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 inspired us to improve the quality of this manuscript. 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: The authors may have an interesting story to tell, but both reviewers were in agreement that major revisions are needed if this is to be acceptable for publication. All of the major the major comments by reviewer #1 are of particular importance to address, even though all of the points by both reviewers should be addressed in a revision

Authors: We thank the editor for the pointing out the importance of the major comments of reviewer #1, we have carefully addressed all the major comments by reviewer #1 in the response to reviewer #1. We have carefully addressed all the comments by both reviewers in this response and amended the original manuscript based on the suggestions and comments. In addition, we added Yaping Wang as the co-author of this manuscript for her contribution in adding temporal analysis part in this revised manuscript.

Responses to the Reviwer#1:

Major issues

Reviewer: This work presents soil water content and biogeochemical data to explain how riparian vegetation changes as distance from the river increases. Vegetation is characterized by species composition and diversity, and occurrence and coverage of different plant functional types. The topic is overall relevant for readers of HESS. The manuscript is relatively clear, but might benefit from proofreading by a native English speaker. Despite the interest of the topic, I have some concerns regarding the analyses conducted and the mismatch between the ecological processes causing the observed vegetation patterns, and the one-time soil sampling adopted for this study.

Authors: We thank the reviewer for the constructive suggestions to improve the quality of this manuscript. We have carefully amended the manuscript by adding the temporal analysis to address the questions. We illustrated the temporal variation of vegetation communities by adding the temporal variation of NDVI during 2000-2014 based on the Landsat TM/ETM

(30m) image (please see Page 18 Line 2 - 8 in result part and Page 26 Line 20 - Page 29 Line 6 in the Discussion section). We further added the temporal variation factors (e.g., groundwater, soil moisture, runoff) in the environment factors to illustrate how spatial heterogeneity and temporal variation factors drive the variation of desert riparian forest (please see "3.4 Pearson correlation between community characteristics and environmental factors" at Page 20 Line 15 - Page 21 Line 19 and "3.5 Key environmental factors that influenced community characteristics" at Page 23 Line 2 - 16 in the Result section; Page 29 Line17 - Page30 Line 7 in the Discussion section). Then, based on the analysis of spatial distribution and temporal variation of desert riparian forest, we proposed suggestions for the restoration under the changing environment (please see Page 31 Line14 - Page 32 Line 4).

Reviewer:

1) Ecological processes vs. one-time sampling.

The plant communities examined in this work are the result of decade- if not century-long successional dynamics, but they are treated as if they are the result of short term processes. I refer specifically to soil water content, used as a predictor of vegetation community despite being measured only once. How representative are these water content measurements of the long-term water availability? Other soil properties vary at slower rates and could be more meaningful predictors (texture, SOM).

Authors: We thank the reviewer for pointing out the discrepancy between the successional dynamics of ecological processes and one-time sampling. Although desert riparian forest communities especially trees have been established for decades or even longer, in our case, the recovery of the community and vegetation characteristics were mainly formed under the influence of the ecological water conveyance implemented in 2000 (Zhang et al., Hydrological Processes, 2011). Because there has been no long-term field data to monitor the vegetation communities since the implementation of ecological water conveyance, we used high-resolution remote sensing image to analyze the long-term temporal vegetation variation in restored area. We added the analysis on the temporal variation of NDVI at our sampling sites based on the Landsat TM/ETM (30m) image since the implementation of ecological water conveyance (from 2000 to 2014) (please see Page 18 Line 2 - 8 in result part and Page 26 Line 20 - Page 29 Line 6 in the Discussion section).

In addition, we added the annual average and change rate of 2 cm soil moisture, 100 cm soil moisture, groundwater and runoff from 2000-2013 based on the retrieved remote sensing data as temporal variation factors to fully address the impact of water availability on the desert riparian forest (please see Page 20 Line 4 – Line 10 in the Result section). We further examined the impact of spatial heterogeneity and temporal variation on the variation of desert riparian forest in the restoration and disentangled the contribution of each factor on vegetation variance (please see “3.4 Pearson correlation between community characteristics and environmental factors” at Page 20 Line 15 - Page 21 Line 19 and “3.5 Key environmental factors that influenced community characteristics” at Page 23 Line 2 – Line 16 in the Result section; Page 27 Line 10 – Page 30 Line 7 in the Discussion section). The temporal variation of soil moisture derived from retrieved remote sensing data since 2008 showed that the soil moisture was relatively stable (please see Page 20, Fig. 7a, b in the Result section) particularly at the deeper soil layers (below 20 cm), which could represent the water condition at the sampling site. Monitoring data also showed that soil moisture formed similar annual variation pattern due to the regulated ecological water conveyance. The soil moisture formed a unimodal pattern and peaked in July, which indicated that the soil moisture in July could reflect the best water condition of the community for the whole year (Fig. S1 in the supplementary material). Thus, our sampling data in July using 0-200cm soil moisture could represent a relatively good water condition of the site that supported most vegetation communities after 15 years’ restoration.

Reviewer: How old are the trees and shrubs in this community? Are these communities shaped by the time they spent growing on a given soil (no information is provided to this regard), or by the edaphic properties of a given site (focus of the current study)?

Authors: We obtained the community age by referring to the studies on the growth characteristics of shrub and trees in the study area and consulting the local forestry government (Xiao et al., Acta Botanica Boreali-Occidentalia Sinica, 2005). The trees established on the sites are beyond 50-60 years old, while the shrubs are quite young with 80% of them developed within the last 15 years. The remaining 20% are between 15 and 30 years of age. Although trees and few shrubs initially grew on the stand in 1950s-1980s, they were in poor growing condition due to the scarce water supply from the dry stream channel (Guo et al., Environment Geology, 2009). The present community condition and characteristics were mainly formed after 2000. We analyzed the change of community composition in our manuscript (please see Page16 Line 1 – Line 9 in result part and Fig. 3 in Page16). About 60% of desert riparian forests remained unchanged with regard to community composition and the remaining mainly shifted from the sparse (e.g. sparse forest land, bareland land) to denser vegetation community (e.g. shrubland and grassland).

As for the driving factors, we analyzed both heterogeneity of soil property and temporal variation of water availability in the revised manuscript. We found that the heterogeneity of soil properties was the main driving force of the vegetation variation, accounting for 98.4% of total explanation, while temporal variation factors explained 35.9% of total explanation and these two groups of factors together accounted for 34.3% of the total explanation (please see

“3.5 Key environmental factors that influenced community characteristics” at Page 23 Line 2 – Line 16 in the Result section; “4.2 Factors influencing the distribution pattern and temporal variation of desert riparian forest” at Page 27 Line 10 – Page 30 Line 7 in the Discussion section). With regards to the fact that large-scale factors (i.e., climate) did not change significantly during the last 15 years (Zhang et al., Arid Land Geography, 2011), we concluded that the communities in our study site were mainly affected by the edaphic properties rather than by time. The water condition and soil properties (soil texture, soil chemical) in our sampling were heterogeneous (please see Page 19 Fig 6 and Page18 Line 15 -Page 19 Line 6 in the Result section), changing from shruby meadow soil to grey–brown desert soils, and finally to aeolian soil along the distance from river channel. Under a given site, the mutual effect between edaphic properties and vegetation resulted in the formation of certain community, and eventually the distribution pattern of the region.

Reviewer: No data are reported on the variability in river discharge – how dynamic is the riparian environment? How frequent are flooding events that can re-shape the community (and soil properties)? Without this information, it is difficult to disentangle time effects from site effects.

Authors: We thank the reviewer for the question. In the downstream Heihe River Basin, the ecological water conveyance delivers water downstream as part of an ecological restoration project conducted by the national government with the aim of restoring the ecosystems of the river since 2000. It is implemented according to water dispatching scheme scheduled in the April, July, August, September and November (Feng et al., Science Press Ltd, 2015). Due to the regulated water discharge, the ecological water conveyance hardly caused any flooding event. Even if a flood happened, it only affected the sites that near the river bank (within 100m radius) (Liu et al., Journal of Glaciology and Geocryology, 2008). It is unlikely to re-shape the community and soil properties of our sampling plots mainly located beyond 100 m from the river channel. Following the reviewer’s suggestion, we added this information of the ecological water conveyance in the Data and methods section (please see Page 9 Line 19-21). In addition, we added the runoff data which indicated the water conveyance in each year and analyzed the relationship between runoff and NDVI (please see Page 21 Line 13 – Line 19 in Result section).

Reviewer: Many of the measurements used as predictors are partly correlated, making it difficult to interpret the regression results. For example, soil water content is related to texture (as noted in P4, L18). Fine textured soils can hold more water, and this effect would appear in the gravimetric water content measurements. Total nutrient (TN and TP, which I assume include organic N and P) are also correlated to SOM, since large SOM stocks are associated with large N and P stocks (as noted in P20, L30). Due to these correlations, it seems difficult to apply regression approaches that assume independence, as in this case (if I interpreted the approach correctly).

Authors: We agree with the reviewer that the factors we chose were partly correlated, such as soil water content and soil texture, TN/ TP and soil organic matter. We selected these factors that covered the aspects of soil moisture and soil properties to better illustrate the relationship between vegetation and soil in the desert riparian forest. Although we did use regression approach in the manuscript, it mainly used to examine variation of community characteristics along the river channel and the result was presented in Fig. 4 (please see Page 17 in the manuscript). The regression approach as mentioned by reviewer is actually a forward selection (please see Page 24 Table 2 in the manuscript) in the RDA (Redundancy Analysis). The RDA is an ordination rather than a regression analysis. Its main aim is sorting the principal components and finding variables that best explain the vegetation distribution. Although these factors are partly correlated, the aim of the forward selection is to identify the significant factors and their contribution rate from each principal component rather than to form the regression equation for predicting the vegetation characteristics. According to the main purpose and function of the RDA, we believe that it is reasonable to involve factors that not totally independent from each other (Lepš et al., Cambridge University Press, 2003). We add the explanation of the RDA in the Data and methods section to clearly illustrate the analysis we used in the manuscript. Please see Page 13 Line 21 – Line 24: "To further separating the key influencing factors of the 18 environment variables, marginal and conditional effects of various variables were calculated through the Monte Carlo forward selection in RDA (Redundancy Analysis), which directly showed the significance and contribution rate of each factor".

Reviewer: The conclusions are based on too short-term a study to be really useful for planning. Either a long-term monitoring or a different study to identify possible historical reasons for the observed patterns would provide (or not!) support to a possibly large and expensive conservation project.

Authors: We thank reviewer for this suggestion. We added the temporal variation of desert riparian forest to better illustrate how vegetation changed after the implementation of ecological water conveyance in 2000 (please see Page 18 Line 2 – Line 8 in Result section and Page 26 Line 20 - Page 27 Line 6 in Discussion section), including the combination soil spatial heterogeneity and water availability during 15 years of restoration (please see "3.3 The spatial and temporal variation of water availability and soil properties" at Page 18 Line 15 - Page 20 Line 10 and in Result section "4.2 Factors influencing the distribution pattern and temporal variation of desert riparian forest" at Page 27 Line 10 - Page 30 Line 7 in Discussion section). We found that the despite the general increase trend of NDVI, the area within 500 m from river channel underwent degradation in recent years due to the intensive human disturbance, which called for further protection near the river bank. In addition, to address the influence of ecological conveyance, we analyze the relationship between runoff and NDVI. Apart from one-year lag found in the impact of runoff which responsible for the initial decrease of NDVI from 2000-2002 (please see Page 21 Line 13 – Line 19 in Result section), we found that soil heterogeneity accounted for most of explanation (98.4%) for vegetation recovery after long term restoration. Thus multiple conservation measures on protecting the soil structure (e.g., build artificial soil cover and livestock grazing exclusion) were recommended for this region to reduce the adverse effects of grazing on soil properties. Moreover, we discerned the community resilience in each gradient based on the distribution pattern of diversity and we proposed suggestion on the restoration under the changing environment (please see Page 30 Line 23 - Page 31 Line 9). Through the analysis of distribution pattern and temporal variation of desert riparian forest during restoration as well as discerned the key influencing factors driving the variation, our study could provide some meaningful supports to the future restoration.

Minor issues

Reviewer: I am listing here only some of the small editorial issues in this MS – better to ask a native English speaker to give a thorough proofreading.

Authors: We have carefully amended the manuscript based on the editorial issues that you provided and gave a thorough proofreading accordingly.

Reviewer: P2, L3: "focused" rather than "stressed"

Authors: We rewrote the abstract (please see Page 2 Line 3 – Line 6), deleted the sentence and changed it into: "Since they are also sensitive to disturbance examining the distribution pattern, temporal variation of desert riparian forest and their influencing factors are important to determine the limiting factors of vegetation recovery after long-term restoration".

Reviewer: P2, L11: optimum in which sense? Is biomass higher around 1000 m, or what criteria was used to establish what the 'best' conditions are?

Authors: We rewrote the manuscript and based the relationship between diversity indices and community resilience, the optimum range of desert riparian forest was replaced by the discussion on the community resilience in each gradient (please see Page 30 Line 23 - Page 31 Line 9).

Reviewer: P2, L19-20: it would be better to write if the mentioned influences are positive or negative.

Authors: We rewrote the abstract and replaced the sentence with the impact of spatial heterogeneity factors on the vegetation and illustrate the positive influence on the vegetation. Please see Page 2 Line 25 – Line 28: "Spatial heterogeneity factors, accounting for 98.4% of the total explanation, positively influenced the community diversity, structure, average NDVI and change rate of NDVI. Temporal variation factors accounting for 35.9% explanation and positively influenced the community density and average NDVI".

Reviewer: P3, L3: vague – what ecosystem services are important in this specific context?

Authors: We specified the ecosystem service such as sand fixation and carbon sequestration service in this study. Please see Page 3 Line 11 – Line 13: "Riparian zone is the linkage between terrestrial and aquatic ecosystem, which plays an important role in ecological processes and provides a variety ecosystem services, such as sand stabilization and carbon sequestration".

Reviewer: P3, L14: the term "ecological water conveyance" is not entirely clear? Is there a more commonly used term?

Authors: The "ecological water conveyance" is a restoration project with delivering the water from the middle reaches of Heihe to the low reaches of Heihe to restore the ecosystem in the low reaches which suffered from the drought stress and vegetation degradation severely. This term appeared in some relevant papers. We explained the term in the Introduction section. Please see Page 3 Line 23 – Line 26: "Since 2000, 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".

Reviewer: P4, L18: the fact that fine textured soils can hold more water than coarse textured soils was well known before Rosenthal (2005).

Authors: We rewrote the Introduction and the citation was deleted in the revised manuscript.

Reviewer: P5, L14: "that are differently…"

Authors: We revised this sentence carefully according to the reviewer's suggestion. Please see Page 6 Line 29 – Line 30: "We investigated variability in desert riparian forests sites that are differently located along the perpendicular direction from the river channel".

Reviewer: P5, L21: the long-term perspective is not covered in this work, so the suggested measures may be consistent with the findings, but do not take into account climate or land use change.

Authors: Using the long-term data as suggested by the reviewer, we added the temporal variation of desert riparian forest to better illustrate how vegetation changed after the implementation of ecological water conveyance in 2000 (please see Page 18 Line 2 – Line 8 in result part and Page 26 Line 20 - Page 27 Line 6 in the Discussion section). This temporal analysis illustrated the vegetation recovery accompanied with change in vegetation composition change during the restoration (please see Page16 Line 1-9 in Result section). The sampling data mainly illustrated the distribution pattern of desert riparian forest along the decreasing gradient of water availability (i.e. the distance from the river), which may provide reference to vegetation pattern during drought with climate change scenario. Based on the temporal and spatial analysis of vegetation variation, we developed a more comprehensive suggestions on management (please see Page 31 Line 14 - Page 32 Line 4 in the Discussion section).

Reviewer: P6, L10: "As the distance…increases, water…"

Authors: We revised the grammatical error of this sentence according to the reviewer's suggestion. Please see Page 8 Line 10: "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 Ejina oasis".

Reviewer: P7, L14: if I understand the sampling design correctly, there are five replicate gradients (transects perpendicular to the river), each with 6 sampling points – perhaps re-phrase?

Authors: Consistent with reviewers' understanding, the sampling was conducted on five replicate gradients that perpendicular to the river and each with 7 sampling points that is 100 m, 500 m, 1000 m, 1500 m, 2000 m, 2500 m, and 3000 m from river channel, respectively. Following the reviewer's suggestion, we rephrased this sentence to make it clearer. Please see Page 9 Line 20 – Line 26: "Therefore, vegetation and soil samplings were conducted perpendicular to the river channel and there were several locations based on the distance from the river channel: 100 m, 500 m, 1000 m, 1500 m, 2000 m, 2500 m, and 3000 m, respectively, generating a total of 35 sampling sites."

Reviewer: P8, L10: is the importance value calculated for each plant functional type as written, or for each species?

Authors: The importance value is calculated for each species (19 species in total). We rephrased this sentence. Please see Page11 Line 19 – Line 20: "The P (importance value) of each tree, shrub and herb in each plant site was calculated for each species using the following formulas".

Reviewer: P8, L14: RF is not present in the equations.

Authors: We revised this mistake and carefully checked throughout the manuscript, Please see Page 11 Line 23: "where RDen is the relative density, RF is the relative frequency, RDom is the relative dominance, RH is the relative coverage and RC is the relative coverage".

Reviewer: P8, L23: the thickness of the canopy layer might not tell much about the actual biomass. Perhaps leaf area would be more representative.

Authors: We agree that leaf area is better than the thickness of canopy in depicting vegetation biomass. Due to the harsh environment, however, it is more difficult to get a precise measurement of the leaf area of all species in the community because some leaf turn into the assimilating branches (i.e. *T. ramosissima*). By contrast, the thickness of each layer is much easier to be measured and the equation of community diversity is commonly used in the literature (Zhu, et al, Ecohydrology, 2013).

Reviewer: P8, L25: what does "them" refer to?

Authors: It refers to the different growth type (tree layer, shrub layer, herb layer). We rephrased this sentence in the manuscript. Please see Page12 Line 5 – Line 7: "Among different growth type, the thickness of 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%".

Reviewer: P9, L2: suggested rephrase: "…and herb layer, which can be calculated…"

Authors: Following the reviewer's suggestion, we rephrased this sentence in the manuscript.

Please see Page12 Line 11 – Line 12: "*A* is the diversity index of the tree layer, shrub layer and herb layer, which can be calculated using the formulae listed below."

Reviewer: Equations 5-8: to calculate D the only equation needed is Eq. 6, but in that equation, what is P? Is P related to IV defined in the previous page? Presented in this way, the equations do not seem to be related to D, which is the variable that needs to be calculated (if I understood the rationale).

Authors: The P refers to the important value of species (P13, L5). We apologize for using "D" in equation 4 and 6, which caused a misinterpretation of the latter. We replaced the "D" with letter "A" to eliminate this error. Please see Page 12 Line 9: $A=\sum W_i A_i$. We also changed the IV to P to make it consistent in the manuscript. Please see Page 11 Line 21 – Line 22: "The P (importance value) of each tree, shrub and herb in each plant site was calculated for each species using the following formulas: $P_{Tree} = (RDen + RDom + RH)/3$ (1) $P_{Shrub\ or\ Grass} = (RDen + RDom + RC)/3$ (2)".

Reviewer: P9, L17: the layers used for gravimetric water content are not consistent with the layers used for other analyses.

Authors: We thank the reviewer for pointing this out. Indeed, the layers used for soil moisture measurement are different from the layer used for measuring other soil properties. We divided the soil moisture into three layers in accordance with the fine root distribution of herb, shrub and tree since different layer of soil moisture showed different influence on the herb, shrub and tree in this area (The result of correlation in Table 1 showed that SWC1 mainly correlated with herb, while SWC2 and SWC3 mainly correlated with community coverage and density). The other soil properties, however, were analyzed using the mean values of each property from 0-100cm layer because the vertical variation of soil chemical properties was not significant in the data preprocessing. Thus we use different layers in analyzing soil moisture and other soil properties. We explained this reason in the Data and methods section. Please see Page 12 Line 25 - Page 13 Line 1: "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 to the fine roots distribution of herbs, trees and shrubs in this area. We averaged the soil moisture at each corresponding finer increment to obtain the value of SWC1, SWC2 and SWC3. Soil chemical properties, however, were analyzed using the mean values of 0 -100cm due to the minor vertical variation".

Reviewer: P16, L22: it is not entirely clear which parameters are being predicted here –

presence/absence for a given species, or the diversity indices?

Authors: The parameters being predicted here are the community characteristics, namely the vegetation indices in Table 1. We explained it in the Result section: 3.5 Key environmental factors that influenced community characteristics. Please see Page 23 Line 2 – Line 4: “To further examine the key environmental factors that controlled the variation of vegetation indices (e.g. community diversity, structure, NDVI), redundant variables were eliminated by a forward selection method”.

Reviewer: P18, L9: suggested rephrase: “… formed a bimodal pattern and reached local maxima at the distance…”

Authors: Following the reviewer’s suggestion, we rephrased this sentence. Please see Page 25 Line 9: “The community coverage reached local maxima at the distance of 1000 m and 3000 m where community consisted of diverse shrub and herb layers.”

Reviewer: P20, L14: “and possibly inducing…”

Authors: Following the reviewer’s suggestion, we revised this sentence. Please see Page 28 Line 20 – Line 24: “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 and possibly inducing the drought stress to the vegetation community”.

Reviewer: P20, L15: as explained in the major issues above, it is not easy to infer water availability effects on the plant community from a one-time water content measurement.

Authors: Following the reviewer’s suggestion, the long-term variance of water availability was illustrated by adding the temporal analysis of soil moisture and groundwater based on the hydrological data (Fig. S1 in the supplementary material) and retrieved remote sensing data (Fig. 7, Page 20 in the manuscript). We analyzed the impact of temporal variation water availability and the heterogeneity of water availability on plant community in the manuscript (please see “4.2 Factors influencing the distribution pattern and temporal variation of desert riparian forest” at Page 27 Line 17 - Page 28 Line 8, Page 29 Line 17 - Page 30 Line 7 in the Discussion section).

Reviewer: P20, L18: suggested rephrase: “…also partly explained the variance of the plant community, with TP representing 8.1% of the explained variance and SOM being negatively…”

Authors: Because we added the temporal variation factors in to environment factors, we re-conducting data analysis and the TP was no longer the key influencing factor, thus we deleted this sentence.

Reviewer: P20, L22: when the groundwater table is "low", shouldn't it be "below" the degradation threshold?

Authors: We intended to use the "low" to express the meaning of "shallow", but because of the reorganization of the Discussion section, we deleted the sentence.

Reviewer: P20, L24: what is the relation between TP and groundwater level?

Authors: In the original manuscript, we found that TP was one of the key factors influencing vegetation characteristics, accounting for 8.1% of variance. However, after we added the temporal variation factors in to environment factors and we re-conducted data analysis, TP only explained 2% vegetation variance and no longer became the key influencing factor (please see Table 2 in Page 24). We therefore deleted this sentence in the manuscript.

Reviewer: P21, L4: "thus halting…"

Authors: Following the reviewer's suggestion, we carefully revised this sentence. Please see Page 29 Line 15: "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".

Reviewer: P21, L7: it is also possible that the points now at 1000 m from the river have been less disturbed, and thus harbor a community with larger biomass, diversity, or coverage.

Authors: Thank the reviewer for pointing out the possibility. In fact, the 1000 m location along the gradient is the area which attract most tourists and herbivores, and consequently is more disturbed compared to other locations. Thus the larger biomass, diversity, or coverage did not result from fewer disturbances in the area.

Responses to the Reviwer#2:

General Comments:

Reviewer: Desert riparian forests are highly fragile ecosystem to climate and environmental changes. On the other hand, they serve as a haven for deteriorating desert ecosystems until their being threatened by impacts of changes. And, it is timely and relevant to have many studies on desert riparian vegetation ecology and function, as this one. The paper is well-structured and written, as well. However, the introduction lacks a clear definition of a problem. The introduction is full of background information; like, what has been done and what is already there…Such statements cannot justify a problem of a scientific work. There has to be a strong explanation of gaps, drawbacks…those pertinent to the subject of the work.

Authors: We thank the reviewer's suggestion and we carefully rewrote the Introduction section. Combing the first reviewer's suggestion on the temporal variation of the desert riparian forest, we added the temporal analysis and revised the main scientific questions in our study. In the revised manuscript, we emphasize the knowledge gaps on: 1) the influence of soil properties on the desert riparian forests rather than the groundwater focuses as in previous studies (please see Page 4 Line 13 - Line 26), 2) comprehensive analysis on the spatial and temporal variation of vegetation characteristic during the restoration process (please see Page 5 Line 17- Line 24), and 3) disentangling the impact of spatial heterogeneity factors and temporal variation factors on the vegetation communities (please see Page 5 Line 25 - Line 29). These knowledge gaps were addressed in the Introduction to justify the need of our work (please see Page 7 Line 6 - Line 13).

Reviewer: Moreover, simple richness and classification analysis could imply "the same old story". It feels to me that more can be done with existing data beyond analysis of richness and diversity of riparian vegetation. An example is combining with current affairs like climate and environmental change, resilience, elasticity…

Authors: We thank the reviewer's constructive suggestion on further delving into the data. As suggested by the reviewer, we included climate change, environmental change, resilience, and diversity indices into our revision. We rewrote the Discussion section and added the discussion on the community resilience and possible management in the "4.3 Community resilience of desert riparian forests and implications for ecological protection" (please see Page 30). Based on the relationship between community characteristics (i.e., species richness and community diversity) and community resilience, we discussed the community resilience in each sampling gradient. We defined the distance of 1000 m and 3000 m from river channel as the critical region with high resilience against disturbance (please see Page 30 Line 23 - Page 31 Line 9). We addressed the potential threats to these locations under climate change (e.g., drought stress) and intensive human disturbance (e.g., grazing and tourism pressure) and we further proposed the possible management to effectively restore the ecosystem in the future (please see Page 31 Line 14 - Page 32 Line 4).

Reviewer: What is “low reaches”? This is not a professional wording; better to use simply “oasis” or “downstream”, or give explanation for what “low reaches” is. It has to keep consistency, as well, in some places printed as “lower”?

Authors: Following the reviewer’s suggestion, we replaced the “low reaches” with the word “downstream” throughout the manuscript to make the description accurate and consistent.

Reviewer: The method needs more explanation how all the sampling and data collection was accomplished in one month (July 2015). Quadrants were set for collection of data on herbaceous vegetation just after the rain; what about desert-herbs those can be found before the rain?

Authors: We thank the reviewer for the suggestion. Water availability in our study site was greatly affected by the regulated water conveyance rather than the scarce precipitation of the region. Our study area belongs to hyperarid zone with mean annual precipitation below 39 mm and only 9.11 mm falls in July. There was only one rainy day (July 21 2015) when we conducted the sampling from July 10 2015 to July 30 2015. The surface soil quickly dried up before the next day due to the high evaporation (approximately 600 mm during the July). Water conveyance in the early July was therefore the only source of water for the area. Based on this condition, germination of desert herb barely benefited from the scarce precipitation, so we did not take into account the desert-herbs that could be found before the rain. As suggested by the reviewer, we added the explanation on sampling and data collection in the Data and methods section (please see Page 9 Line 14 - Page 10 Line 3).

Detail comments:

Reviewer: Title: delete the second “soil” in the second line

Authors: Because of adding the temporal analysis of vegetation variance, we changed the title of the manuscript to “The distribution pattern and temporal variation of desert riparian forests and its influencing factors in the downstream Heihe River Basin, China”, please see Page 1.

Reviewer: Page 2 Line 3: delete “of”

Authors: Following the reviewer’s suggestion, we deleted this word.

Reviewer: Page 6 line 8: “this area”, which area?

Authors: “this area” means the downstream Heihe River. We rewrote this sentence and delete “this area” and the revised sentence is “Due to sparse precipitation and hyperarid environment, Heihe River is the main source of recharge for the groundwater system in Ejina Oasis” (please see Page 8 Line 7 - Line 9).

Reviewer: Page 6 line 17-18: please provide professional soil-type names; “grey desert soil” is not in nomenclature of soils.

Authors: We replaced “grey desert soil” with professional soil-type names (i.e. shruby meadow soil and aeolian soil). We rewrote the sentence. Please see Page 8 Line 17 – Line 18: “The main soil types in the area are shruby meadow soil, aeolian soil and grey-brown desert soils. Saline-alkaline soils and swamp soils also exist in the lake basins and lowlands”.

Reviewer: Page 7 line 4-6: seems part of introduction, not methods

Authors: Following the reviewer’s suggestion, we deleted these lines.

Reviewer: Page 7 line 9: please define what “desert riparian forests” are in your research area?

Authors: As suggested by the reviewer, we added the detailed definition of “desert riparian forests” in the downstream Heihe River Basin. Please see Page 9 Line 2-4: “In the downstream Heihe River Basin, the desert riparian forest makes up the main body of the desert oasis, mainly comprised of tree, shrub and grass communities. The forests are distributed along the Heihe River from 0 m to 2000 m from river channel”.

Reviewer: Page 8 line 1-8: preferable to put in table

Authors: Thanks the reviewer’s suggestion, we put these lines in the annotation of Table 1 in the manuscript. Please see Page 22 Line 5 – Line 8: “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”.

Reviewer: Page 10 line 1-14: Why Monte Carlo run needed? Can’t Principal Component Analysis handle that size of data?

Authors: The Monte Carlo forward selection is a part of RDA (Redundancy Analysis). The RDA is an ordination analysis with the aim of finding variables as the best predictors for the vegetation distribution. As the Monte Carlo forward selection can directly shows significance and contribution rate of each factor (Lepš et al., Cambridge University Press, 2003), we chose this method rather than the Principal Component Analysis (PCA). We added these explanations in the Data and methods section. Please see Page 13 Line 21 – Line 24: “To further separating the key influencing factors of the 18 environment variables, marginal and conditional effects of various variables were calculated through the Monte Carlo forward selection in RDA (Redundancy Analysis), which directly showed the significance and contribution rate of each factor”.

Reviewer: Page 10 line 17-22: please give details of TWINSPAN analysis in methods

Authors: As suggested by the reviewer, we provided detailed description of the method of TWINSPAN analysis in Data and methods section. Please see Page 13 Line 15 - Line 20: “To depict the variation of desert riparian forests composition, we used Two-way Indicator Species Analysis (TWINSPAN, in WinTWINSPAN, version 2.3), a method of community hierarchical classification based on the importance value of each species (Hill, 1979), to classify the possible desert riparian forests 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 importance value for each class were set as: 0, 0.1, 0.2, 0.4, 0.6 and 0.9”.

Reviewer: Page 10 line 27-28: what does disturbed community mean?

Authors: The “disturbed” is actually “distributed”, we thank the reviewer for pointing out this oversight. Please see Page 14 Line 18: “This community mainly distributed near the river bank, mostly within 500 m from the river channel”.

Reviewer: Page 13: Figure 3 and 4 can be combined

Authors: Following the reviewer’s suggestion, we combined these two figures into Figure 4 (please see Page 17).

Reviewer: Page 14 line 2: We know for what SWC stands for, what are those attached numbers stands for? Ok, it is given in the caption, but, is also needed in the main text.

Authors: As suggested by the reviewer, we added the explanation of SWC when it appears in the main text.

Reviewer: Page 17: the need for Table 3 is clear; why is Table 2 (marginal and conditional effects are not main target of the study)

Authors: Table 2 allows the selection of the key influencing factors from the marginal and conditional effects. Marginal effects reflected the effects of the environmental variable 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. The forward selection in the Table 2 allowed key variables to be determined through the strength of their effects and significance. Based on the key influencing factors selected in the Table 2, we further analyzed the variation of community characteristics explained by different groups of key environmental factors (Table 3). We also revised the title of Table 2. Please see Page 23 Line 22 – Line 23: "The selection of the key influencing factors based on the marginal and conditional effects obtained from the forward selection of Monte Carlo test". We explained the purpose of Table 2 in the Result section. Please see Page 23 Line 10 – Line 13: "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)".

Reviewer: Page 18 line 17-18: the peculiar result from the vegetation analysis is the bi-modal distribution; do the soil properties show the same pattern; so that to say "variation in soil properties…." Page 19 line 22-24: YES! this can be an inference to the bi-modal distribution (in reference to the above comment)

Authors: We thank the reviewer's suggestion on improving our Discussion on how "variation in soil properties" may affect vegetation community. We developed this topic by referring to the results regarding the variation in soil moisture. Please see Page 25 Line 19 – Line 21: "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)."

Reviewer: Page 21 line 11-12: Here it says "vicinity to the main roads"? In the methods, it is indicated sampling was done far from roads; explain why?

Authors: In the Data and methods section, the description of "we chose sites that were far from farmlands, roads, irrigated channels and reservoirs" means that we chose plots that were distant from the roads and paths to minimize the human disturbance (i.e., grazing and firewood cutting) on vegetation communities. However, in the study area, there is a main road extending across the oasis and almost parallel to the river channel. As the distance of each sampling plots from the river channel is fixed, it is difficult to avoid sampling near the main road which extents parallel to the river channel. Currently, the vegetation community growing nearby the road is relatively undisturbed as the road is separated from the surrounding by iron wire. Therefore, we believe that sampling near the main road did not go against our general principle about minimizing human disturbance (i.e., grazing and firewood cutting) on the vegetation communities. While the vegetation communities growing nearby the main road (e.g., 1000 m from river channel) might become vulnerable to human disturbance in the future due to increasing population, we described the area that distant 1000 m from river channel as "vicinity to the main roads" in the original manuscript and listed the possible human influence on this gradient in the Discussion section. In the revised manuscript, we explained the information of the main road and clarified our sampling principle in the Data and methods section. Please see Page 9 Line 28 - Page 10 Line 3: "Those 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 nearby the road is considered to be undisturbed by the road as the road is separated from the surroundings by iron wire". We added the main road in the Figure 1 to make it easier to be understood (please see Page 8). To avoid further confusion, we rewrote the part in Discussion section and mainly focused on address the potential disturbance near river channel instead of near the road. Please see Page 31 Line 20- Line 23: "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. 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".

Reviewer: Page 21 line 12-15: To give management options for livestock control; there is a need to have socio-economic background information, specifically to livestock, somewhere in the introduction or in methods.

Authors: Following the reviewer's suggestion, we added the socio-economic background information (e.g. population, farming, tourism) in the Data and methods section. Please see Page 8 Line 1 – Line 6: "The population in the Ejina oasis is 32,410. The local economy mainly depends on the cantaloupe plantation and animal husbandry (e.g., sheep, cattle and camel). 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. Two primary roads are built parallel to the river channel and across the south of the oasis respectively, mainly used for transportation and traveling".

Reviewer: Page 22 line 4: what are "artificial channels"? Or take the whole sentence to Introduction; also line 6, if human disturbance is a problem give a brief background in the Introduction.

Authors: The "artificial channels" are concrete channels built perpendicular to the river with the aim of delivering water for irrigation. They, however, generate little benefit to the surrounding vegetation communities since they lack the seepage property that natural channels have. As we chose our plots that were distant from the roads, farmlands and irrigated channels, human disturbance mentioned in line 6 was not the main factor that shaped the vegetation community, although the extent might increase in the future. To make it easier understand, we replaced the sentence of "artificial channel" with "concrete channel" in the Introduction. Please see Page 3 Line 26 - Line 28: "Every year, about 300 billion m^3 of water were delivered using concrete channels that were built perpendicular to the river aiming to expand the river impact and to deliver water for irrigation". We also added the information of possible human disturbance in the Data and methods section. Please see Page 8 Line 1 – Line 6: "The population in the Ejina oasis is 32,410. The local economy mainly depends on the cantaloupe plantation and animal husbandry (e.g. sheep, cattle and camel). 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. Two primary roads are built parallel to the river channel and across the south of the oasis respectively, mainly used for transportation and traveling".

Reviewer: Page 22 line 21-26: many more services can be told.

Authors: Following the reviewer's suggestion, we added additional discussion materials regarding ecosystem services, such as sand fixation, carbon storage and water conservation to fully illustrate the importance of conserving the ecosystem. Please see Page 31 Line 16 – Line 23: "Since the influence of ecological water conveyance was mainly limited to 1000 m distance from river, 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. 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.”

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The distribution pattern and temporal variation of desert riparian forests and its influencing factors~~relationship with soil moisture and soil properties~~ in the ~~low reaches~~ downstream ~~of~~ 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~~ that provide~~ and a variety of ecosystem services in this arid environment~~s~~. Since t~~T~~hey are also sensitive to disturbance, ~~endangered ecosystem types that are sensitive to disturbance and threatened by desertification.~~ examining the distribution pattern, temporal variation of desert riparian forest and ~~as well as~~ their influencing factors are important to determine the limiting factors of vegetation recovery after long−term restoration. ~~Despite of previous studies stressed on the interactions between desert riparian forests and water availability, the lack of comprehensive information on the forests distribution range and their relationship with soil properties constraints further conservation efforts of this community under a changing climate.~~ In this study, ~~vegetation community characteristics, soil moisture and soil properties were investigated within a 3000 m radius around the river channel in the low reaches of Heihe River Basin, northwest China~~ field experiment and remote sensing data were used to determine the ~~distribution variation~~ spatial and temporal pattern of desert riparian forests and their relationship with environmental factors. Across different distance from the river channel, we classified f~~F~~ive types of vegetation communities.~~ were identified based on Two-way Indicator Species Analysis (TWINSPAN) they gradually shifted from the riparian tree-shrub-herb communities to riparian-desert shrubs with increasing distance from the river channel. Vegetation community coverage and~~ Community coverage and diversity ~~indices~~ formed bimodal pattern~~s~~ peaked at the distance of 1000 m and 3000 m from the river channel~~ while community height and density declined significantly as the distance from the river increased~~. In general, temporal NDVI trend was positive 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 already underwent degradation since 2011. Spatial heterogeneity of soil properties (e.g. soil moisture, soil physical properties and soil nutrition) and temporal variation of water availability (e.g. annual average and annual variability of groundwater, soil moisture and runoff) explained 74% of the vegetation variance. Spatial heterogeneity factors, accounting for 98.4% of the total variance explained, positively influenced the community diversity, structure, average NDVI and change variability of NDVI trend. Temporal variation factors accounting for 35.9% the total variance explained, positively influenced the community density and average NDVI. ~~Soil moisture, soil physical properties, and soil nutrition explained 53.6% of the variance in community characteristics and different environment variables influenced different community characteristics. Soil moisture, accounting for 62.7% of the~~

~~total explanation, mainly influenced the community coverage and density. Soil physical properties (e.g., bulk density, soil particle composition) exerted influence on shrub layer, while soil nutrition mainly affected community richness.~~ With surface (0-30 cm) and deep (100-200 cm) soil moisture, bulk density and ~~total phosphorus~~annual average of 100 cm soil moisture regarded as major determining factors of ~~in the~~ community ~~structure and diversity~~distribution and temporal variation, conservation measures that protect ~~the~~ soil structure and prevent soil moisture deficiency (e.g., artificial soil cover and water conveyance channel) ~~were~~ are suggested to better protect ~~the~~ desert riparian forests under climate change and intensive human disturbance.

1 Introduction

Riparian zone is the linkage between terrestrial and aquatic ecosystem (Naiman and Décamps, 1997), which plays an important ~~part~~ 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', are considered as the main body of riparian zone in the hyperarid areas, ~~and are~~ mainly located in the floodplains of the major Central Asian rivers (Gärtner et al., 2014). They provide critical habitats for various species and function~~s~~ as the "ecological shelter" against desertification in the hyperarid area (Thevs, 2008; Ding et al., 2016). However, due to the low diversity level and weak resilience, desert riparian forests are sensitive to ~~the~~ disturbance and likely to be threatened by desertification under changing environment (Ling et al., 2015; Li et al., 2013).

Desert riparian forests are the main communities in the ~~low reaches of~~ Heihe River Basin, the second largest inland river ~~of~~ in China (Feng et al., 2015). During the past century, human population increase and overexploitation of the upstream water resources ~~in the middle reaches~~ led to significant degradation of the downstream desert riparian forests ~~in the low reaches~~ (Wang et al., 2014). Since 2000, ecological water conveyance project (EWCP), a restoration project aimed to deliver water downstream has been implemented to ~~with the aim of restoring~~ restore the ecosystems of the Heihe River ~~basin~~ Basin (Yu et al., 2013). Every year, about 300 billion m^3 of water were delivered using concrete channels, built perpendicular to the river aiming to expand the river impact and to deliver water for irrigation. While most downstream~~the~~ vegetation has been restored ~~recovered in the low~~

~~reaches~~ (Wang et al., 2014; Lü et al., 2015), nearly 20% of the oasis area covered by desert riparian forests still underwent major degradation ~~process~~ in spite of the rising groundwater level and better downstream water condition ~~in the low reaches.~~ (Zhang et al., 2011a; Lu et al., 2015). To conserve and restore this fragile ecosystem more effectively, studies that address the variation of desert riparian forests and their relationship with the environmental factors need to be conducted.

The distribution pattern of desert riparian forests is the result of long-term interaction between vegetation and multiple environmental factors ~~combined effects of many environmental factors,~~ particularly water availability (Goebel et al., 2012; Li et al., 2013). With river acting as the main supply of water ~~in hyperarid zone~~in desert riparian forests, the distance from river channel ~~w~~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 have indicated that in the hyperarid zone, groundwater was a crucial water source for vegetation growth (Zheng et al., 2005; Hao et al., 2010).~~ Species diversity would peak where groundwater depth was around 2-4 m, ~~as opposed to the deficiency in soil moisture and degradation of vegetation~~before it started to decrease once groundwater went below 4-4.5m and deficiency in soil moisture occurred (Zheng et al., 2005; Li et al., 2013). While this could be the case~~true~~ for some hyperarid zones (e.g., Tarim river) where groundwater dropped rapidly away from the river bank to about 6 m deep at the distance of 1000 m from river channel (Aishan et al., 2013), ~~in the low reaches of Heihe River Basin,~~ the ~~perennial~~ groundwater table remained above 4 m at the distance of 3800 m from the Heihe river channel (Wang et al., 2011; Fu et al., 2014). Yet some sites were not completely restored at the Heihe riparian zones and the downstream vegetation community~~, the vegetation community at lower Heihe riparian zones~~ still shifted from multiple layers of trees to shrubs ~~and some sites were not completely restored~~ (He and Zhao, 2006; Zhang et al., 2011a).~~,~~ Previous study by Zhu et al. (2013) showed that Patrick's richness index and Shannon–Wiener's index of downstream vegetation formed a bimodal pattern along groundwater depth in the Heihe River Basin, indicating that there could be other factors affecting the distribution of desert riparian forests.

~~The distribution pattern of desert riparian forests is the result of combined effects of many environmental factors, particularly water availability (Goebel et al., 2012; Li et al., 2013). With river acting as the main supply of water in hyperarid zone, the distance from river channel would be regarded as a proxy to water availability which declined with the weakening of river influence (Hao et~~

~~al., 2010; Chen et al., 2014).~~ Apart from water, soil properties, such as soil moisture, soil physical and soil chemical properties also shape the community characteristics by influencing the ecological and hydrological process (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). ~~The shallow soil moisture layer recharged by the river flooding, mainly affected the richness of herbaceous plant and the regeneration of trees, while the deep layer soil moisture recharged by the groundwater, mainly affected the abundance of shrubs and trees (Li et al., 2008).~~ Interactions between communities and extreme environmental stress could cause non-unimodal responses in the hyperarid zone (Oksanen and Minchin, 2002), although other study in semiarid zone showed a unimodal pattern (Li, 2006; Hao et al., 2010; Li et al., 2013). With different depth of soil moisture exerted different impacts on vegetation (D'Odorico et al., 2007; Fang et al., 2016), the decline of soil moisture would reduce the abundance of tree and herb species, resulting in the community shift to drought-tolerant vegetation types along the distance from river channel (Zhu et al., 2014). Some studies also found that the heterogeneity in soil properties was the reason for the evolution of dominant species in arid area 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 temporal variation of vegetation can reflect how communities respond to the changing environment during ecological restoration (Bakker et al., 1996; Scott et al., 1996). 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.

~~Since soil moisture is greatly influenced by soil properties, the distance from the river channel is~~

~~therefore a synthesis, not only of water availability but also soil properties (e.g., bulk density, soil particle size, and soil nutrition) (Zhang and Zhao, 2015). Rosenthal et al. (2005) suggested that water was more tightly bound to clay than to sand particles and soils with higher clay content had greater resistance to water movement than soils with higher sand content. Similarly, soil nutrition (e.g., soil organic matter and total nitrogen) is the basic substance that sustains vegetation growth of desert riparian forests (Yarwood et al., 2015), as opposed to salt content which mainly halts the restoration of vegetation (Kong et al., 2010; Chen et al., 2014). These interactions between water availability and soil properties mainly resulted in the heterogeneity environment and are likely to become important selective forces in shaping plant adaptation strategies and vegetation distribution pattern (Rosenthal et al., 2005). Although the variation of floristic composition and community structure (e.g. height, density, coverage) generally showed clear pattern along the distance from river channel (i.e., exponential decrease or unimodal variation) (Li, 2006; Hao et al., 2010; Li et al., 2013), interactions between communities and extreme environmental stress may cause non-unimodal responses in the hyperarid zone (Oksanen and Minchin, 2002). Previous study by Zhu et al. (2013) for example showed that Patrick's richness index and Shannon–Wiener's index formed a bimodal pattern along groundwater depth in the low reaches of Heihe River Basin. Study on the impacts of soil moisture and soil properties on desert riparian forests can therefore contribute to the comprehensive understanding of vegetation community variation and act as scientific basis for more advanced ecological restoration under changing circumstances.~~

~~Currently, studies on desert riparian forests distribution pattern have indicated floristic composition and community structure form different patterns along the distance gradient. While vegetation community variation along the distance from river channel could help defining the distribution range of desert riparian forests, it has not been clarified in the previous studies due to the heterogeneity of landforms, communities, and environments variability in different geomorphic and hydrologic patterns (Lü et al., 2003; Décamps et al., 2004). Similarly, the influence of soil moisture and soil properties on the desert riparian forests community characteristics were rarely discussed in comparison to the effects of groundwater in hyperarid zone.~~ In this research, we aim to 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~~therefore~~ investigated variability in desert riparian forests sites that are differently located along the perpendicular direction~~distance~~ from the river channel. Changes of floristic composition, community structure and diversity were used to depict community distribution pattern, and the variation of NDVI at each gradient from 2000-2014 was used to depict the temporal variation. Spatial heterogeneity factors (e.g., soil moisture, soil physical properties and soil nutrition) and temporal variation properties (e.g., annual average and annual variability of groundwater, soil moisture and runoff) ~~while different depth of soil moisture, soil physical properties and soil nutrition~~ 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 ~~variation pattern of floristic composition and community characteristics along the distance~~ 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 ~~soil moisture and soil prosperities~~ 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 ~~advanced~~ 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 ~~lower reaches of~~ Heihe River (40°20′–42°30′N; 99°30′–102°00′E), in the Ejina Oasis, Inner Mongolia, Northwest China. The oasis covers an area of 3×10^4 km^2, with declining surface elevation (i.e., 1127 m to 820 m above sea level) from the southwest to the northeast ~~in the range of 1127 to 820 meters above sea level~~ (Qin et al., 2012). This region has a typical continental arid climate with mean annual temperature of 8.77 ℃. Its maximum and minimum temperatures usually occur in July (41°C) and January (−36 ℃) (Wen et al., 2005). The mean annual precipitation is <39 mm, 84% of which occurs during the growing season (May to September), while the mean annual potential evaporation is >3,390 mm (Chen et al., 2014). 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 flow into the East Juyan

Lake and the West Juyan Lake in Ejina. The population in the Ejina oasis is 32,410 (Ejina statistical office, 2012). The local economy mainly depends on the cantaloupe plantation and animal husbandry (e.g. sheep, cattle and camel). 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., 2014). Two primary roads are built parallel to the river channel and across the south of the oasis respectively, mainly used for transportation and traveling.

Due to sparse precipitation and hyper~~-~~arid environment, ~~no perennial runoff is originated from in this area.~~ Heihe River is ~~therefore the only runoff flow through the area and~~ the main source of recharge for the groundwater system in Ejina Oasis (He and Zhao, 2006). As the distance from river channel ~~increasing~~increases, water availability declines and the vegetation shifts from desert riparian forests to desert scrub. The desert riparian forests are the main components of Ejina oasis. ~~It~~ They mainly grow~~s~~ along the river banks and spread across~~distributed in~~ the fluvial plain, with the dominant vegetation including *Populus euphratica*, *Tamarix ramosissima*, *Lyceum ruthenicum*, *Sophara alopecuriodes*, *Karilinia caspica*, and *Peganum harmala* (Zhao et al., 2016). The sparse and drought tolerant desert species such as *Reaumuria soongorica*, *Zygophyllum xanthoxylon* and *Calligonum mongolicunl* are mainly distributed in ~~low mountainous area and~~ the Gobi desert. The main soil types in the area are shruby meadow soil, aeolian soil ~~grey desert soils~~ and grey~~-~~brown desert soils. Saline-alkaline soils and swamp soils also exist in the lake basins and lowlands (Chen et al., 2014).

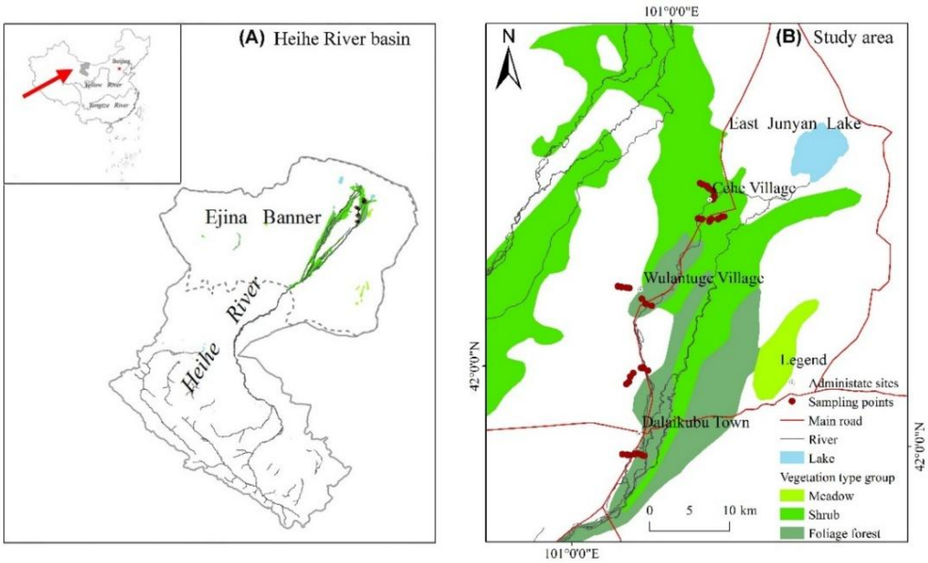

Figure 1. The ~~low reaches of~~ Heihe River basin in China (A) and the location of sampling points in the study area (B). Two primary roads are built parallel to the river channel and across the south of the oasis, respectively.

2.2 Spatial f~~F~~ield ~~sampling~~survey and experimental design

In the downstream Heihe River Basin, the desert riparian forest makes up the main body of the desert oasis, mainly comprised of tree, shrub and grass communities. The forests are distributed along the Heihe River from 0 m to 2000 m from river channel (Si et al., 2005; Guo et al., 2009). ~~Riparian zone is defined as the area that spread from both sides of the land-water ecotone, up to the point where the effects of river disappeared. Some studies, for examples, showed that the range of river influence was around 0-2000 m from the river channel in the low reaches of Heihe (Si et al., 2005;Guo et al., 2009). The spatial extent of the riparian zone, however~~However, the spatial extent of the riparian zone is difficult to be ~~precisely~~ delineated due to the heterogeneity of landform mosaics ~~of landforms, communities, and environments varied in different geomorphic and hydrologic pattern~~ (Décamps et al., 2004). ~~We t~~Therefore ~~conducted our research in~~ our study covered a length across ~~the range of 0-~~3000 m distance from the Heihe river channel to fully cover the distribution pattern of its desert riparian forests.

~~The~~ Our field survey was conducted in July 2015, after the ecological water conveyance delivered ~~to low reaches~~. The ecological water conveyance is implemented according to the water dispatching scheme and conducted in the April, July, August, September and November with scheduled discharge (Feng et al., 2015). Five transects~~sites~~ perpendicular to the river were selected randomly as replicates ~~in each distance from river channel gradient~~ under the premise of consistenc~~y~~e 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 100 m radius) (Liu et al., 2008). Therefore, vegetation and soil samplings were conducted perpendicular to the river channel and the distance from the river channel was stratified into seven gradients~~-~~: ~~To minimize the impact of human disturbance and other water resources, we chose sites that were far from farmlands, roads, irrigated channels and reservoirs. Sampling was conducted perpendicular to the river channel and the distance from river channel was stratified into six gradients:~~ 100 m, 500 m, 1000 m, 1500 m, 2000 m, 2500 m, and 3000 m, respectively, generating a total of 35 sampling sites. ~~Five sites were selected randomly as replicates in each distance from river channel gradient under the premise of consistence in soil type and micro-topography. A total of 35 sites were sampled in the low reaches of Heihe River Basin.~~ Those 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 nearby 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 in each site. The number of each species (tree and shrub), plant height, coverage and 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, vegetation cover and height.

At each site, soil samples and soil moisture samples were randomly collected in three replicates using 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, 200 cm, 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 ~~(i.e., 21 sites)~~, the SWC sampling stopped~~was ended~~ at the depth of groundwater table. ~~To measure soil moisture content, samples were collected with aluminum boxes and weighed at the time of sampling as well as after oven drying at 105 ℃ for 48 hours. To measure b~~Bulk density (BD) was measured~~, the~~ by collecting undisturbed soil cores at surface layer ~~were collected~~ using a stainless-steel cutting ring (100 cm^3 in volume) with three replicates each site and oven dried at 105 ℃ until they reached constant weight. Soil particle size distribution and soil chemical properties (soil organic matter, total nitrogen, total phosphorus and total salt content) were analyzed in the laboratory using 0-100cm soil samples that were collected separately in each site.~~)~~ ~~Disturbed 0-100 cm soil samples were collected at five depth increments (0-20, 20-40, 40-60, 60-80 and 80-100 cm) in each sites to determine soil composition and nutrients. Three samples at each layer were mixed evenly to form one composite sample and sealed in air-tight bags. After sorted for roots, air-dried and passed through a 2 mm sieve, surface soil samples (0-20cm) were subsequently 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 including the concentrations of soil organic matter (SOM), total nitrogen (TN), total phosphorus (TP) and total salt content (TS) at 0-20, 20-40, 40-60, 60-80 and 80-100 cm were also analyzed in the laboratory.~~

2.3 Temporal data collection and processing

In order to analyze the long term vegetation variation since the implementation of ecological water conveyance, we analyzed NDVI data from 2000 to 2014. As the NDVI measures vegetation status, including coverage and vigor, 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 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/). The variable environment factors such as 2 cm soil moisture, 100 cm soil moisture and groundwater in each site during the research period were extracted from the retrieved remote sensing data with 1000 m resolution (Zeng et al., 2016). Land use change information from 2000-2014 was extracted from land use data at a scale of 1:100,000 (for 2000 and 2014) (Liu et al., 2002; Zhong et al., 2015). The diurnal and annual variation of soil moisture were depicted by the monitoring data of soil moisture from 2013-2015 (Liu et al., 2011; Li et al., 2006). The retrieved remote sensing data, monitoring data and land use data were acquired from Environmental & Ecological Science Data Center for West China, National Natural Science Foundation of China (http://westdc.westgis.ac.cn). Runoff data at Zhengyixia, a hydrological station at the border of the downstream Heihe, was collected from the Hydrological Almanac of China from the Chinese Academy of Sciences.

2.~~3~~ 4 Statistical analysis

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

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

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

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

In our study, the total diversity index of community was deployed to depict the community diversity in each site. According to the characteristic of community vertical structure, the total diversity index of community is measured using the weight of indices 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):

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

where C is the total coverage of community ($C = \sum C_i$); i = 1, tree layer; 2, shrub layer; 3, herb layer, and the meaning of i same below; h is the thickness of the leaf layer for various growth types ($h = \sum h_i$), W_i is the weighted parameter of diversity index 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 ~~them~~different growth type, the thickness of 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:

$$\cancel{D}A = \sum W_i \cancel{D}A_i \quad (4)$$

where W is the weighted parameters of the tree layer, shrub layer and herb layer. ~~D~~ A is the diversity index of the tree layer, shrub layer and herb layer~~.~~, which ~~The diversity index of different layers~~ can be calculated using the formulae listed below.

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

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

and Simpson's index of dominance was calculated as

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

and Pielou's index of evenness was calculated as

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

Finally, Patrick's index of richness was calculated as

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

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

Within each gradient, vegetation community, ~~data of~~ soil moisture and soil properties of the ~~5~~ five sites ~~at each distance range~~ were calculated as 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 to the fine roots distribution of 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. Soil chemical properties, however, were analyzed using the mean values of 0-100cm due to the minor vertical variation.~~Similarly, the SOM, TN, TP, TS at 0-100 cm were the average value of each property at 0-20, 20-40, 40-60, 60-80 and 80-100 cm.~~ The annual average value and annual variability were used to depict the temporal variation of community characteristics and environment factors. The annual average of NDVI (NDVI_a), groundwater (GWT_a), 2cm soil moisture (SWC2cm_a), 100cm soil moisture (SWC100cm_a) were calculated by the mean values from 2000-2014. The annual variability of NDVI (NDVI_c), groundwater (GWT_c), 2cm soil moisture (SWC2cm_c), 100cm soil moisture (SWC100cm_c) were calculated by the mean values of change rate at each year.

Regression analysis was used to examine variation pattern~~tendency of the height, density and cover with distance from river channel~~. Exponential and polynomial regressions were fit to the data to best explain the statistical relationship. Pearson correlation was used to determine the strength of possible relationship between community characteristics and environmental factors. Significant differences were evaluated at the 0.05 and 0.01 level. Statistical analysis was performed using SPSS (ver. 18.0).

To depict the variation of desert riparian forests composition, we used Two-way Indicator Species Analysis (TWINSPAN, in WinTWINSPAN, version 2.3), a method of community hierarchical classification based on the importance value of each species (Hill, 1979), to classify the possible desert riparian forests community types. The ~~presence/absence~~importance value data for all plant species, obtained from the vegetation survey were used in this analysis and the cutoff levels of importance value for each class were set as: 0, 0.1, 0.2, 0.4, 0.6 and 0.9~~ under the consideration of important value frequency~~. To further separating the key influencing factors of the 18~~12~~ environment variables, marginal and conditional effects of various variables were calculated through ~~the Monte Carlo test in the process of forward selection.~~ the Monte Carlo forward selection in RDA (Redundancy Analysis), which directly showed the significance and contribution rate of each factor. Marginal effects reflected the effects of the environmental variable 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 determined through the forward selection, this method allowed key variables to be determined through the strength of their effects and significance. Variation of community characteristics explained by ~~the key~~the different group of environmental factors was analyzed 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 ~~was~~ were performed 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 of vegetation composition

~~We found that vegetation community diversity was relatively low in the low reaches of Heihe. Only 19 plant species (frequency ≥2) were recorded in 35 sites. Out of these 35 sites, the tree layer only appeared in 7 sites, while the shrub and herb layer appeared in 32 and 29 sites, respectively. The~~ S~~s~~pecies composition at each site in the ~~low reaches~~ downstream ~~of~~ Heihe River Basin is shown in Table S1 and the following five plant community types distributed across the ~~along the distance of~~ ~~0-~~3000 m transect from river channel were obtained based on 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~~s type with multiple layers of tree-shrub-herb~~, its coverage was relatively low (38.05%). The community was dominated by 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 mainly distributed ~~disturted~~ 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 of shrub and herb layers with high community coverage of 81.43%. *Tamarix ramosissima* was the dominant species of the shrub layer with the importance value of 0.84-1.00. The herb layer contains both hygrophyte and xerophyte species, such as *Kochia scoparia* and *Peganum harmala*. This community was mainly distributed near the river bank~~, distanced –~~ (about 1000 m from the river channel).

(iii) Community III was *Tamarix ramosissima*, found at sites 8, 9, 20, 23 and 25. This community was mainly constituted of shrub layers, except that sparsely grown herbs existed at site 8. The community was dominated by *Tamarix ramosissima* with average community coverage of 75.93% and mainly distributed at the distance between~~of~~ 1000m ~~–~~ and 2000 m from the river channel.

(iv) Community IV was Ass. *Lycium ruthenicum–Tamarix ramosissima* + xerophytes herbs, found at sites 12, 13, 14, 17, 18, 22, 24, 27, 32 and 34. This community mainly composed of shrub and herb layers with average community coverage ~~at~~ of 68.86%. *Lycium ruthenicum* was the dominant 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 ~~at the distance of~~ between 1500m~~-~~ and 2500 m from the river channel.

(v) Community V was Ass. *Tamarix ramosissima–Lycium ruthenicum–Reaumuria songarica*, 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 shrub community, indicated by the presence of *Reaumuria songarica*, a typical desert shrub. *Tamarix ramosissima* was the dominant species of the shrub layer and mainly exist in the form of shrub dune, with the importance value of 0.38-0.93. The *Karilinia caspica and Phragmites communis* herbs ~~were~~ only existed in one sampling site and they were only sparsely distributed~~ sparsely and only existed in one sampling site~~. This community was mainly distributed around~~at the distance of~~ 2500-3000 m from the river channel, with a relatively low community coverage (54.40%).

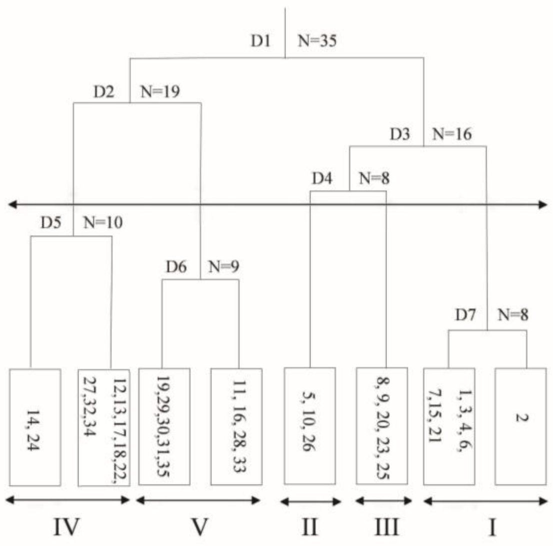

Figure 2. The dendrogram of the sampling sites based on the TWINSPAN classification

Note: Number 1-35 represents the site number of the sampling sites. D is for the classification levels and N is for the numbers of sampling sites for the classification. I to V represent community I to V. Arrows depicted all the sites were divided into five major groups after the fourth classification.

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

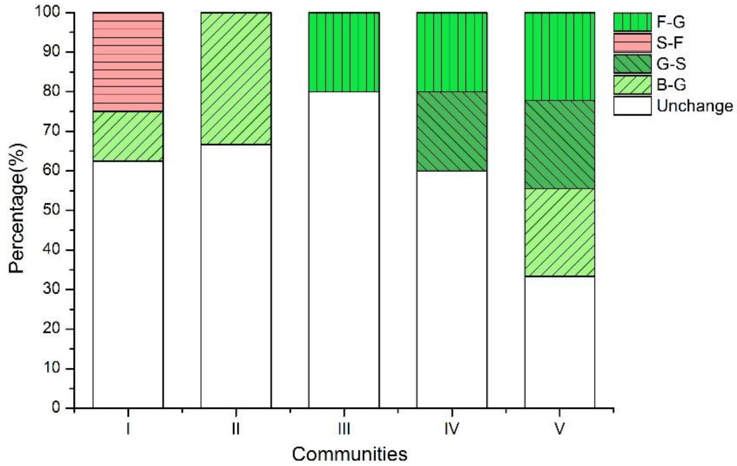

Figure 3. The percentage changes of vegetation composition in each community from 2000-2014

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 ~~Variation of vegetation community structure and diversity along the distance from the river channel~~ The spatial and temporal variation of community characteristics in desert riparian forest

Community characteristics formed different patterns along the distance from the river channel (Fig. 4). Vegetation community height and density dropped rapidly after 500 m ~~-along the distance from the river channel~~ (Fig. ~~3a~~4a, b)~~.~~, ~~C~~ while community coverage formed a bimodal pattern, ~~experienced a bimodal pattern,~~ peaked at the distance of 500-1000 m and 3000 m, respectively ~~with the coverage of 88% and 70%, respectively~~ (Fig. ~~3c~~4c). The variation of vertical structure was depicted by the following hierarchical~~y~~ coverage (Fig. 4~~3~~d):~~.~~ (i) ~~The~~ the tree layer mainly existed within 1000 m ~~from~~

~~river channel, while~~ (ii) the ~~coverage of~~ shrub ~~formed a unimodal pattern,~~ peak~~ing~~ed ~~at the distance of~~ around 1500-2000 m~~.~~, and (iii) t~~T~~he ~~coverage of~~ herb fluctuated along the distance gradient, peaking at 500 m and 2500-3000 m from the river channel. ~~Community diversity was low along the whole gradient and a~~All diversity indices showed a bimodal pattern along the distance from river channel ~~(Fig. 4)~~. The Shannon-Wiener diversity index, Pielou evenness index and Patrick richness index peaked at ~~the distance of~~ 1000 m and 3000 m (Fig. ~~4a~~4e-~~c~~g). The Simpson dominance index, however, formed an opposing trend to the other three diversity indices, by peaking at ~~the distance of~~ 500 m and 2000 m where the other indices were at their low level (Fig. ~~4d~~4h).

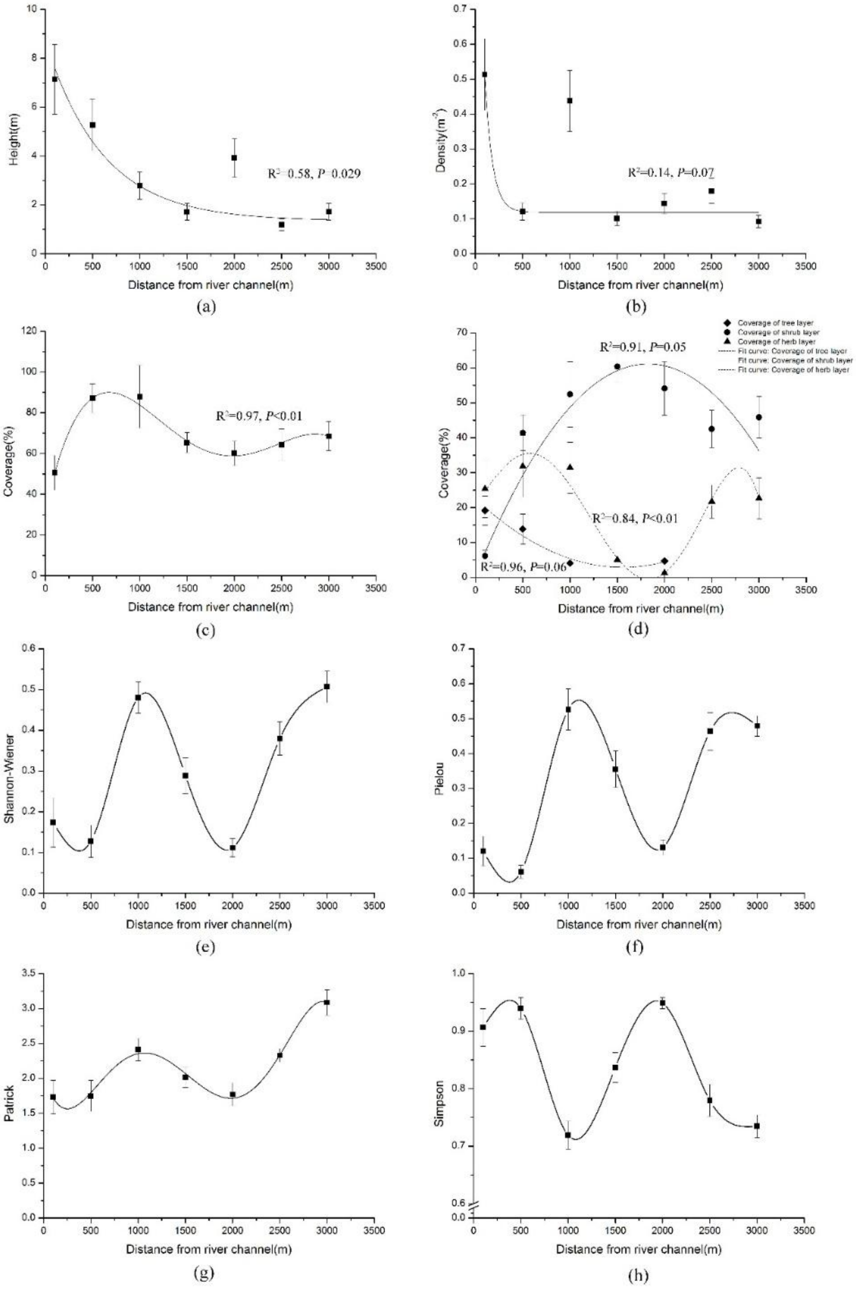

Figure ~~3~~4. The variation of community structure and diversity along the distance from the river channel.

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

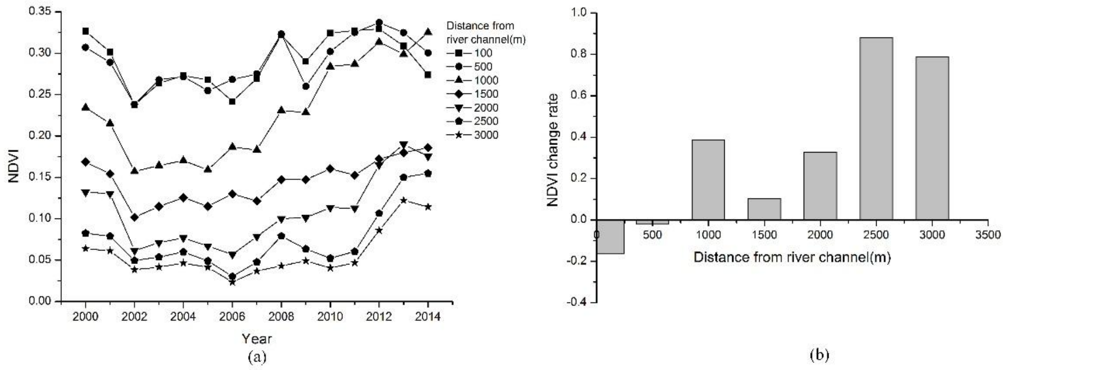

Figure 5. The variation of NDVI (a) and annual variability of NDVI (b) from2000 to 2014 at different distance from the river channel.

3.3 ~~Variation of water availability and soil properties along the distance from the river channel~~ 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). ~~Our results indicated that~~ 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). ~~diversity, evenness, and richness indices along the gradient from river channel (Fig. 5a).~~ 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 ~~the distance of~~ 2500 m (Fig. 6 a). The proportion of silt and clay was highest ~~peaked~~ at the distance of 1000 m from the river channel (Fig. 6 ~~5~~c), while bulk density reached its lowest point (1.07 g·cm^{-3}) (Fig. 6~~5~~ b). ~~After peaking at 1500 m, sand proportion decreased gradually and the soil composition consisted of 43.4% silt and 4.5% clay at the distance of 2500 m from river channel. At the end of~~

~~gradient, the proportion of sand and gravel reached 58.9% and 4.5%, respectively, with the highest bulk density (1.35 g·cm^{-3}).~~ The variation of SOM, TN, TP showed the similar pattern with vegetation diversity along the ~~ecological~~ gradient (Fig. 4 e-g, Fig. 6~~5~~d-g). They generally decreased along the distance from river channel and reached a relatively high value ~~content~~ 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.

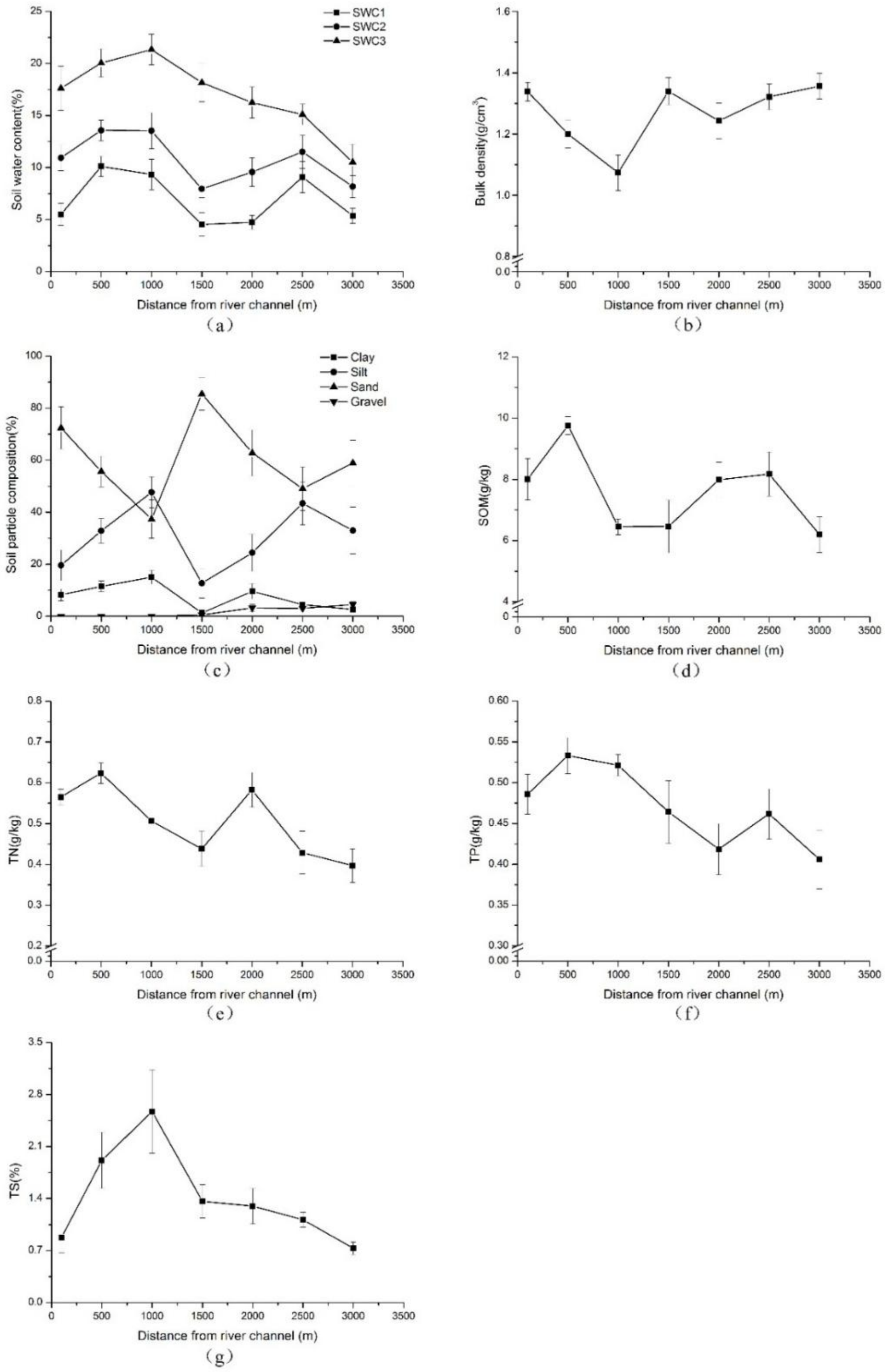

Figure ~~5~~6. The variation of soil moisture (a), soil bulk density (b), soil particle composition (c), soil organic matter (d), total nitrogen (e), total phosphorus (f), total salinity (g) along the distance from river channel.

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.

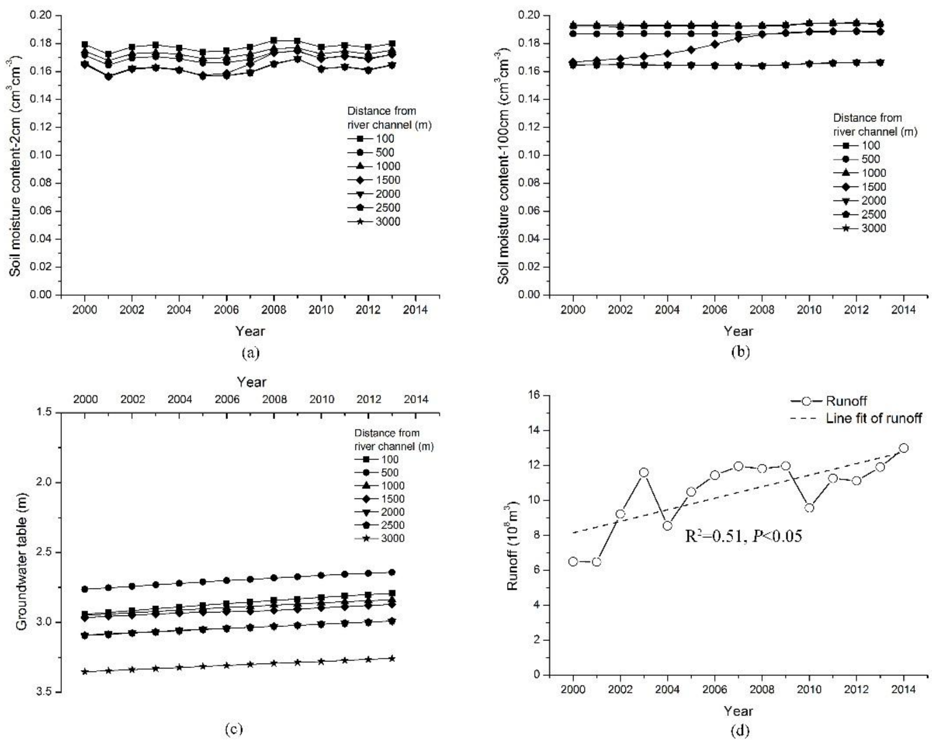

Figure 7. The variation of 2 cm soil moisture (a), 100 cm soil moisture (b), groundwater table (c), runoff (d) from 2000-2014 at different distance from the river channel.

3.4 Pearson correlation between community characteristics and environmental factors

Pearson correlation analysis between community characteristics and environmental factors ~~wa~~is shown in Table 1. The community density showed significant positive correlation with SWC2~~ (r=0.382, P<0.05)~~, SWC3~~ (r=0.362, P<0.05)~~, SWC2cm_a and SWC100cm_a, but negative correlations with BD

~~(r=—0.353, *P*<0.05)~~ and GWT_a. Community coverage positively correlated with all the three layers of soil moisture (*P*<0.0.1) but negatively correlated with BD ~~(r=—0.350, *P*<0.05)~~. ~~Specifically,~~ Tree and shrub layers layer influenced by GWT_a and BD, respectively, while herb layer positively correlated with SWC1 and SCW3.~~the coverage of shrub layer was negatively correlated with BD (r=—0.465, *P*<0.01), while the coverage of herb layer was positively correlated with SWC1 (r=0.514, *P*<0.01). The coverage of tree layer did not showed any significant relationship with any environmental factors.~~ Among the diversity indices, the Patrick richness index was ~~negatively~~ significantly correlated with SOM and gravel ~~(r=—0.398, *P*<0.05)~~, while Simpson domination index was ~~positively~~ significantly correlated with sand (r=0.354, *P*<0.05) and ~~negatively correlated with~~ silt (r=—0.344, *P*<0.05). As for temporal variation of community characteristics, NDVI_a was mainly influenced by soil moisture (SWC1, SWC2, SWC3), soil particle composition (clay, gravel) and bulk density, while NDVI_c was significantly correlated with SWC3, gravel and TS.

With r~~R~~unoff ~~i~~as the main water resource in the ~~low reaches~~ downstream ~~of~~ Heihe~~.~~, ~~As~~ there was~~is~~ time lag between the increase of runoff and NDVI~~,~~. The correlation coefficient between NDVI and runoff was measured to examine the relationship between runoff and the same year's NDVI, while correlation coefficient between one year lag NDVI and runoff was measured to exam the relationship between runoff and the next year's NDVI. One year lag NDVI-runoff correlat~~e~~ion coefficient decreased significantly with the distance from river channel (P=0.086), as opposed to ~~compared with~~ insignificant variation of NDVI-runoff correlation~~e~~ coefficient along the distance from river channel (Fig. 8).

Table 1. Pearson correlation between community characteristics and environmental factors

~~—~~	~~H~~	~~C~~	~~R~~	~~J_{sw}~~	~~Height~~	~~Density~~	~~Cover-a~~	~~Cover-t~~	~~Cover-s~~	~~Cover-h~~
~~SWC1~~	~~0.26~~	~~-0.29~~	~~0.17~~	~~0.18~~	~~-0.09~~	~~0.25~~	~~**0.55**~~	~~-0.02~~	~~0.17~~	~~**0.51**~~
~~SWC2~~	~~0.05~~	~~-0.10~~	~~-0.07~~	~~0.07~~	~~-0.11~~	~~**0.38**~~	~~**0.44**~~	~~0.01~~	~~0.28~~	~~0.26~~
~~SWC3~~	~~0.14~~	~~-0.15~~	~~0.16~~	~~0.11~~	~~-0.24~~	~~**0.36**~~	~~**0.45**~~	~~-0.14~~	~~0.18~~	~~0.38~~
~~Clay~~	~~0.11~~	~~-0.13~~	~~0.01~~	~~0.05~~	~~0.05~~	~~0.29~~	~~0.20~~	~~0.04~~	~~-0.09~~	~~0.27~~
~~Silt~~	~~0.31~~	~~**-0.34**~~	~~0.12~~	~~0.31~~	~~-0.12~~	~~0.11~~	~~0.32~~	~~-0.07~~	~~0.25~~	~~0.17~~
~~Sand~~	~~-0.33~~	~~**0.35**~~	~~-0.15~~	~~-0.31~~	~~0.13~~	~~-0.17~~	~~-0.31~~	~~0.08~~	~~-0.17~~	~~-0.22~~
~~Gravel~~	~~0.23~~	~~-0.16~~	~~0.35~~	~~0.18~~	~~-0.28~~	~~-0.08~~	~~-0.19~~	~~-0.17~~	~~-0.18~~	~~0.01~~
~~BD~~	~~0.17~~	~~-0.13~~	~~0.28~~	~~0.12~~	~~-0.04~~	~~**-0.35**~~	~~**-0.35**~~	~~0.05~~	~~**-0.47**~~	~~0.06~~
~~SOM~~	~~-0.26~~	~~0.19~~	~~**-0.40**~~	~~-0.10~~	~~0.19~~	~~0.06~~	~~-0.19~~	~~0.12~~	~~-0.12~~	~~-0.30~~
~~TN~~	~~-0.19~~	~~0.14~~	~~-0.33~~	~~-0.06~~	~~0.10~~	~~0.03~~	~~-0.28~~	~~0.11~~	~~-0.30~~	~~-0.22~~
~~TP~~	~~-0.24~~	~~0.20~~	~~-0.30~~	~~-0.10~~	~~0.12~~	~~0.02~~	~~-0.18~~	~~0.08~~	~~-0.09~~	~~-0.29~~
~~TS~~	~~-0.14~~	~~0.11~~	~~-0.13~~	~~-0.10~~	~~-0.18~~	~~0.27~~	~~0.01~~	~~-0.09~~	~~0.03~~	~~-0.13~~

__	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

Significant correlations (P<0.05) are shown in bold and significant correlations (P<0.01) in bold with underline.

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;

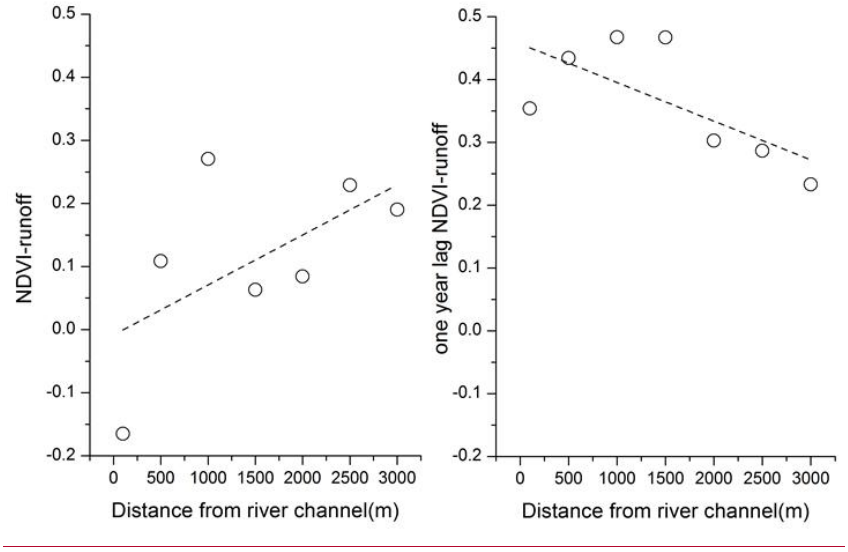

Figure 8. Pearson correlate coefficient of NDVI-runoff and one year lag NDVI-runoff at different distance from river channel.

3.5 Key environmental factors that influenced community characteristics

To further examine the key environmental factors that controlled the variation of vegetation indices (e.g. community diversity, structure, NDVI)~~desert riparian forests community~~, redundant variables were eliminated by a forward selection method. Table 2 shows the key influencing factors ~~showed the changing conditions of~~based on the marginal and conditional effects of ~~12~~ 18 variables under the Monte Carlo test in the process of forward selection. All the environmental factors explained ~~53.6~~74% variance ~~in~~ of total variance. In the Monte Carlo test of forward selection (P<0.05), SWC1, SWC3, BD and SWC100cm_a~~, and TP~~ were regarded as the key environmental factors influencing the variation of community characteristics. A total ~~78.74~~71.62% of the environmental information was extracted by the key environmental factors, and SWC1 contributed the most information (~~37.69~~27.03%). To further investigate the variation explained by spatial heterogeneity factors and temporal variation factors~~four key environmental factors~~, we divided those ~~four~~ 18 factors into ~~three~~ two groups for partitioning analysis (Table 3). Spatial heterogeneity factors explained 43.5% vegetation variance and accounted for 98.4% of the total variance explanation, while temporal variation factors only explained 15.9% vegetation variance, accounting for 35.9% of total variance explanation. These two groups of factors jointly explained 15.2% vegetation variance, accounting for 34.3% the total variance explanation.~~:~~ ~~(i) SWC1 and SWC3 to represent the effect of soil moisture, (ii) BD to represent soil physical properties, and (iii) TP to represent soil nutrient. The total variation of community characteristics explained by the three groups was 32.8%. SWC1 and SWC3 accounted for 62.7% of explanation power, followed by BD (19.8%) and TP (8.1%). The variation mutually explained by the three groups, however, was small (below 1.5%).~~

Table 2. The selection of the key influencing factors based on the m~~M~~arginal and conditional effects obtained from the ~~summary of~~ forward selection of Monte Carlo test ~~forward selection~~.

~~Environmental factors~~	~~Marginal effects~~	~~Environmental factors~~	~~Conditional effects~~	~~P value~~	~~R value (%)~~
	~~Percentage of variance explained (%)~~		~~Percentage of variance explained (%)~~		
~~SWC1~~	~~20.2~~	~~SWC1~~	~~20.2~~	~~0.006~~	~~37.69~~
~~SWC3~~	~~18.8~~	~~SWC3~~	~~8.2~~	~~0.030~~	~~15.30~~
~~SWC2~~	~~12.4~~	~~BD~~	~~7.9~~	~~0.036~~	~~14.74~~
~~BD~~	~~11.4~~	~~TP~~	~~5.9~~	~~0.040~~	~~11.01~~
~~TN~~	~~7.1~~	~~Clay~~	~~3.8~~	~~0.126~~	~~——~~
~~Silt~~	~~7.0~~	~~Sand~~	~~2.7~~	~~0.214~~	~~——~~
~~Sand~~	~~6.1~~	~~TN~~	~~1.2~~	~~0.500~~	~~——~~
~~SOM~~	~~4.1~~	~~TS~~	~~1.0~~	~~0.588~~	~~——~~
~~Clay~~	~~3.8~~	~~SWC2~~	~~0.4~~	~~0.842~~	~~——~~
~~TP~~	~~3.6~~	~~Gravel~~	~~0.4~~	~~0.868~~	~~——~~

~~Gravel~~	~~2.6~~		~~Silt~~	~~1.9~~	~~0.384~~	~~——~~
~~TS~~	~~0.5~~		~~SOM~~	~~<0.1~~	~~0.996~~	~~——~~
~~—~~	~~—~~	~~—~~	~~Total~~	~~53.6~~	~~0.036~~	~~——~~

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		GWT_c	3	0.096	——
Sand	6.1		TP	2	0.25	——
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	0.62	——
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	0.96	——
—	—	—	Total	74	0.036	——

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

Table 3. The percentage of community characteristic variations explained by key environmental factors.

~~Fraction~~	~~Variation~~	~~% of All~~	~~% of Explained~~	~~F~~	~~*P*~~
~~SWC1+SWC3~~	~~0.210~~	~~20.6~~	~~62.7~~	~~5.9~~	~~0.002~~
~~BD~~	~~0.065~~	~~6.5~~	~~19.8~~	~~4.0~~	~~0.032~~
~~TP~~	~~0.027~~	~~2.7~~	~~8.1~~	~~2.2~~	~~0.132~~
~~SWC1+SWC3+BD~~	~~0.015~~	~~1.5~~	~~4.5~~	~~5.9~~	~~0.002~~
~~BD+TP~~	~~0.002~~	~~0.2~~	~~0.5~~	~~4.1~~	~~0.024~~
~~SWC1+SWC3+TP~~	~~0.008~~	~~0.8~~	~~2.6~~	~~2.3~~	~~0.122~~
~~SWC1+SWC3+BD+TP~~	~~0.006~~	~~0.6~~	~~1.8~~	~~5.2~~	~~0.002~~
~~Total Explained~~	~~0.330~~	~~32.8~~	~~100~~	~~—~~	~~—~~

Fraction	Variation	% of All	% of Explained	F	*P*
a	0.43539	43.5	98.4	5.9	0.008
b	0.1588	15.9	35.9	4	0.088
a+b	0.1519	15.2	34.3	2.2	0.016
Total Explained	0.44229	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; 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 distribution pattern of desert riparian forests along the distance from the river channel~~

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

The characteristics and indices of desert riparian forests formed ~~a clear~~different patterns along the distance from the river channel in the ~~low reaches~~ downstream ~~of~~ Heihe River Basin. ~~As it went further from the river, the desert riparian forests community shifted from the riparian tree-shrub-herb community (Community I) to riparian desert transition shrubs community (Community V).~~ Community height and density declined significantly as dominant~~ce~~ species changed~~s~~ from trees to riparian-desert shrubs along the distance gradient. The community coverage ~~of community formed bimodal pattern and~~ reached local maxima ~~high level~~ at the distance of 1000 m and 3000 m where community ~~mainly~~ consisted of diverse shrub and herb layers. ~~While many studies~~ Our findings were different from those in relatively humid region (e.g., coastal region or boreal forest), which suggested 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)~~, we found the bimodal pattern of~~ ~~diversity indices~~ ~~Shannon-Wiener diversity, Pielou evenness, Patrick richness and Simpson dominance indices along the distance from river channel(Fig. 4a~~4e~~-cg)~~. These variation patterns of community diversity can illustrate how community response to the ecological gradient ~~-depends not only on water availability, either from the river or from groundwater~~ (Zhu et al., 2013)~~, but also on variation in soil properties~~ and ~~their~~ interact~~ions~~ with environmental factors in this~~e~~ 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. ~~Vegetation community flourished near the river (1000m) with the multiple layers of tree-shrub-herb, where~~ In addition, the presence of deep-rooted tree, ~~tree~~ *Populus euphratica* could benefit the growth of shallow-rooted species (e.g. herbs) by redistributing the deep soil water to the shallow layer as a strategy of mutualism ~~reported by~~ (Hao et al., ~~(~~2013). At further~~greater~~ distance 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 capacity and soil nutrition around the shrub patches (‘fertile islands’). (Ravi et al., 2010; Zhou et al., 2015) ~~-the community was mainly a transition community of riparian and desert shrubs. Tthough~~ Although situated at the transition region (from riparian forest to desert shrubs), the soil here was still rich in ~~consisted of 35.6%~~ fine particles (clay and silt; 35.6%), brought ~~which mainly caused~~ by the interaction between wind erosion and shrubs (Ravi et al., 2009). ~~The removal of nutrient-rich fine soil particles from the intercanopy areas driven by wind erosion could effectively be trapped by shrubs (especially 2 m high from the ground) (Ravi et al., 2010; Zhou et al., 2015)~~. ~~This redistribution of soil particles resulted in relatively high soil infiltration capacity and soil nutrition around the shrub patches, which made it possible for~~ These 'fertile islands' allowed the growth of some xerophytic herbs, ~~consequently~~ increasing the level of diversity in this gradient (Stavi et al., 2008; Ravolainen et al., 2013). By contrast, Simpson dominance index ~~showed different trend to other indices,~~ peaked~~ing~~ at the distance of 500 m and 2000 m where other indices were at ~~reached~~ their low level (Fig. ~~4d~~4 h). We suggested that inter-species competition for ~~the scarcely~~ water and nutrient resources ~~in this harsh environment~~ could be responsible for the trend (Maestre et al., 2006; Boever et al., 2015). The dominant species with high important value (i.e., trees and shrubs at 500 m and 2000 m, respectively) often had high competition for resources, halting 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)~~, which~~ resulting~~ed~~ in a large domination index (Fig. 4 h~~d~~). ~~Our findings thus indicated that interactions between species and extreme environmental stress could cause skewed or non-unimodal responses in hyperarid area, which were different from studies in humid riparian zone (Pabst and Spies, 2011; Macdonald et al., 2014).~~

Since the implementation of ecological water conveyance project in 2000, the vegetation in desert riparian forest has recovered significantly, shown by the increasing NDVI at different distances from the river channel (Fig. 5 a). Although there was initial decrease of NDVI during 2000-2001, likely due to the one year lag effect of runoff and relatively low runoff at these early years (Jin et al., 2008; Ge et al., 2009), NDVI generally increased with the restoration time. The conversion of low coverage community (e.g. sparse forest land, bareland land) to shrubland and grassland at the distance of 2000-3000 m from the river channel likely contributed to the increase in NDVI with better water availability in Heihe River Basin (e.g. increase of surface soil moisture and elevate of groundwater). In contrast, NDVI around the river bank underwent a slight degradation in the recent years (2012-2014), likely result from the conversion of shrubland to sparse forest land (Fig. 5 b). In the arid zone, grazing is mainly limited to the region near 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 tourism pressure may also hinder vegetation growth during the growing season (May to October) since *Populus euphratica* trees are becoming popular tourist destination (Hochmuth., 2014).

4.2 Factors influencing the distribution pattern and temporal variation of desert riparian forest~~The effects of soil moisture and other soil properties on the desert riparian forests~~

~~The interactions between vegetation and environmental factors resulted in the distribution pattern of desert riparian forests.~~ 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 ~~soil moisture and soil properties~~ explained ~~53.6~~74.0% ~~community~~ vegetation variance in total (Table 2), which indicated that ~~they~~ both spatial heterogeneity and temporal factors play important role in determining the community characteristics of desert riparian forests ~~distribution~~ in the ~~low reaches~~Heihe River Basin.

Among those factors, SWC1, SWC3, BD, annual average of 100 cm soil moisture were considered the key influencing factors, ~~. Soil moisture alone (i.e.,~~with SWC1 and SWC3~~)~~ contributed to ~~62.7~~45.95% of the total explanation of vegetation variance. ~~High level of SWC1 often indicated high water availability and vegetation coverage. It accounted for most information of environmental factors (37.69%) and mainly influenced the coverage of herb layer and the whole community (Table 1). This~~ ~~As~~ SWC1 (0-30 cm soil moisture) contributed to high coverage of herb layers as it become~~was~~ the main water ~~re~~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* ~~which mainly utilized the 40-80 cm soil moisture (Yi et al., 2012). and~~ SWC3, recharged by flood-raised groundwater table (Liu et al., 2015), was the water ~~re~~source for phreatophyte like *P. euphratica* or desert shrubs ~~that mainly depended on the groundwater and deep soil moisture~~ (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. ~~Similar to the study by Ridolfi et al. (2007) , our results showed that high content of SWC1 contributed to rich herb layers and community coverage while SWC2 and SWC3 played important role in supporting the growth of shrub and tree layer in desert riparian forests which contributed greatly to the community density and coverage.~~ 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~~Apart from soil moisture~~, soil physical properties were also important in determining vegetation community with BD accounted for ~~19.8~~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). ~~Bulk density negatively correlated with the community density, community coverage and shrub coverage, while soil composition such as silt and sand showed positive relationship with the Simpson domination index (Table 1).~~ 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~~In hyperarid zone~~, 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 ~~may~~ inducing the drought stress to the vegetation community~~in the surface soil~~ (Stirzaker et al., 1996). Such process constrained ~~the~~ vegetation recovery especially ~~growth of~~ 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 ~~in~~ community.~~–~~ ~~Soil nutrition also accounted for the variance of vegetation community, with TP represented 8.1% of the explanation and SOM was negatively correlated with Patrick richness index (Table 1, Table3). While soil P is an essential element for photosynthesis and mainly provided by the decomposition of SOM (Runyan and D’Odorico, 2012; Xu et al., 2016), it did not show significant relationship with community characteristics. We suggested that~~

~~low groundwater table (i.e., above the degradation threshold of 4 m) as well as the low fluctuation range of groundwater were mainly responsible for the insignificant influence of TP in our study. Previous study at Tarim River found that the effect of TP was more obvious with the rapidly decrease of groundwater table (Zhang et al., 2015b), which was quite different in the low reaches of Heihe River Basin where the perennial groundwater table remained above the degradation threshold (4 m) at the distance of 3800 m from river channel(Wang et al., 2011; Fu et al., 2014).~~ Soil nutrition explained no more than 3% of vegetation variance, and we found that SOM negatively correlated with species richness. This finding was ~~Our results were also~~ different from the commonly ~~previous studies which found~~ positive relationship between SOM and species richness in semiarid zone (e.g. ~~such as~~ 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 ~~often~~ had high competition for resources, thus ~~halted~~ halting the diversity and growth~~development~~ of other species ~~and result in low community richness~~ (Su, 2003).

The temporal variation factors partly explained vegetation variations (35.9%) 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). 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 ~~Critical distribution range~~Community resilience of desert riparian forests and implications for ecological protection

~~Our results showed that the distance up to 1000 m from the river channel provide the optimum condition for desert riparian forests, indicated by high level of community characteristics and favorable environmental factors. With appropriate groundwater table and flourish community, this range is the main vegetation restoration area influenced by the implement of ecological water conveyance (Wang et al., 2011). Yet this living range was also the most suitable region for grazing due to the abundance of herbs and prone to human disturbance due to its vicinity to the main roads. Since our result showed that soil physical properties also influenced the community structure, exposure to human disturbance, including trampling by livestock might potentially destroy the soil physical properties, leading to vegetation degradation and aggravated wind erosion on bare land (Greenwood and Mckenzie, 2001; Zhao et al., 2012; Daryanto et al., 2013). We therefore suggested multiple conservation measures to protect the soil structure and promote vegetation growth in this critical range such as: (i) setting critical fence area for ecological protection and (ii) constructing artificial shield or establishing straw checker boards on the bare land to prevent land degradation caused by wind erosion.~~

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 in the downstream Heihe River Basin at most gradients, it was significantly higher at 1000 m and 3000 m gradients (Fig 4). High resistance to drought stress was observed at these gradients, with trees and shrubs lifting up water from the deep to the shallower layer as a strategy of mutualism (Hao et al., 2013). Since trees and shrubs contributed differently in the ecosystem functions (e.g. trees mainly contribute to carbon storage while shrub and herb to sand fixation), they could maintain a stable habitat after drought stress and/or human disturbance (Cheng et al., 2007; Krieger et al., 2001; Lu et al., 2015). In contrast, communities at the other gradients could easily undergo degradations due to low resilience under disturbance (e.g., drought stress, grazing and tourism) such as those already happened at 500 m gradient, indicated by decreasing NDVI in these recent years (Fig.5a). 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 (Greenwood and Mckenzie, 2001; Zhao et al., 2012; Daryanto et al., 2013).

~~While desert riparian forests survived up to 2500 m from the river channel, this critical distance was considered as the ecotone between oasis and peripheral desert, characterized by lower environmental quality and low self-recovery capability (Zhao et al., 2006; D'Odorico et al., 2013; Lü et al., 2014). After this distance, soil moisture, soil fine particle and soil nutrients decreased sharply, followed by the appearance of desert species.~~ 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), ~~With~~ 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. ~~more intense evaporation and more frequent drought (Zhang et al., 2015a), the desert riparian forests might experience high deficiency of soil moisture, leading to vegetation degradation and desertification in the low reaches of Heihe River Basin (Wang et al., 2014). Since this distance was also far from the influence of ecological water conveyance (Si et al., 2005;Guo et al., 2009), desert riparian forests could experience narrowed living range and a sharp community transition away from the river channel with more frequent drought scenario.~~ To halt degradation in this critical zone, we suggested the development of natural channels that perpendicular to the river to fully extend the influence scope of 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) setting critical fence area for ecological protection, and (ii) constructing artificial shield or establishing straw checker boards on the bare land to prevent land degradation, are recommended around the periphery of the river. ~~So far, the existing artificial channels were built out of concrete for irrigation purpose and consequently, they did not have the seepage property of natural channels, generating little benefit to these dry areas. In addition, fence and additional regulation should be set to minimize human disturbance (e.g., grazing, firewood cutting) in this gradient as vegetation on the surface of shrub dune was extremely important for stabilizing the sand dunes and preventing desertification process.~~

5 Conclusions

Through extensive field observations at multiple desert riparian forests locations and analyses of long-term remote sensing images, we found that~~: (i) vegetation community in the desert riparian forests shifted from the riparian tree-shrub-herb community to desert riparian forests community with increasing distance from river channel, and (ii)~~ species diversity indices formed bimodal patterns instead of unimodal pattern. In locations with high diversity indices (1000 m and 3000 m), high community resilience was maintained by the multiple interactions between vegetation and soil properties. Still, these locations are facing challenge under climate change and intensive human disturbance. ~~due to the interactions between vegetation and soil properties. While desert riparian forests were distributed within 2500 m from the river channel, the first 1000 m provided the optimum condition based on the variation of community characteristics and environmental factors. Since soil moisture, supported by favorable groundwater depth, and other soil properties (e.g., BD, SOM, TN) accounted for 53.6% of desert riparian forests variance, future ecological restoration should emphasize the importance of soil factors in the low reaches of Heihe River Basin.~~ Extending the distance~~influence scope~~ of ecological water conveyance~~, for example, was~~ is therefore recommended ~~in regions that far from river bank~~ to recharge the surface soil moisture and benefit the growth of ground cover (i.e., herb species). Despite the increasing NDVI trend, areas with low diversity (within 500 m from river channel) already underwent degradation in recent years. ~~which contribute greatly to the community diversity in hyperarid zone. In addition, m~~Multiple conservation measures that protect the soil structure (e.g.,

~~build~~ artificial soil cover and livestock grazing exclusion) ~~we~~are recommended for 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 and experience significant community transition under projected climate change scenario and more intensive human disturbance.

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