: P4, L11: "another study"

Authors: As we rewrote the Introduction, we delete this sentence. Please see Page 4 Line 23 in the manuscript.

Reviewer: P4, L12: sentence structure does not work "with… exerted"?

Authors: According to the reviewer's suggestion, we revised the grammatical error. Please see Page 4 Line 24-28 in the manuscript: "As different depths of soil moisture exert different impacts on vegetation (D'Odorico et al., 2007; Fang et al., 2016), a decline in soil moisture would reduce the abundance of tree and herb species, resulting in a community shift towards drought-tolerant vegetation types with distance from the river channel (Zhu et al., 2014)."

Reviewer: P7, L9: "water conveyance was delivered" (?)

Authors: We revised the grammatical error according to the reviewer's suggestion. Please see Page 8 Line 13 in the manuscript: "Our field survey was conducted in July 2015 after the ecological water conveyance was delivered".

Reviewer: P7, L16 and elsewhere: gradients should include measurement points at different distances. Here it seems you are referring to zones or bands at a given distance from the river.

Authors: We thank the reviewer for pointing out the unclear expression. We measured points at different distances in field experiment, thus we referred to gradients instead of band in the field sampling. To make it clear, we replaced "gradients" with "distances from the river channel" and carefully checked the unclear expression throughout the manuscript. Please see Page 8 Line 19- Page 9 Line 2 in the manuscript: "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."

Reviewer: P7, L25: try to be specific "number of herb species" or "number of individual plants"?

Authors: We revised this sentence carefully according to the reviewer's suggestion. Please see Page 9 Line 9-11 in the manuscript: "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"

Reviewer: Section 2.3: clarify which product you are using for the soil moisture fields and the expected accuracy. Without that, it is hard to trust the observed trends.

Authors: We added the resource of the retrieved remote sensing data product in the "2.3 Temporal data collection and processing". Please see Page 10 Line 2-9 in the manuscript: "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) using the land model CLM4.5 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 Supplement S4."

As to the accuracy of the soil moisture data, the providers of the dataset validated this dataset in the published paper (Zeng et al., Hydrology and Earth System Sciences, 2016). The result showed that soil moisture derived from the retrieved remote sensing data could well reflect the temporal variation pattern. We added the validation of remote sensed soil moisture in the Supplement. Please see Page 3 Line 21- Page 4 Line 9: "S4 Validation of the retrieved remote sensing data" in the Supplement: "1) Validation result of soil moisture. The provider of the retrieved remote sensing dataset used observation data from the automatic weather station (AWS) system of the Bajitan Gobi Desert station in the middle of Heihe River to validate the simulation of soil moisture. The result showed that the variation pattern of soil moisture was similar to the observation. Although surface soil moisture simulation had positive bias in spring and winter, the simulation could generally capture the peak value of soil moisture induced by rain events in summer. Please refer to Figure 6 (c) in the paper of Zeng et al (Zeng et al., Hydrology and Earth System Sciences, 2016; www.hydrol-earth-syst-sci.net/20/2333/2016/). In our manuscript, we mainly emphasized on the depiction of temporal variation of soil moisture and the vegetation growth was mainly affected by soil moisture condition in summer. Thus considering that the remote sensed soil moisture data could well reflect the temporal variation pattern and water condition across different distances from river channel in the vegetation growing season, we used this remote sensed soil moisture data to depict the temporal variation of soil moisture in this manuscript (Fig. S6 a, b)."

Reviewer: Also, how was soil moisture sampled in 2013-2015? Same sampling regime as in the present study?

Authors: The soil moisture sampled in 2013-2015 was not derived from the field sampling as the soil gravimetric water content sampled in the 2015. The soil moisture sampled in 2013-2015 was soil volumetric water content that recorded in a riparian forest site (101°8′1″E, 41°59′25″N) using micrometeorological sensors. This monitoring data was used for proving that soil moisture under 20 cm was relatively stable and could represent water condition at the sampling site in the Supplement ("S2 The diurnal and annual variation of soil moisture at different soil depth in desert riparian forest site."). We added the resource of this soil moisture data in the Method section. Please see Page 10 Line 15-19 in the manuscript: "The diurnal and annual variations of soil moisture were obtained from the 2013-2015 monitoring data of soil moisture, recorded at 0.5 Hz, with 10 min averages through a suite of micrometeorological sensors (CR800, CR23X, CR23XTD, Campbell Scientific Inc.) that installed in Heihe riparian forest (101°8′1″E, 41°59′25″N)(doi:10.3972/hiwater.241.2015.db; doi:10.3972/hiwater.318.2016.db) (Liu et al., 2011).”

Reviewer: P9, L3: as stated, RH and RC are defined in the same way – do they differ or not?

Authors: We thank the reviewer for pointing out the expression error. Actually, RH referred to the relative height, we revised this error. Please see Page 11 Line 3-4 in the manuscript: “where *RDen* is the relative density, *RDom* is the relative dominance, RH is the relative height and *RC* is the relative coverage.”

Reviewer: Figure 3, legend: “Unchanged”

Authors: We revised the grammatical error according to the reviewer’s suggestion. Please see Page 16 Figure 3 in the manuscript.

Reviewer: P14, L10: sentence structure does not work “with… were”?

Authors: Following the reviewer’s suggestion, we rephrased this sentence. Please see Page 17 Line 6-9 in the manuscript: “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).”

Reviewer: Figure 5(b): units are missing. Values suggest that this NDVI change rate is not simply calculated as the difference between NDVI values between two years. Please clarify what is shown on the y-axis.

Authors: We thank the reviewer for pointing out this mistake. We recalculated the NDVI change rate based on the equation as follows: NDVI change rate = (NDVI at the year of 2014—NDVI at the year of 2000)/ NDVI at the year of 2000*100%. We add the unit (%) at y-axis and revised the Figure 5(b). Please see Page 18 Figure 5 in the manuscript. In addition we added the calculation of NDVI change rate at the Method section. Please see Page 12 Line 12-13 in the manuscript: “The NDVI change rate was calculated based on the percentage change of NDVI from 2000 to 2014.”

Reviewer: P17, L2: “gradients” or “bands” at a given distance?

Authors: We derived the NDVI from the sampling points at different distances instead of the average value of a band. To make it clear, we replaced “gradients” with “distances from the river channel” in this sentence. Please see Page 8 Line 2-4 in the Supplement: “The depth of groundwater table increased consistently across different distances from the river channel since 2000, following the downstream runoff which more than doubled during the research period, from 2.07×108 m^3 in 2000 to 5.11×108 m^3 in 2014.”

Reviewer: Figure 8, caption: “Pearson correlation coefficient”

Authors: We revised the grammatical error according to the reviewer’s suggestion. Please see Page 22 Line 13-14 Figure 6 in the manuscript: “Pearson correlation coefficients of NDVI-runoff and one-year lag NDVI-runoff at different distance from the river channel.”

Reviewer: Section 3.5: not clear how spatial and temporal data have been integrated. In Table 3, the fractions of explained variance in space and time are combined, yielding the odd result that adding explanatory variables (i.e., adding temporal factors to the spatial factors) decreases the fraction of explained variance. Overall this part of the results is not clear. Also check the number of significant digits in Table 3.

Authors: We thank the reviewer for pointing out this unclear expression. Actually, the “a+b” in the Table 3 means the variation that jointing explained by the temporal factors to the spatial factors instead of the total variation that explained by the temporal factors to the spatial factors. To make it clear, we replaced the “a+b” with “c” and added the notation below the Table 3. Please see Page 24 Table 3 and Page 24 Line 3-4 in the manuscript: “c: the variation that jointly explained by group a and b”. We also drew a sketch map to illustrate the meaning of a, b, c in Table 3 as supplement. Please see the Page 8-9 in the Supplement: “S6 The sketch map explaining the meaning of a, b, c in Table 3”.

In addition, we checked the number of significant digits and kept at most three digits in Table 3. Please see Page 24 Table 3.

Reviewer: P21, L4: soil moisture is higher around 1000 m from the river because the soil has finer texture. This pattern has not to do with the available amount of water, but it is caused by using volumetric or gravimetric moisture content data across a texture gradient.

Authors: Following the reviewer’s suggestion, we rewrite this sentence and deleted the depiction of water availability. Please see Page 25 Line 5-8 in the manuscript: “They increased the soil water holding capacity and improved the gravimetric moisture content in the upper soil layer, which provided suitable habitat for the growth of diverse herb species with shallow rooting systems (Liu et al., 2008).”

Reviewer: P21, L11: fine particles are expected to decrease the infiltration capacity, not increase it (saturated hydraulic conductivity is lower in fine-textured soils)

Authors: We thank the reviewer for pointing out this mistake. We replaced the “soil infiltration capacity” with “soil water holding capacity”. Please see Page 25 Line 18-21 in the manuscript: “The presence of fine soil particles increased 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 diversity in this region (Stavi et al., 2008).”

Reviewer: P22, L2: check sentence structure “elevate of groundwater”?

Authors: As we rewrote the Discussion section, we deleted this sentence. Please see Page 28 Line 1 in the manuscript: “e.g., increased surface soil moisture and a higher groundwater table”.

Reviewer: P23, L10: “soil nutrients”

Authors: We revised the grammatical error and we checked the error carefully throughout the manuscript. Please see Page 27 Line 1-6 in the manuscript: “Soil with a low bulk density usually had high water and nutrient holding capacity associated with fine soil particles as opposed to soil with high bulk density which often consisted of coarse soil particles (Ravi et al., 2010).”

Reviewer: P23, L16: check sentence structure “vegetation recovery especially herbs”?

Authors: Following the reviewer’s suggestion, we rephrased this sentence. Please see Page 27 Line 6-8 in the manuscript: “The latter could induce water stress and limit vegetation growth especially for herb species, which contributed greatly to the community coverage, density and diversity”

Reviewer: P24, L4: “a sharp decrease”

Authors: In order to condense the manuscript, we delete this sentence. Please see Page 31 Line 25 in the manuscript.

Reviewer: P24, L29: tree cover has no significant relation with soil biogeochemical pools, including organic matter (if I interpret correctly Table 1), so the claim on the role of trees is not supported

Authors: We thank the reviewer for pointing out this inconsistent expression. We revised the sentence. Please see Page 32 Line 21-25 in the manuscript: “Different species contributed differently to the ecosystem functions (e.g., trees and shrubs with large crowns mainly contribute to sand fixation, while diverse herbs contributed to biodiversity), maintaining a stable habitat after drought stress and/or human disturbance (Krieger et al., 2001).”

Reviewer: P25, L4: “gradient” or “band”?

Authors: To make it clear, we replaced “gradients” with “distances from the river channel” in this sentence. Please see Page 32 Line 28- Page 33 Line 2 in the manuscript: “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).” To avoid unclear expression, we replaced “gradients” with “distances from the river channel" throughout the manuscript.

Reviewer: P25, L6: use "change" instead of "destroy"?

Authors: Following the reviewer's suggestion, we revised this sentence. Please see Page 33 Line 2-8 in the manuscript: "While exposure to human disturbance (e.g., tourism, grazing) might 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; Zeng et al., 2016)."

Reviewer: P25, L12 and L18: other odd sentences, please re-phrase.

Authors: Following the reviewer's suggestion, we rephrase these sentences. Please see Page 33 Line 2-8 in the manuscript: "While exposure to human disturbance (e.g., tourism, grazing) might 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; Zeng et al., 2016)." Page 33 Line 18-21 in the manuscript: "As conservation measures, we suggest building 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)."

In addition, we have carefully checked and revised other the language issues throughout the manuscript.

Responses to the Reviwer#3:

Major issues

Reviewer: The authors used one-time field survey data in July 2015 to detect the spatial pattern of community characteristics in desert riparian forest across different distances from the rivers, and NDVI data from 2000-2014 to analyze the temporal variation of desert riparian forests.

My first concern is that the gaps of previous studies to be figured out or the novelty of this study is not explicitly highlighted or addressed.

Authors: We thank the reviewers' suggestion. The gaps of previous study were: 1) lack of study that accurately delineate the temporal variation of desert riparian forest; 2) lack of research that incorporates the spatial and temporal variation of desert riparian forest due to the scale inconsistent between spatial and temporal data. The novelty of this study were: 1) accurately delineate the temporal variation of Heihe desert riparian forest along different distances from river channel based on high resolution images; 2) explore both the spatial distribution and temporal variation of Heihe desert riparian forest as well as their influencing factors.

To figure out the gaps of studies and highlighted the novelty of our study, we rewrote the Introduction section. Please see Page 5 Line 11-21 in the Introduction section in the manuscript for details: “While large-scale remote sensing data (e.g., MODIS-NDVI, SPOT-NDVI) could 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.” We also illustrated the novelty of this study in objectives part at the Introduction section. Please see Page 6 Line 1-4 in the manuscript: “(i) explore both the spatial distribution and temporal variation of Heihe desert riparian forest at different distances from the river channel, (ii) disentangle the impacts of spatial heterogeneity in soil properties and temporal variation in water availability on the vegetation community”

Reviewer: The second concern is that the effects of environment factors on spatial pattern and temporal variation of desert riparian forests should be analyzed separately. In the current version, it seems that there are mixed. The spatial pattern is mainly subjected to spatial heterogeneity of soil properties, soil water content and ground water, but the temporal variation is mainly affected by variation of soil water content, ground water and runoff. The soil properties did not played an important role in the temporal variation of desert riparian forests in certain cite as it almost remained unchanged.

Authors: Following the reviewers’ suggestion, we analyzed the influencing factors of distribution pattern of desert riparian forest and temporal variation of desert riparian forest in section 4.1 “The spatial distribution in Heihe desert riparian forest and its influencing factors” and section 4.2 “The temporal variation in Heihe desert riparian forest and its influencing factors” separately in the Discussion section. In the section 4.1, we first discussed the spatial distribution of desert riparian forest and then analyzed the effects of environment factors on spatial distribution of vegetation with the emphasis on the impact of spatial heterogeneity of soil properties (e.g., soil moisture, soil physical properties and soil chemical properties). Please see Page 24-27 in the manuscript: “4.1 The spatial distribution in Heihe desert riparian forest and its influencing factors”. In the section 4.2, we discussed the temporal variation of desert riparian forest and its influencing factors with emphasis on the variability of water availability (e.g., runoff, variation of soil moisture and groundwater). Please see Page 27-31 in the manuscript: “4.2 The temporal variation in Heihe desert riparian forest and its influencing factors”

In addition, as the soil physical and chemical properties almost remain unchanged reported by previous studies (Cao et al., Journal of Desert Research, 2010; Chen et al., Environmental Earth Sciences, 2014), we did not include the variation of soil properties in explaining the temporal variation of desert riparian forest, which may cause the low explanation of temporal variation factors in this study. We added these explanations in the section 4.2 in the manuscript. Please see Page 31 Line 9-18 in the manuscript: “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 data, 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 most of the physical and chemical properties of the soils remained 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.”

As the Discussion section was rewritten, we revised the Abstract section accordingly. Please see Page 2 Line 15-20 in the manuscript: “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 the temporal variation of water availability (e.g., annual average and variability of groundwater, soil moisture and runoff).”

Reviewer: Third, the writing is somewhat tedious, and it should be condensed and polished.

Authors: Following the reviewer’s suggestion, we condensed the manuscript in both Method and Result section. In the Method section, we condensed the content about study area and data resource. Please see Page 6-10 in the manuscript. In the Result section, we short the section 3.1 (Please see Page 13-14 in the manuscript: “3.1 Vegetation community types and temporal changes of vegetation composition”) and put the section of 3.3 “The spatial and temporal variation of water availability and soil properties” in the Supplement (Please see Page 6-8: “S5 The spatial and temporal variation of water availability and soil properties” in the Supplement). Moreover, we have carefully revised the language throughout the manuscript and the language in our manuscript has been polished by a native English speaker.

Minor issues:

Reviewer: 1. There were five transects along the river to conduct field survey. Is there any variability of vegetation characteristic among those transects?

Authors: We thank the reviewer for the question. We used the least significant difference

(LSD) test to determine the significance of vegetation characteristic variability among those transects. The vegetation characteristics didn't show significant difference ($P>0.05$) among five transects, thus we treated five transects as replicates in this manuscript. Please see Page 2-3: "S3 The variability of vegetation characteristic among five sampling transects" in the Supplement. We also added the relevant explanation in Method section. Please see Page 12 Line 3-4 in the manuscript: "The least significant difference (LSD) test was used to determine the significance of the variability in vegetation characteristics among five transects (Supplement S3)."

Reviewer: 2. The soil moisture and ground water during 2000-2014 were extracted from the retrieved remote sensing data. The results should be validated by comparing with measured data available in some years or some sites. This is important.

Authors: We thank the reviewer for giving us valuable suggestions on the validation of the retrieved remote sensing data. The retrieved remote sensing data was generated by the CLM_RIV model, a coupled model that combined the process of stream-aquifer interaction with the Community Land Model Version 4.5 (CLM4.5), based on the high-resolution ASTER DEM dataset, multi-source integrated Chinese land cover map (MICLCover), Heihe watershed allied telemetry experimental research land cover map (HiWATER Land Cover Map), and the China soil characteristics dataset. The providers of the dataset validated this dataset in the published paper (Zeng et al., Hydrology and Earth System Sciences, 2016). Comparisons of simulation outputs and observations from automatic weather station systems and water wells demonstrated that CLM_RIV showed considerable ability to reproduce the natural conditions along riverbanks. The soil moisture was well simulated, while the groundwater table was much deeper than the observation groundwater. Based on the validation by the providers, we further corrected the simulated groundwater table by using the monitoring groundwater data along a groundwater monitoring transect (i.e. Wulantuge transect). We added the validation of the retrieved remote sensing data in the Supplement. Please see Page 3-5: "S4 Validation of the retrieved remote sensing data" in the Supplement.

We added the relevant explanation of data validation in the Method section, Please see Page 10 Line 8-9 in the manuscript: "The validation of the retrieved remote sensing data is provided in the Supplement S4". As there were still deviations between simulated data and observed data, we added the possible influence of the accuracy of the remotely sensed soil moisture data on the result of our study in the Discussion section. Please see Page 31 Line 5-8 in the manuscript: "In addition, the deviations between simulations and observations could also partly account for 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."

Reviewer: 3. The Ejina Oasis is mainly subjected to the runoff at Donghe station, not Zhengyixia station which influences the whole downstream of Heihe River Basin.

Authors: We thank the reviewer for the suggestion. We replace the runoff of Zhengyixia station with the runoff of Donghe station. We made corresponding changes in the Method section. Please see Page 10 Line 20-23 in the manuscript: “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)”. And we recreated the corresponding Figures. Please see Page 22 Figure 6 in the manuscript and Page 8 Figure S6 d in the Supplement.

Reviewer: 4. The variation of groundwater across different distance should be shown in Fig. 6, and incorporated to the analysis of correlation between distribution pattern and environmental factors.

Authors: Following the reviewer’s suggestion, we added the spatial variation of groundwater across different distance from river channel. Please see Page 7 Figure S5h in the Supplement. As monitoring the groundwater table in all the sampled sites (35 sites) is difficult, we did not record the groundwater table at all sampling sites in this study. We obtained the groundwater monitoring data at one transect that near the Wulantuge Village (i.e. Wulantuge transect) and used the annual average groundwater during the monitoring period (2010-2012) to depict the spatial distribution of groundwater table along the distance from river channel (Figure S5 h). We added the data resource in the Method section. Please see Page 10 Line 20-23 in the manuscript: “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)”. We added the depiction of groundwater table variation across different distances. Please see Page 6 Line 13-15 in the Supplement: “The annual average groundwater table range from 2.16m near the river bank to 3.27m at the distance of 3000m from river channel. Generally, the groundwater table fluctuated declining with the distance from river.”

As we monitoring the groundwater at one transect not all sampling sites, we use the annual average groundwater (GWT_a) and annual average variability of groundwater (GWT_c) derived from the retrieved remote sensing data to explore how groundwater influence the vegetation characteristics. Please see Page 21 Table1 and Page 23 Table 2 in Result section and Please see Page 30 Line 30 -Page 31 Line 8 in the Discussion section: “A combination of those aforementioned processes also result in the more stable growth rate of groundwater and soil moisture during 2000-2014 (Fig. S6a, b, c) compared to the runoff fluctuations (Fig. S6d). 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, the deviations between simulations and observations could also partly account for 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.”

Groundwater data that derived from retrieved remote sensing data was validated by the sampling data in monitoring data along the Wulantuge transect. Please see in Page 4 Line 17-25 in the Supplement: “In our manuscript, to make the simulated groundwater table fit the actual range of groundwater table in the downstream Heihe, we corrected the simulated groundwater table data by establishing the regression relationship between simulation and observation along Wulantuge transect in the downstream Heihe (Fig. S3). After correction, the corrected groundwater table data (Fig. S4) showed the same temporal variation pattern across different distances from river channel with the simulated data and the groundwater table range from 2.5m-3.5m which was accorded with the range of observed groundwater table (Fig. S5 h). Thus, we use the corrected groundwater table data to analyze the temporal variation of groundwater (Fig. S6 c).”

Reference:

Cao, S. K., Feng, Q., Si J. H., Zhang, X. F., Liu, W., Chang, Z. Q.: Research on vegetation and environmental factors in Ejina Oasis: A review, Journal of Desert Research, 30:1416-1423, 2010.

Chen, X., Duan, Z., and Luo, T.: Changes in soil quality in the critical area of desertification surrounding the Ejina Oasis, Northern China, Environmental Earth Sciences, 72, 2643-2654, 2014.

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The spatial distribution ~~pattern~~ and temporal variation of desert riparian forests and their~~its~~ 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~~ pattern,~~ and temporal variation of desert riparian forests and their influencing factors is~~are~~ important for~~to~~ determining~~e~~ 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 ~~pattern~~ of desert riparian forests and their relationship with the environmental factors. ~~Across different distances from the river channel, we~~ We classified five types of vegetation communities at different distances from the river channel. Community coverage and diversity formed a bimodal pattern, peaking~~ed~~ 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~~across~~ 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~~already underwent~~ degradation since 2011. ~~Spatial heterogeneity of soil properties (e.g. soil moisture, soil physical properties and soil nutritionnutrients) and temporal variation of water availability (e.g. annual average and annual variability of groundwater, soil moisture and runoff)~~ 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 the temporal variation of water availability (e.g., annual average and variability of groundwater, soil moisture and runoff). ~~explained 74% of the vegetation variance. Spatial heterogeneity factors, explaining 43.5% of the vegetation variance, positively influenced the community diversity, structure, average NDVI and change variability of NDVI trend. Temporal variation factors accounting for 35.9% of the total variance explained, positively influenced the community density and average NDVI. With~~ Since surface (0-30 cm) and deep (100-200 cm) soil moisture~~,~~ and bulk density and the annual average of ~~100 cm~~ 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 ~~deficiency~~ (e.g., artificial soil cover and water conveyance channels) ~~are~~ 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 plays an important role in ecological processes and provides a variety of ecosystem services, such as sand stabilization and carbon sequestration (~~Naiman et al., 1993;~~ Décamps et al., 2004). Desert riparian forests, also known as 'Tugai forests', mainly located in the floodplains of the major Central Asian rivers, are considered to be~~as~~ the core ~~main body~~ of the riparian zone in ~~the~~ hyperarid areas~~,~~ ~~mainly located in the floodplains of the major Central Asian rivers~~ (Gärtner et al., 2014). They provide critical habitats for various species and function as an~~the~~ '~~"~~ecological shelter'~~"~~ against desertification in ~~the~~ hyperarid areas (~~Thevs, 2008;~~ Ding et al., 2016). However, due to their low diversity level and weak resilience, desert riparian forests are sensitive to disturbance and likely to be threatened by desertification under a changing environment (~~Ling et al., 2015;~~ 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 the human population ~~increase~~ and overexploitation of the upstream water resources led to significant degradation of the downstream desert riparian forests (Wang et al., 2014). Since 2000, the ecological water conveyance project (EWCP), a restoration project aimed to deliver water downstream has been implemented to restore the ecosystems of the Heihe River Basin (Wang et al., 2011) ~~(Yu et al., 2013)~~. Every year, approximately ~~about~~ 300 billion m^3 of water have been~~were~~ delivered using concrete channels, which were built perpendicular to the river ~~aiming~~ to expand the river impact and ~~to~~ deliver water for irrigation. While most of the downstream vegetation has been restored (~~Wang et al., 2014;~~ Lü et al., 2015), nearly 20% of the oasis area covered by desert riparian forests still underwent major degradation in spite of the rising groundwater level and better downstream water conditions (Zhang et al., 2011a~~; Lu et al., 2015~~). To conserve and restore this fragile ecosystem more effectively, studies that address the variation in~~of~~ desert riparian forests and their relationships with ~~the~~ environmental factors need to be conducted.

The spatial distribution ~~pattern~~ of community characteristics along an ecological gradient can reflect how~~desert riparian forests is the result of long-term interaction between vegetation~~ the spatial distribution ~~pattern~~ of vegetation was shaped by ~~and~~ multiple environmental factors~~, particularly water availability~~ (Goebel et al., 2012; Li et al., 2013). In the hyperarid zone, groundwater has been regarded as the major driving factor of vegetation distributions.~~With river acting as the main supply of water in desert riparian forests, the distance from river channel could be regarded as a proxy to water availability (including groundwater), which declined with the weakening of river influence (Hao et al., 2010; Chen et al., 2014).~~ Previous studies showed that s~~S~~pecies diversity ~~would~~ peaked where the groundwater depth was approximately~~around~~ 2-4 m~~,~~ before it started to decrease when~~once~~ groundwater dropped~~went~~ below 4-4.5 m and ~~deficiency in~~ soil moisture limitation occurred (~~Zheng et al., 2005;~~ Li et al., 2013). While this could be the case for some hyperarid zones (e.g., the Tarim ~~river~~River) where the groundwater drops~~sped~~ rapidly away from the river bank to approximately~~about~~ 6 m deep at a~~the~~ distance of 1000 m from the river channel (Aishan et al., 2013), the groundwater table remains~~sed~~ above 4 m at a~~the~~ distance of 3800 m from the Heihe R~~r~~iver channel (Wang et al., 2011; Fu et al., 2014). However,~~Yet~~ some sites have~~were~~ not been completely restored in~~at~~ the Heihe riparian zones, and the downstream vegetation community is still ~~shifted from multiple layers of trees~~ dominated by ~~to~~ shrubs instead of multiple layers of tree (He and Zhao, 2006; Zhang et al., 2011a). A p~~P~~revious study by Zhu et al. (2013) showed that Patrick's richness index and the Shannon–Wiener~~'s~~ diversity index for the~~of~~ downstream vegetation formed a bimodal pattern instead of a unimodal pattern with~~along~~ groundwater depth in the Heihe River Basin, indicating that there could be other factors affecting the spatial distribution of desert riparian forests.

Apart from groundwater~~water~~, soil properties, such as soil moisture, soil physical and~~ soil~~ chemical properties also shape the community characteristics 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 ~~the~~ desert riparian forests (Wang et al., 2012). ~~Interactions between communities and extreme environmental stress could cause non-unimodal responses in the hyperarid zone (Oksanen and Minchin, 2002), although other~~ another ~~study in semiarid zone showed a unimodal pattern (Li, 2006; Hao et al., 2010; Li et al., 2013). With~~ As different depths of soil moisture exert~~ed~~ different impacts on vegetation (D'Odorico et al., 2007; Fang et al., 2016), a~~the~~ decline in~~of~~ soil moisture would reduce the abundance of tree and herb species, resulting in a~~the~~ community shift towards drought-tolerant vegetation types ~~along the~~ with distance from the river channel (Zhu et al., 2014). Some studies have also found that ~~the~~ variation~~heterogeneity~~ in soil properties explains ~~was the reason for~~ the evolution of dominant species in arid areas and the changes in soil nutrients contribute greatly to species diversity (~~DíAz and Cabido 2001;~~ Yang et al. 2008).

~~As desert riparian forest is the main community that maintains the ecosystem function in hyperarid zone, comprehensive research on the spatial and temporal variation of the vegetation will benefit restoration of the whole area. Spatial distribution and~~ The temporal variation in~~of~~ 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-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 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. ~~Although variation of vegetation characteristic during restoration process and its relationship with runoff and groundwater have been addressed in previous studies by using large scale dataset (e.g., MODIS-NDVI, SPOT-NDVI) (Jia et al., 2011; Wang et al., 2014; Geng et al., 2014), they only captured the general trend of the whole study area rather than focusing on the desert riparian forest. More importantly, their data resolution could not accurately delineate the temporal variation pattern at different distances from river channel. Currently, there have been limited number of studies that tried to disentangle the impacts of spatial heterogeneity and temporal variation factors on the vegetation communities (Zhu et al., 2013; Xi et al., 2016) due to the lack of long term monitoring data, inhibiting the effective restoration of desert riparian zone.~~

In this study~~research~~, we aim to (i) explore both the spatial distribution and temporal variation of Heihe desert riparian forest at different distances from the river channel, (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.~~explore the impacts of those aforementioned factors and to examine the distribution pattern and temporal variation of vegetation communities in the Heihe desert riparian forest.~~ We used 3000 m transects~~investigated variability in desert riparian forests sites that are differently located along the~~ running perpendicular to~~direction from~~ the river channel to include different distances from the river channel and to depict the spatial distribution of vegetation (e.g., ~~-~~ c~~C~~hanges in~~of~~ floristic composition, community structure and diversity) at each distance from the river channel. ~~were used to depict community distribution pattern,~~ Consistent with this field sampling, we used the variation of the NDVI at each distance 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.~~and the variation of NDVI at each gradient from 2000-2014 was used to depict the temporal variation.~~ Spatial heterogeneity ~~factors~~ of soil properties (e.g., soil moisture, soil physical properties and soil nutrition) and temporal variation ~~properties~~ of water availability (e.g., annual average and annual variability of groundwater, soil moisture and runoff) were used to explain the vegetation community variance. ~~The objectives of this study were to: (1) explore the distribution pattern of desert riparian forest along the perpendicular direction from the river channel and the temporal variation of NDVI in desert riparian forest since 2000, (2) analyze the effect of spatial heterogeneity factors and temporal variation factors on the community characteristics of desert riparian forests, and (3) explore the community resilience of desert riparian forest along the distance from river and suggest suitable restoration and protection measures for desert riparian forests under changing environment.~~

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, n~~N~~orthwest 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 ~~(Qin et al., 2012)~~. This region has a typical continental arid climate with a mean annual temperature of 8.77 °C. 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). ~~Prevailing wind direction is northwest, mean annual wind velocity is 2.9-5.0 m s^{-1}, and annual number of gale (>8 m s^{-1}) days is 70 days or so (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 ~~the~~ East Juyan Lake and ~~the~~ West Juyan Lake in Ejina. The population ~~in~~ of the Ejina O~~o~~asis is 32,410 (Ejina statistical office, 2012). The local economy mainly depends on ~~the~~ cantaloupe farming~~plantation~~ 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~~Two~~ primary road~~s~~ is~~are~~ built parallel to the river channel, and another runs across the south of the oasis ~~respectively,~~. These roads are ~~mainly~~ used mainly for transportation and travel~~ing~~.

~~Due to sparse precipitation and hyperarid environment, Heihe River is the main source of recharge for the groundwater system in Ejina Oasis (He and Zhao, 2006). As the distance from river channel increases, water availability declines and the vegetation shifts from desert riparian forests to desert scrub.~~ The desert riparian forests are the main components of the Ejina O~~o~~asis. They mainly grow along the river banks and spread across the fluvial plain, with the dominant vegetation including *Populus euphratica*, *Tamarix ramosissima*, *Lyci~~e~~um ruthenicum*, *Sopho~~a~~ra alopecur~~i~~oides*, *Kare~~i~~linia caspica*, and *Peganum harmala* ~~(Zhao et al., 2016)~~. ~~The s~~Sparse and drought-~~-~~tolerant desert species, such as *Reaumuria soonga~~o~~rica*, *Zygophyllum xanthoxylon* and *Calligonum mongolicum~~nl~~* are mainly distributed in the Gobi D~~d~~esert. The main soil types in the area are shrubby meadow soil, aeolian soil and grey-brown desert soils. Saline-alkaline soils and swamp soils also exist in the lake basins and lowlands (Chen et al., 2014).

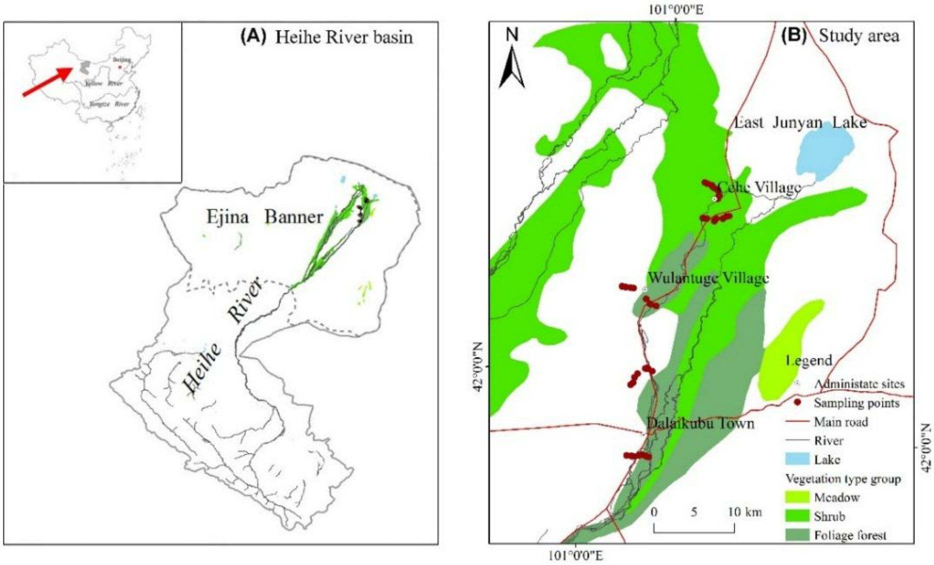


Figure 1. The Heihe River B~~b~~asin in China (A) and the location of sampling points in the study area (B). ~~Two~~ One primary roads is~~are~~ built parallel to the river channel, and another runs across the south of the oasis~~, respectively~~.

2.2 Spatial field survey and experimental design

In the downstream Heihe River Basin, ~~the~~ desert riparian forests make~~s~~ up the ~~main body~~core of the desert oasis, mainly composed~~comprised~~ 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~~; Guo et al., 2009~~). However, the spatial extent of the riparian zone is difficult to ~~be~~ delineate~~d~~ due to the heterogeneity of the landforms ~~mosaics~~ (Décamps et al., 2004). Therefore, our study covered ~~a length across~~ distances up to 3000 m ~~distance~~ from the ~~Heihe~~ river channel to fully cover the distribution pattern of the~~its~~ desert riparian forests in the downstream Heihe River.

Our field survey was conducted in July 2015~~,~~ after the ecological water conveyance was delivered. ~~The e~~Ecological water conveyance is implemented according to the water dispatching scheme and is conducted in ~~the~~ April, July, August, September and November with a scheduled discharge (Feng et al., 2015). ~~Five transects perpendicular to the river were selected randomly as replicates under the premise of consistency in soil type and micro-topography.~~ Due to the regulated water discharge, the ecological water conveyance only affects the sites near the river bank (within a 100~~-~~m radius) (Liu et al., 2008). ~~Therefore, w~~We conducted vegetation and soil sampling~~s~~ ~~were conducted~~ perpendicular to the river channel and sampled at distances of ~~the distance from the river channel was stratified into seven gradients:~~ 100 m, 500 m, 1000 m, 1500 m, 2000 m, 2500 m, and 3000 m from the river channel.~~,~~

~~respectively,~~ Five replicates were sampled at each distance from the river channel and ~~generating~~ a total of 35 sampling sites were established. The~~o~~se 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~~by~~ 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 at~~in~~ 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 ~~plants~~herb species, vegetation cover and height.

At each site, soil samples and soil moisture 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~~,~~ and weighed at the time of sampling as well as after oven drying at 105 ℃ for 48 hours. ~~At some sites where groundwater was less than 2 m, the SWC sampling stopped at the depth of groundwater table.~~ Bulk density (BD) was measured by collecting undisturbed soil cores ~~at~~ from the surface layer using a stainless-steel cutting ring (100 cm^3 in volume) with three replicates at each site, which were then ~~and~~ oven dried at 105 ℃ ~~until they reached~~to a constant weight. The s~~S~~oil particle size distribution and soil chemical properties (soil organic matter, total nitrogen, total phosphorus and total salt content) were ~~analyzed~~ analysed in the laboratory using 0-100 cm soil samples that were collected separately at~~in~~ each site.

2.3 Temporal data collection and processing

~~In order t~~To understand~~analyze~~ the long~~-~~term vegetation variation since the implementation of ecological water conveyance, we ~~analyzed~~ 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~~. The maximum NDVI during growing season (May-October) generally indicated the best vegetation state of the whole year~~ (Wang et al., 2014).~~ The~~ NDVI data ~~in each sampling site~~ 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~~in~~ each site during the research period, were extracted from the remotely sensed data with 1000 m resolution ~~retrieved remote sensing data~~(doi:10.3972/heihe.0034.2016.db) ~~with 1000 m resolution~~using the land model CLM4.5 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 Supplement S4. Land use change information from 2000-2014 was extracted from land use data at a scale of 1:100,000 (for 2000 and 2014) (doi:10.3972/heihe.020.2013.db; doi:10.3972/hiwater.155.2014.db) (~~Liu et al., 2002;~~ Zhong et al., 2015). The spatial variation of groundwater table with distance from the river was obtained from groundwater monitoring data recorded along a transect (i.e., the Wulantuge transect). These monitoring data were recorded as 18-hour averages 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 ~~depicted by~~obtained from the monitoring data of soil moisture, recorded at 0.5 Hz, as 10-min averages from 2013-2015 using a suite of micrometeorological sensors (CR800, CR23X, CR23XTD, Campbell Scientific Inc.) installed in the Heihe riparian forest (101°8′1″E, 41°59′25″N)~~from 2013-2015~~ (doi:10.3972/hiwater.241.2015.db; doi:10.3972/hiwater.318.2016.db) (Liu et al., 2011~~; Li et al., 2006~~). The retrieved remote sensing data, monitoring data~~ and~~ , land use data~~ and~~ , 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). ~~Runoff data at ZhengyixiaDonghe station, a hydrological station at the borderrecorded the runoff of the downstream Heihe, was collected from the Hydrological Almanac of China from the Chinese Academy of Sciences.~~

2.4 Statistical analysis

The P (importance value) of each tree, shrub and herb at~~in~~ each sampling~~plant~~ site was calculated for each species using the following formulas (Zhang and Dong, 2010):

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

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

where *RDen* is the relative density, *RDom* is the relative dominance, *RH* is the relative ~~coverage~~ height and *RC* is the relative coverage.

In our study, the total diversity index of the community was ~~de~~employed to depict the community diversity at~~in~~ 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~~in~~ different growth types. The weight is the average of the relative coverage and ~~the~~ 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~~for~~ various growth types ($h = \sum h_i$);~~,~~ W_i is the weighted parameter of the diversity index for the~~of~~ 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 ~~is~~ at 50% and the herb layer ~~is~~ 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 *W* is the weighted parameters of the tree layer, shrub layer and herb layer. *A* is the diversity index of the tree layer, shrub layer or~~and~~ herb layer, which can be calculated using the formulase listed below.

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

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

~~and~~ Simpson's index of dominance was calculated as

$$D = 1 - \sum_{i=1}^{s} P_i^2 \qquad (6)$$

and Pielou's index of evenness was calculated as

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

Finally, Patrick's index of richness was calculated as

$$R = S \qquad (8)$$

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

The least significant difference (LSD) test was used to determine the significance of the variability in vegetation characteristics among five transects (Supplement S3). For~~Within~~ each distance from the river channel~~gradient~~, vegetation community characteristics, soil moisture and soil properties of the five sites were calculated as the mean ± standard error (SE) of the mean. 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~~to~~ the ~~fine roots~~ 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 s~~S~~oil chemical properties, however, were analys~~z~~ed using the mean values of 0-100 cm due to the low~~minor~~ 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 ~~by~~ 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~~by~~ the mean values of change rate for~~at~~ 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. 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 (ver. 18.0).

~~To depict the variation of desert riparian forests composition, we used~~ Two-way i~~I~~ndicator s~~S~~pecies a~~A~~nalysis (TWINSPAN, in WinTWINSPAN, version 2.3), a method of community hierarchical classification ~~based on the importance value of each species~~ (Hill, 1979), was used to classify the possible desert riparian forest~~s~~ 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 separat~~e~~ing the key influencing factors of the 18 environmental variables, the marginal and conditional effects of the various variables were calculated through ~~the~~ Monte Carlo forward selection in RDA (r~~R~~edundancy a~~A~~nalysis), which directly showed the significance and contribution rate of each factor. Marginal effects reflected the effects of the environmental variables on the community characteristics, while conditional effects reflected the effects of the environmental variables on the community characteristics after the anterior variable was eliminated by the forward selection method. Since the redundant variables were eliminated and a group of key environmental factors was identified~~determined~~ through ~~the~~ forward selection, this method allowed key variables to be determined through the strength of their effects and significance. The v~~V~~ariation of community characteristics explained by the different group of environmental factors was analys~~z~~ed 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~~by~~ 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~~of~~ vegetation composition

The s~~S~~pecies composition at each site in the downstream Heihe River Basin is shown in Table S1 in the Supplement, 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.~~, found at sites 1, 2, 3, 4, 6, 7, 15 and 21. Although this community, with multiple layers of tree-shrub-herb, was typical at desert riparian forest, its coverage was relatively low (38.05%).~~ Characterized by multiple layers of tree-shrub-herb, the community coverage was low (38.05%) and ~~The community was~~ dominated by the tree species *Populus euphratica* with sparse understory vegetation. ~~*Tamarix ramosissima* was the only species of shrub layer and the herb layer was dominated by *Sophora alopecuroides*.~~ 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~~, found at sites 5, 10 and 26~~. This community was ~~constituted~~ composed of shrub and herb layers with high community coverage ~~of (~~81.43%). *Tamarix ramosissima* was the dominant shrub species of the shrub layer~~ with the~~

~~importance value of 0.84-1.00.~~, while t~~T~~he herbs were dominated by ~~layer contains~~ both hygrophyte and xerophyte species, such as *Kochia scoparia* and *Peganum harmala*. This community was mainly distributed near the river bank (approximately~~about~~ 1000 m from the river channel).

(iii) Community III included~~was~~ *Tamarix ramosissima*~~, found at sites 8, 9, 20, 23 and 25~~. This community was mainly composed~~constituted~~ of shrub layers~~, except that sparsely grown herbs existed at site 8.~~ and ~~The community was~~ dominated by *Tamarix ramosissima* with average community coverage of 75.93%. It was~~and~~ 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~~s~~ herbs~~, found at sites 12, 13, 14, 17, 18, 22, 24, 27, 32 and 34~~. This community was mainly composed of shrub and herb layers with average community coverage of 68.86%. *Lycium ruthenicum* was the dominant shrub species ~~of the shrub layer~~ (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*~~, found at sites 11, 16, 19, 28, 29, 30, 31, 33 and 35~~. This community was the transition community from desert riparian shrub forests to desert shrubs~~ community~~, indicated by the presence of *Reaumuria soongarica*, a typical desert shrub. *Tamarix ramosissima* was the dominant species of the shrub layer~~ and~~, mainly existing in the form of shrub dunes~~, with the importance value of 0.38-0.93~~. ~~The *Karilinia caspica* and *Phragmites communis* herbs only existed in one sampling site and they were only sparsely distributed.~~ This community was mainly distributed approximately~~around~~ 2500-3000 m from the river channel, with ~~a relatively~~ low community coverage (54.40%).

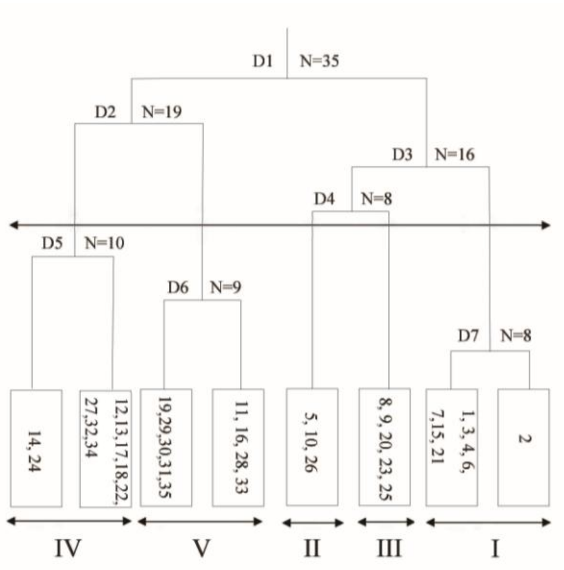


Figure 2. The dendrogram of the sampling sites based on the TWINSPAN classification.

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

Between 2000 and 2014, changes in the~~of~~ v~~V~~egetation composition ~~change in~~of each community type (I to V) (Fig. 3) ~~was~~ were obtained from ~~the~~ changes in the land use map ~~from 2000 to 2014~~ (Fig. 3). Among the five community types, community V underwent the most changes, with 22.22% of the sites changing~~ed~~ from sparse forest to grassland, 22.22% from grassland to shrubland and 22.22% from bareland to grassland~~, respectively~~. The majority (>60%) of the vegetation composition remained unchanged in communities~~y~~ 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~~y~~ 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).

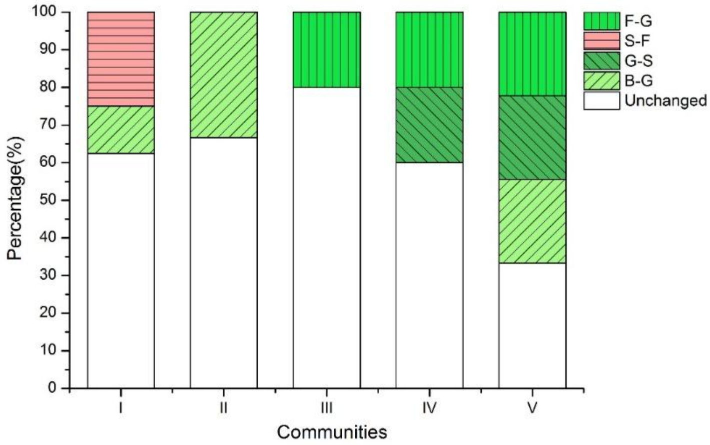


Figure 3. The percent~~age~~ changes in~~of~~ vegetation composition in each community from 2000-2014.

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 ~~formed different patterns~~ varied with~~along the~~ 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~~ed~~ at the distances of 500-1000 m and 3000 m~~, respectively~~ (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~~around~~ 1500-2000 m, and (iii) the herb layer fluctuated with~~along the~~ distance from the river channel~~gradient~~, peaking at 500 m and 2500-3000 m from the river channel. All diversity indices showed a bimodal pattern with~~along the~~ 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). ~~The~~ Simpson dominance index, however, formed an opposite~~ng~~ 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).

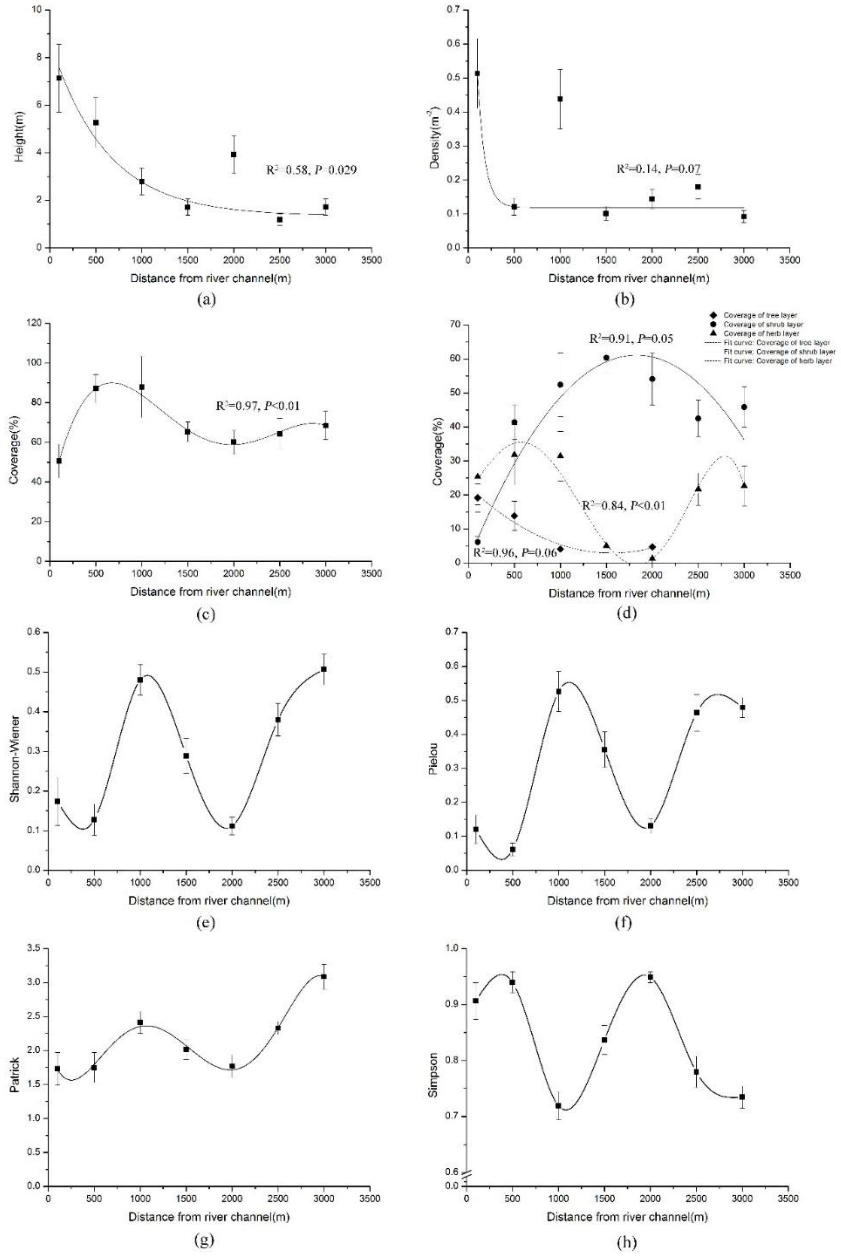


Figure 4. The variation of community structure and diversity ~~along the~~with distance from the river channel.

The temporal variation in~~of~~ community characteristics was depicted by the variation in~~of~~ NDVI (Fig. 5). At different distances from the river channel~~gradients~~, ~~temporal variation of~~ the NDVI showed an ~~similar pattern with an overall~~ increasing trend throughout the research period except for a small~~little~~ decrease during the initial years (2000-2002). The NDVI decreased with~~along the~~ distance from the river channel, ~~with~~ peaked at 100 m and 500 m from the river channel, and reached the ~~highest and the~~ lowest ~~NDVI~~ values ~~were found closest (100 m, 500 m) and~~at the furthest ~~away~~ distance from the river channel (3000 m)~~, respectively~~ (Fig. 5a). The annual variability in the NDVI ~~annual variability~~, however, showed a contrasting ~~contrary~~ trend, increasing ~~as it moved away~~with distance from the river channel~~, but decreasing as it moved closer to the river channel~~ (Fig. 5b).

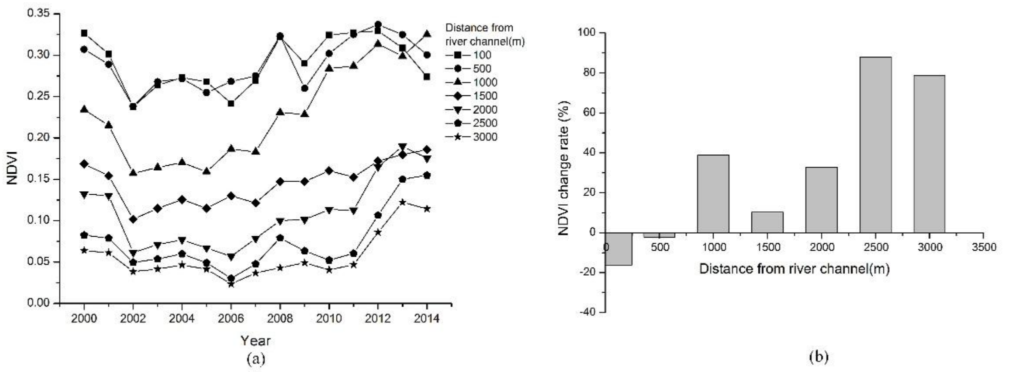
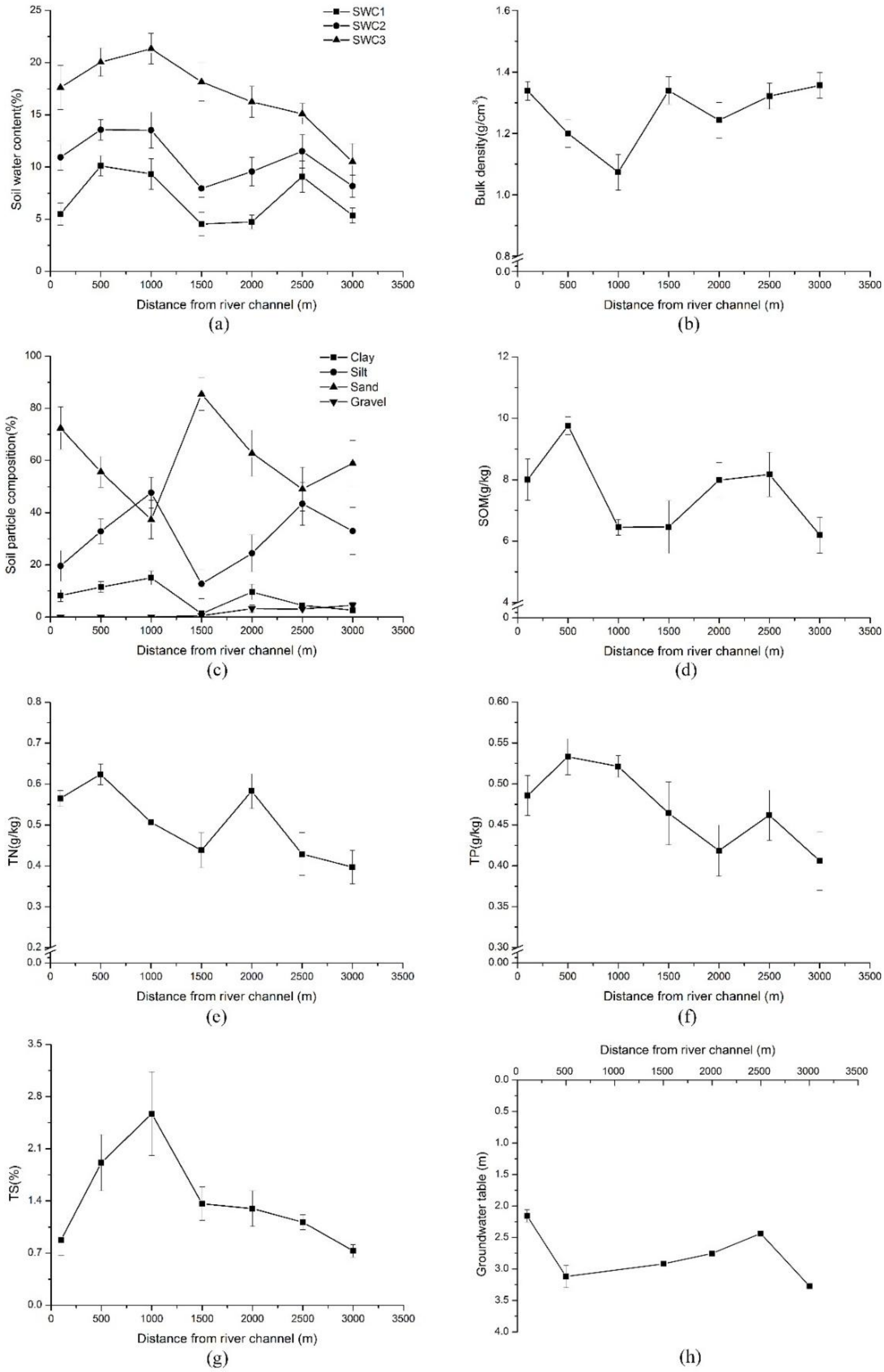


Figure 5. The temporal variations of NDVI (a) and annual variability of NDVI (b) from 2000 to 2014 at different distances from the river channel.

~~**3.3 The spatial and temporal variation of water availability and soil properties**~~

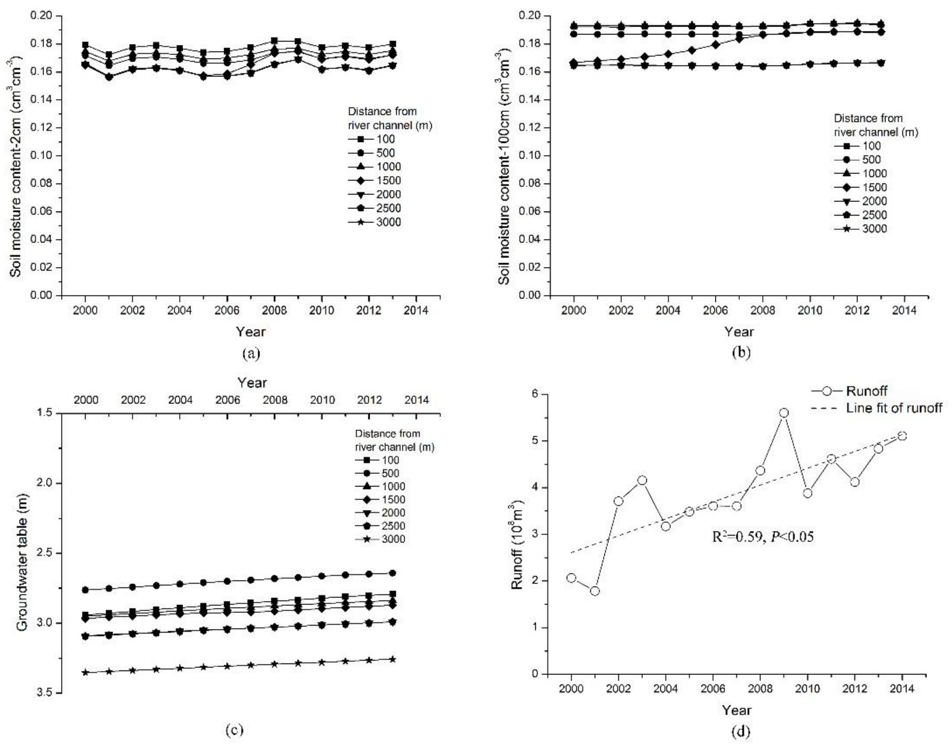
~~Water availability and soil properties varied significantly along the distance from the river channel (Fig. 6). SWC1 (0-30 cm soil moisture) and SWC2 (30-100 cm soil moisture) peaked at the distance of 500-1000 m and 2500 m, following the same pattern with vegetation community coverage, and diversity indices (Fig. 4 c-f). SWC3 (100-200 cm soil moisture), however, showed a different pattern by peaking at the distance of 1000 m from river channel and dropped rapidly after 2500 m (Fig. 6 a). The proportion of silt and clay was highest at the distance of 1000 m from the river channel (Fig. 6 c), while bulk density reached its lowest point (1.07 g cm^{-3}) (Fig. 6 b). The variation of SOM, TN, TP showed the similar pattern with vegetation diversity along the gradient (Fig. 4 e-g, Fig. 6 d-g). They generally decreased along the distance from river channel and reached a relatively high value at the distances of 500 m and 2000-2500 m. The total salt content peaked at the distance of 1000 m (2.57%) and dropped gradually until the end of the gradient.~~



~~**Figure 6.** The variation of soil moisture (a), soil bulk density (b), soil particle composition (c), soil organic matter (d), total nitrogen (e), total phosphorus (f), total salinity (g) along the distance from river channel.~~

~~SWC1, 0-30cm soil moisture; SWC2, 30-100cm soil moisture; SWC3, 100-200cm soil moisture; BD, bulk density; SOM, soil organic matter; TN, total nitrogen; TP, total phosphorus; TS, total salt content.~~

~~The temporal variation of water availability and soil properties was depicted by soil moisture, groundwater table and runoff. Soil moisture decreased with the distance from river channel (Figs.7 a, b) and different gradient formed a similar temporal variation pattern. Shallow (2 cm) soil moisture showed greater fluctuation than deep (100 cm) soil moisture, which was almost constant with time. The depth of groundwater table increased consistently across different gradients since 2000, following the downstream runoff which doubled during the research period, from 6.5×10^8^ m^3^ in 2000 to 13×10^8^ m^3^ in 2014.~~



~~**Figure 7.** The variation of 2 cm soil moisture (a), 100 cm soil moisture (b), groundwater table (c), runoff (d) from 2000-2014 at different distance from the river channel.~~

3.~~4~~ 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 c~~C~~ommunity coverage was positively correlated with all the three soil moisture layers ~~of soil moisture~~ (*P*<0.0.1) but negatively correlated with BD. The t~~T~~ree and shrub layers ~~layer~~ 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 index was significantly correlated with sand ~~(r= 0.354, *P*<0.05)~~ and silt ~~(r=−0.344, *P*<0.05)~~. ~~As F~~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.

~~With runoff as the main water resource in the downstream Heihe, there was time lag between the increase of runoff and NDVI.~~ The correlation coefficient between the NDVI and runoff was measured to examine the relationship between runoff and the ~~the same year's~~ 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 ~~the next year's~~ NDVI of the following year (Fig. 6). ~~One year lag NDVI-runoff correlation coefficient~~ 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. ~~decreased significantly with the distance from river channel (P=0.086), as opposed to insignificant variation of NDVI-runoff correlation coefficient along the distance from river channel (Fig. 86).~~

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

	H	R	C	Jsw	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 ~~significant correlations (P<0.01)~~

in bold with underline, respectively. R, Patrick richness 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, 0-30cm soil moisture; SWC2, 30-100cm soil moisture; SWC3, 100-200cm 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 silt (<0.02mm), clay (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 2cm soil moisture; SWC100cm_a, annual average of 100cm soil moisture; GWT_c, annual variability of groundwater table; SWC2cm_c, annual variability of 2cm soil moisture; SWC100cm_c, annual variability of 100cm soil moisture;

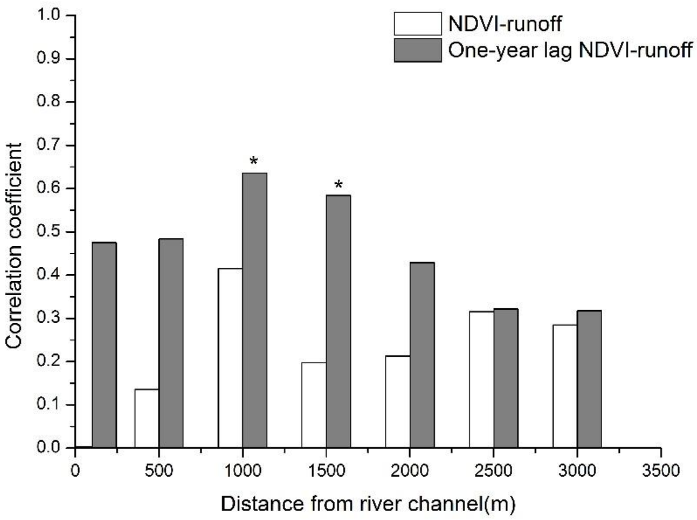


Figure ~~8~~6. Pearson ~~correlate~~ correlation coefficients of NDVI-runoff and one-year lag NDVI-runoff at different distance from the river channel.

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

3.~~5~~ 4 Key environmental factors that influenced community characteristics

To further examine the key environmental factors that controlled the variation in the~~of~~ vegetation indices~~ (e.g. community diversity, structure, NDVI)~~, 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% ~~variance~~ 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 influencing the variation of community characteristics. ~~A total 71.62% of the environmental information was extracted by the key environmental factors, and SWC1 contributed the most information (27.03%).~~ 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 vegetation variance and accounted for 98.4% of the total variance explanation, while temporal variation factors only explained 15.9% of the vegetation variance, accounting for 35.9% of the total variance explanation. These two groups of factors jointly explained 15.2% of the vegetation variance, accounting for 34.3% of the total variance explanation.

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: Percentage of variance explained (%)	Environmental factors	Conditional effects: Percentage of variance explained (%)	P value	R value (%)
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, 0-30cm soil moisture; SWC2, 30-100cm soil moisture; SWC3, 100-200cm 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 2cm soil moisture; SWC100cm_a, annual average of 100cm soil moisture; GWT_c, annual variability of groundwater table; SWC2cm_c, annual variability of 2cm soil moisture; SWC100cm_c, annual variability of 100cm soil moisture.

Table 3. The percentage of community characteristic variation~~s~~ explained by ~~key~~ different groups of

environmental factors.

Fraction	Variation	% of a~~A~~ll	% of e~~E~~xplained	F	*P*
a	0.435~~39~~	43.5	98.4	5.9	0.008
b	0.159~~88~~	15.9	35.9	4.0	0.088
~~a+b~~c	0.152~~19~~	15.2	34.3	2.2	0.016
Total e~~E~~xplained	0.442~~29~~	44.2	100	5.9	—

a: spatial distribution factors, including SWC1, SWC2, SWC3, BD, clay, silt, sand, gravel, SOM, TN, TP, TS; b: temporal factors, including 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 ~~pattern and temporal variation of community characteristics~~ in Heihe desert riparian forest and its influencing factors

~~The characteristics and indices of desert riparian forests formed different patterns along the distance from the river channel in~~ In the downstream Heihe River Basin~~.~~ , ~~C~~community height and density declined significantly as the dominant species changed from trees to riparian-desert shrubs with increasing~~along the~~ distance from the river channel~~distance gradient~~. ~~The c~~Community coverage reached two local maxima at ~~the distance of~~ 1000 m and 3000 m from the river, ~~where community consisted of~~ with diverse shrub and herb layers. These spatial distribution ~~variation patterns of~~ community diversity can illustrate how ~~community~~vegetation respons~~e~~ds and interacts with numerous environmental factors along~~to the~~ different ecological gradients ~~(Zhu et al., 2013) and interact with environmental factors in this resource limited region~~ (Oksanen and Minchin, 2002). Our findings under these hyperarid conditions were different from those found in the relatively humid regions (e.g., coastal regions or boreal forest), which suggests~~ed~~ that riparian forest species diversity either decreased or formed a unimodal pattern with increasing distance from the stream (Pabst and Spies, 2011; Macdonald et al., 2014). ~~These variation patterns of community diversity can illustrate how community response to the ecological gradient (Zhu et al., 2013) and interact with environmental factors in this resource limited region (Oksanen and Minchin, 2002). Although located quite far from the river, soil moisture~~

~~(e.g. SWC1, SWC2, and SWC3) reached its maximum at 1000 m from river channel (Fig. 6), supporting rich vegetation community (multiple layers of tree-shrub-herb). High soil moisture (up to 100 cm deep) provided adequate water resource for the growth of diverse species as soil moisture also explained for 49.95% of vegetation variance.~~ At the distance of 1000 m from the river channel, –the fine-textured soils found in the upper soil layer partly contributed to the diversity of this region. They increased the soil water holding capacity and improved the gravimetric moisture content in the upper soil layer, which provided suitable habitat for the growth of diverse herb species with shallow rooting systems (Liu et al., 2008). At the same time, the presence of the deep-rooted tree, *Populus euphratica*, redistributed the deep soil water to the shallow layer as a strategy for mutualism, ~~In addition, the presence of deep-rooted tree, *Populus euphratica* could~~ benefiting the growth of shallow-rooted herbaceous species ~~(e.g. herbs) by redistributing the deep soil water to the shallow layer as a strategy of mutualism~~ (Hao et al., 2013). Similar mechanism also occurred a~~A~~t further distance (i.e., 3000 m) from the river~~ (3000 m)~~.~~, high species diversity could be supported by the presence of fine soil particles, which resulted in relatively high soil infiltration~~ water holding ~~capacity and soil nutrition~~~~nutrients~~ ~~around the shrub patches ('fertile islands') (Ravi et al., 2010; Zhou et al., 2015).~~ Although situated in~~at~~ the transition region (from riparian forest to desert shrubs), the soil ~~here~~ at the distance of 3000 m from the river channel was still rich in fine particles (clay and silt; 35.6%), brought by the interaction between wind erosion and shrubs (Ravi et al., 2009). The presence of fine soil particles increased the soil water holding capacity and soil nutrients around the shrub patches ('fertile islands') (Ravi et al., 2010), ~~These 'fertile islands'~~ allowing~~ed~~ the growth of some xerophytic herbs~~,~~ and increasing the level of diversity in this ~~gradient~~ region (Stavi et al., 2008~~; Ravolainen et al., 2013~~). By contrast, Simpson dominance index peaked at the distances of 500 m and 2000 m ~~where other indices were at their low level~~ (Fig. 4 h), likely due to~~. We suggested that~~ inter-species competition for water and nutrient resources ~~could be responsible for the trend~~ (Maestre et al., 2006~~; Boever et al., 2015~~). At these sites, low community diversity dominated by a few species contributed greatly to the diversity index (Zhu et al., 2013). ~~The d~~Dominant species with a high importance~~t~~ value (i.e., trees and shrubs at 500 m and 2000 m, respectively) often had high competition for resources, hinder~~alt~~ing the growth of other species (i.e., herbs) (Koerselman and Meuleman, 1996). ~~In these sites, low number of species indicated low community diversity and the dominant species made a large contribution to the diversity index of the community (Zhu et al., 2013), resulting in a large domination index (Fig. 4 h).~~

Among different ~~the~~ environmental factors, changes in water availability associated with soil properties are considered to be~~as~~ the most important selective forces shaping 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). ~~environmental factors explained 74.0% vegetation variance in total (Table 2), which indicated that both spatial heterogeneity and temporal factors play important role in determining the community characteristics of desert riparian forests in the Heihe River Basin.Among those factors, SWC1, SWC3, BD, annual average of 100 cm soil moisture were considered the key influencing factors, with SWC1 and SWC3 contributed to 45.95% of the total explanation of vegetation variance.~~ The surface soil moisture~~SWC1~~ (0-30 cm soil moisture; SWC1) contributed to the high coverage of the herb layers, as it is~~become~~ the main water source for the dominant herb species, such as *S. alopecuroi~~io~~des* and *K. caspica*, whose fine roots were mainly distributed within the top 30 cm ~~from~~of the surface soils (Fu et al., 2014). Meanwhile, deep soil moisture (SWC2 and SWC3) mainly influenced the community density and coverage~~the annual fluctuation of NDVI~~. SWC2 (30-100 cm soil moisture) was the main water resource for shrubs such as~~,~~ *T. ramosissima*~~.~~ and SWC3, recharged by the flood-raised groundwater table (Liu et al., 2015), was the main water source for phreatophytes such as~~like~~ *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 ~~the~~ vegetation growth~~,~~ and increase~~ing the~~ community density and ~~NDVI~~coverage.

Apart from the soil moisture,~~Among spatial heterogeneity factors,~~ 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 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). ~~with BD accounted for 13.51% of the total explanation of vegetation variance. Bulk density mainly influenced community density, community coverage, shrub coverage, and annual average of NDVI, while soil composition (clay, silt, gravel) mainly affected the Simpson diversity indices, annual average of NDVI, and annual average change of NDVI. Bulk density and soil composition are critical for water and nutrient holding capacity and the ability of absorbing soil nutrition(Stirzaker et al., 1996; Meskinivishkaee et al., 2014).~~

Soil with a low bulk density ~~is characterized by~~ usually had high water and nutrient holding capacity associated with fine soil particles~~ porosity, which allows more water to infiltrate into the deep soil, promoting the growth of deep root vegetation and benefiting community density, coverage and annual average NDVI in each gradient. While,~~ as opposed to soil with high bulk density which often consisted of ~~high~~ coarse soil particles~~silt and sand, but low percentage of clay which resulted in low water holding capacity in the surface soil~~ (Ravi et al., 2010). The latter could induce water stress and limit vegetation growth, especially for herb species, which contributed greatly to the community coverage, density and diversity~~ and possibly inducing the drought stress to the vegetation community~~ (Stirzaker et al., 1996).~~ Such process constrained vegetation recovery especially herbs, which contributed greatly to the community coverage, density and diversity. It also hindered the NDVI increase, resulting in low diversity and a large domination index of the community.~~ Interestingly, we found that s~~S~~oil nutrients~~tion~~ explained no more than 0.1~~3~~% of the vegetation variance~~,~~ and that ~~we found that~~ SOM (soil organic matter) was negatively correlated with the species richness. Th~~i~~ese findings ~~was~~ere different from the ~~commonly~~ positive relationship commonly found between SOM and species richness in semiarid zones (e.g., the Loess Plateau) ~~found in previous study~~ (Jiao et al., 2011; Yang et al., 2014). Although SOM ~~content~~ determines~~d~~ 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 (Fig. ~~5~~S5-d). 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, ~~they~~ also had high competition for resources, ~~thus halt~~hindering the diversity and growth of other species (Su, 2003).

4.2 ~~Factors influencing the distribution pattern and~~ The temporal variation ~~of~~in Heihe desert riparian forest and its influencing factors

Our results showed that the NDVI has generally increased s~~S~~ince the implementation of the ecological water conveyance project in 2000, except for ~~the vegetation in desert riparian forest has recovered significantly, shown by the increasing NDVI at different distances from the river channel (Fig. 5 a). Aalthough there was~~ an initial decrease~~of NDVI during~~ between 2000 and ~~-2001~~2002, likely due to the ~~one year~~ lagging effect ~~of runoff~~ and the relatively low amount of runoff ~~at~~ during these ~~early~~ years (Jin et al., 2008~~; Ge et al., 2009),~~). ~~NDVI generally increased with the restoration time.~~ 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), t~~T~~he conversion of ~~low coverage community (e.g.~~ sparsely forested land~~,~~ or bareland~~ land)~~ to shrubland and grassland at these distances ~~of 2000-3000 m from the river channel~~ likely contributed to this ~~the~~ increase~~ in NDVI with better water availability in Heihe River Basin (e.g. increase of surface soil moisture~~ increasing ~~and elevate of groundwater~~ lifting~~)~~. In contrast, the NDVI near~~around~~ the river bank underwent a slight decrease~~degradation~~ ~~in~~ during ~~the~~ recent years (2012-2014), likely due to ~~result from~~ the conversion of shrubland to sparse forest land (Fig. 5 b),~~.~~ ~~In the arid zone,~~ increasing grazing pressure ~~is mainly limited to the region near~~ in the periphery of the river~~ bank due to the abundance of palatable grass and available of drinking water, which may hinder vegetation recovery compared to other gradients~~ (Todd., 2006),~~.~~ ~~In addition, high soil moisture and low salinity supported the regeneration of *Populus euphratica* trees. As they became the dominant species, they limited the growth of other species due to inter-species competition, leading to decrease in NDVI. High~~ and high tourism pressure~~ may also hinder vegetation growth during the growing season (May to October) since *Populus euphratica* trees are becoming popular tourist destination~~ (Hochmuth et al., 2014).

~~4.2 Factors influencing the distribution pattern and temporal variation of desert riparian forest~~

~~Among the environmental factors, changes in water availability associated with soil properties are considered as the most important selective forces shaping ecosystem stability in hyperarid zone (Rosenthal and Donovan, 2005; Ravi et al., 2010; Feng et al., 2015). Our study showed that environmental factors explained 74.0% vegetation variance in total (Table 2), which indicated that both spatial heterogeneity and temporal factors play important role in determining the community characteristics of desert riparian forests in the Heihe River Basin.~~

~~Among those factors, SWC1, SWC3, BD, annual average of 100 cm soil moisture were considered the key influencing factors, with SWC1 and SWC3 contributed to 45.95% of the total explanation of vegetation variance. SWC1 (0-30 cm soil moisture) contributed to high coverage of herb layers as it become the main water source for the dominant herb species, such as *S. alopecuriodes* and *K. caspica* whose fine roots mainly distributed within 30 cm from the surface soil (Fu et al., 2014). SWC2 and SWC3 mainly influenced the community density and the annual fluctuation of NDVI.~~

~~SWC2 (30-100 cm soil moisture) was the main water resource for shrubs such as, *T. ramosissima*. SWC3, recharged by flood-raised groundwater table (Liu et al., 2015), was the water source for phreatophyte like *P. euphratica* or desert shrubs (Yi et al., 2012). As tree and shrub contributed greatly to the community composition, the increase in SWC2 and SWC3 could significantly promote the vegetation growth, increasing the community density and NDVI. All three layers of soil moisture positively affected both community coverage and the annual average of NDVI (NDVI_a), which indicated that improved water availability directly promoted vegetation recovery in different gradients and high community coverage in this current stage.~~

~~Among spatial heterogeneity factors, soil physical properties were also important in determining vegetation community with BD accounted for 13.51% of the total explanation of vegetation variance. Bulk density mainly influenced community density, community coverage, shrub coverage, and annual average of NDVI, while soil composition (clay, silt, gravel) mainly affected the Simpson diversity indices, annual average of NDVI, and annual average change of NDVI. Bulk density and soil composition are critical for water and nutrient holding capacity and the ability of absorbing soil nutrition(Stirzaker et al., 1996; Meskinivishkaee et al., 2014). Soil with low bulk density is characterized by high porosity, which allows more water to infiltrate into the deep soil, promoting the growth of deep root vegetation and benefiting community density, coverage and annual average NDVI in each gradient. While, soil with high bulk density often consisted of high silt and sand, but low percentage of clay which resulted in low water holding capacity in the surface soil (Ravi et al., 2010) and possibly inducing the drought stress to the vegetation community (Stirzaker et al., 1996). Such process constrained vegetation recovery especially herbs, which contributed greatly to the community coverage, density and diversity, It also hindered the NDVI increase, resulting in low diversity and a large domination index of the community. Soil nutrition explained no more than 3% of vegetation variance, and we found that SOM negatively correlated with species richness. This finding was different from the commonly positive relationship between SOM and species richness in semiarid zone (e.g. Loess Plateau) found in previous study (Jiao et al., 2011; Yang et al., 2014). Although SOM content determined soil nutrient storage and supply of available nutrients, our sites in hyperarid zone were often characterized by barren soil with less than 1% soil organic matter (Fig. 5d). Such low amount of SOM might not be able to boost the growth of various species in desert riparian forests (Wang et al., 2016). At the same time, the dominant species (i.e., *P. euphratica* and *T. ramosissima*),~~

~~despite producing high amount of litter, they also had high competition for resources, thus halting the diversity and growth of other species (Su, 2003).~~

~~All three layers of soil moisture positively affected both community coverage and the annual average of NDVI (NDVI_a), which indicated that improved water availability directly promoted vegetation recovery in different gradients and high community coverage in this current stage.~~ 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 NDVI (NDVI_a) by supplying water to both shallow- and deep-rooted riparian vegetation (Fu et al., 2014). The deep soil moisture (SWC3), recharged by the increasing groundwater table, was 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 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 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 (e.g., sites at distances of 2500 and 3000m from the river channel; Fig. S5b, c in the Supplement) (Ravi et al., 2009). This resulted in low water holding capacity in the upper soil layer and constrained the growth of shallow-rooted vegetation, lowering the average NDVI and inhibiting 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 the annual variability of the NDVI in this desert riparian forest. This runoff significantly improved 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 indicated the lagging effects of runoff. These 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). A combination of those aforementioned processes also result in the more stable growth rate of groundwater and soil moisture during 2000-2014 (Fig. S6a, b, c) compared to the runoff fluctuations (Fig. S6d). 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, the deviations between simulations and observations could also partly account for 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 data, 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 most of the physical and chemical properties of the soils remained 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.

~~and SWC100cm_a was considered the key influencing factor. Along with GWT_a and SWC 2cm_a, they contributed to the recovery of desert riparian forest, shown by the increase in community density (Table 1). As soil moisture up to 100 cm deep is beyond the impact of increasing evaporation under climate change (Zhang et al., 2015a) and less influenced by the fluctuation of groundwater, it could be considered as reliable water source for vegetation. We, however, found that the coverage of tree layer showed a negative relationship with GWT_a, contrary to studies in Tarim river where a sharply decrease of groundwater level was observed along the distance from river channel (Chen et al., 2015). In Heihe River, the groundwater did not fluctuate much and the perennial groundwater table remained above 4 m. High water table allowed the deep-rooted trees to face more competition from shallow-rooted species and therefore with the deepening of groundwater, the habitat become more suitable for the growth of deep-rooted vegetation (e.g. tree and shrub) than the shallow-root one (e.g. herb) (Ditommaso et al., 1989). Compared to the annual average of water availability in each gradient,~~

~~the annual variability of soil moisture and groundwater due to runoff did not have significant impact on community characteristics, most likely because the latter did not fluctuate much during 2000-2014 (Fig.7~~S9~~).~~ ~~Ecohydrological processes in riparian zone such as seepage, interflow, groundwater movement and vegetation evapotranspiration (Liu et al., 2012) lifted up groundwater and soil water condition, moderating the effect of rapid runoff increase. The recovery of vegetation was therefore more likely benefited from long term improvement in water condition instead of the annual water variability (i.e., runoff) as mutual effect of the aforementioned ecohydrological processes would result in a more stable re-charge of soil moisture and groundwater.~~

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

~~As the main communities in the downstream Heihe River Basin, desert riparian forest strongly influenced the ecosystem resilience and resistance against disturbance. Studies have shown that species-rich communities can maintain ecosystem functions during stress-based perturbations due to the complementary of function traits and ecological redundancy (Luck et al., 2013; Isbell et al., 2015).~~ Although community diversity was generally low at most sites in the downstream Heihe River Basin ~~at most gradients~~, our findings suggest 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 ~~it was significantly higher at 1000 m and 3000 m gradients~~ (Fig 4). Consistent with other findings (Hao et al., 2013), ~~High~~ high resistance to drought stress was observed at these distances from the river channel~~gradients~~, with trees and shrubs lifting ~~up~~ water up from the deeper to ~~the~~ shallower layers as a strategy for~~of~~ mutualism ~~(Hao et al., 2013)~~. ~~Since trees and shrubsd~~Different species contributed differently to~~in~~ the ecosystem functions (e.g., trees and shrubs with large crowns mainly contribute to sand fixation,~~carbon storage~~ while ~~shrub and~~ diverse herbs contributed to biodiversity~~sand fixation~~), ~~they could~~ maintaining a stable habitat after drought stress and/or human disturbance (~~Cheng et al., 2007;~~ Krieger et al., 2001~~; Lu et al., 2015~~). 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 ~~gradients~~ could easily undergo degradations, ~~due to low resilience under disturbance (e.g., drought stress, grazing and tourism)~~

such as ~~those~~ that ~~already happened~~ at the distance of 500 m from the river channel~~gradient~~, indicated by the decreasing NDVI in ~~these~~ recent years (Fig. 5a). While e~~E~~xposure to human disturbance (e.g., tourism, grazing)~~, including trampling by livestock~~ might potentially ~~destroy~~ change ~~the~~ soil physical properties~~,~~ and ~~reducing~~ reduce~~the~~ ecosystem services such as water and soil conservation in this region (~~Greenwood and Mckenzie, 2001;~~ 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; Zeng et al., 2016).

~~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. Since the influence of ecological water conveyance was mainly limited to 1000 m distance from river (Si et al., 2005; Guo et al., 2009), projected rise in temperature could lead to the collapse of riparian vegetation (e.g. *Tamarix ramosissima*, *Lycium ruthenicum*) at further gradients, resulting in decrease of ecosystem service (e.g. sand fixation and carbon storage). In addition to potential threat posed by climate change, the periphery of the river is also more likely to be disturbed by grazing and heavy tourism pressure (Zenner, et al. 2012). Exposure to human disturbance, including trampling by livestock might potentially destroy the soil physical properties, reducing the ecosystem services such as water and soil conservation. To halt degradation in this critical zone,~~ As conservation measures, we suggest~~ed~~ building ~~the development of~~ natural channels ~~that~~ perpendicular to the river to fully extend the influencing~~e~~ 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: (i)~~ establishing~~setting~~ critical fenced areas for ecological protection~~,~~ and ~~(ii)~~ constructing artificial shields or establishing straw checker boards on the bare land to prevent erosion~~land degradation~~, are recommended around the periphery of the river.

5 Conclusions

Through extensive field observations at multiple desert riparian forest~~s~~ locations and analyses of long-term remote sensing images, we found that community characteristics differed spatially and temporally~~species diversity indices formed bimodal patterns instead of unimodal pattern~~ with distance from the river channel. In locations with high diversity indices ~~(1000 m and 3000 m)~~, high community resilience could be~~was~~ maintained by the multiple interactions between vegetation and soil properties. In contrast~~Still~~, regions with low diversity might~~these locations are~~ face~~ing~~ greater challenges under climate change and intensive human disturbance. Since the influence of ecological water conveyance is currently limited to a distance of 1000 m from the river (Si et al., 2005; Zeng et al., 2016), e~~E~~xtending the distance of ecological water conveyance is~~ therefore~~ recommended to recharge the surface soil moisture and benefit the growth of ground cover (i.e., herb species), which contribute greatly to species diversity. ~~Despite the increasing NDVI trend, areas with low diversity (within 500 m from river channel) already underwent degradation in recent years.~~ In addition, ~~M~~multiple conservation measures that protect the soil structure (e.g., artificial soil cover and livestock grazing exclusion) are recommended for regions close to the river ~~this region~~ to reduce the adverse effects of grazing on soil properties. Unless these necessary precautions are taken, desert riparian forests may become ~~restricted to the periphery of the river~~fragmented and experience significant community transition under projected climate change scenarios and more intensive human disturbance.

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