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Attribution of satellite observed vegetation trends in a hyper-arid region of the Heihe River Basin, Central Asia

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Response to Anonymous Comments by Referee 1

Referee comments in Italics

General comments

1. *The manuscript "Attribution of satellite observed vegetation trends in a hyper-arid region of the Heihe River Basin, Central Asia" by Wang et al. focuses on the method of distinguishing between changes in NDVI due to prosperity changes in desert vegetation or changes in irrigation schemes. While I appreciate the author's efforts to assess their method regarding sensitivity to distinct rainfall databases, I doubt that the manuscript can be considered as research article according to HESS' manuscript types, unless results are discussed in the context of other studies with similar or contrasting results and in the context of climate and land use. In this regard, the authors seem to lower the expectations of the reader towards the goal of the study from (i) a general assessment of the suitability of remote sensing imagery (title) to (ii) the impact of climate change on vegetation cover (abstract) and, eventually, (iii) a case study for Central Asia (introduction). As long as the authors don't elaborate on any possible implications regarding management of land use (vegetation and water resources), their method remains meaningless and could possibly (at the discretion of the Editor) be considered as technical note if much more detailed technical information is provided.*

We thank the reviewer for the comments and suggestion. In terms of comparable work, there have been many previous studies that presented NDVI (or similar) trends in vegetation as per the citations we gave in the manuscript. We have added the similar studies that try to discriminate the effect of climate change and of human activities on NDVI or NPP by qualitative description (Dai et al., 2011), model estimation (Zhang et al., 2011; Zhou et al., 2013), and regression and residual approximation (Wang et al., 2012) in the section 4. We used a formal analytic framework to attribute the change of regional vegetation cover quantitatively. It is that disaggregation that creates the management options. That was previously explained in the introduction. We have also added that perspective to the abstract and discussion to make that clear.

Specific comments

2. *Throughout the paper there are tense issues, particularly with regard to the presentation of methods (Section 2) and results (Section 3), which should always be written in past tense rather than present or future tense. Further, some inconsistencies occur with regard to equations and sub-headers.*

We have revised the tense and inconsistencies relating to English in the manuscript.

3. *Title: The title is too vague given that the paper only uses NDVI based on MODIS rather than a range of other "satellite observed vegetation trends".*

This is a matter of opinion but we note that the method proposed is suitable for use with any satellite vegetation cover product. It is not specific to MODIS (which we mentioned in the abstract).

4. *P1529L5-7 and P1532L10-13: While the abstract suggests assessing the "trend of fractional green vegetation cover to climate change and to human activity", the last paragraph of the introduction lowers the bar to "a component due to greening (browning) of the deserts and a second component due to changes in irrigation". I see how irrigation is a human activity. What I don't see is how climate change fits into the picture. Since the paper doesn't consider any trends in climate changes (neither in the past nor in the future) I assume the authors refer to climate or weather variability rather than change.*

Good point. We agree that we did not examine independent measures of climate and did not attempt to attribute the trend in desert greenness to one or more factors. In this hyper-arid region, precipitation availability is the most important factor for the desert vegetation. Therefore precipitation variability seems to be the most important climate factor over the decadal period considered here. We agree with the referee, a period of thirteen or less years is too short to detect trends in climate change, so we have used climate variability instead in the revision. In addition to this, we have revised the sentence of P1532L10-13 to "The aim of this study is to test whether it is possible to separate the vegetation trends in a small relatively well studied basin into a component due to climate variability related greening (browning) of the deserts and a second component due to changes in irrigation."

5. *P1531L11-17: References are required for each of the possible causes of vegetation changes.*

We have added more references into the revision.

6. *P1532L6-7: What are the management implications for the two distinct scenarios? This should be discussed in detail in Section 4.*

Management options are restricted to the irrigated areas where human intervention has, and will continue to, occur. We have discussed more about the management implications of the irrigated areas and scientific implications of the results in Section 4 in the revision.

7. *P1535L11: Elaborate on the "trial and error" approach to conclude that areas with NDVI > 0.1 are irrigated. At this stage this approach is too arbitrary to be considered as scientifically sound.*

Good point. We have modified the manuscript and now provide detailed information describing exactly how we decided on the NDVI > 0.1 threshold to delineate the desert from irrigated lands (Section 2.3). We have incorporated the explanation and uncertainty analysis in the revisions and added a new Table 1 detailing how our results depended on the NDVI threshold.

P1535L20 and P1536L11: Equations (1) and (2) refer to the same variable (fv), yet they are different. Change variable names to make the equations unique.

The first equation defines f_v in terms of the original satellite measurement. The second refers to the disaggregation in terms of area/cover of the two land cover types. We need to keep both equations.

8. *P1536L11 and L15: Equations (2) and (3) refer the same variable and should be renamed as (2a) and (2b).*

Agreed. Done.

9. *P1537L24: Be consistent with the terminology. You refer to fv as "foliage cover", whereas in other parts of the paper fv is referred to as ""fractional vegetation cover" (e.g., P1535L18).*

fv is referred to as "fractional vegetation cover" in this paper. We have revised it throughout to avoid confusion. Thank you.

10. *P1538L9 and L21: Sections 3.2 and 3.2.2 are entitled the same.*

Thank you for pointing out. We have revised the title of section 3.2 into "Sensitivity Analysis and Trend Attribution".

11. *P1538L17-18: Language issue: "The most sensitive factor is relative variations in the fractional irrigated area". Please reword.*

Agreed. We have revised the sentence: From that equation we infer that the relative change in fractional green vegetation is most sensitive to variations in the fractional irrigation area (A_I*).

12. *P1541L4-6: This finding has to be discussed in the context of other studies with similar or contrasting results in the context of climate and land use.*

We have discussed this in the section 4 with similar studies effect of climate change and of human activities on NDVI or NPP using different methods (P12, Line25- P13, Line4 in the new version).

P1541L7: Refer to fD as non-irrigated areas in the discussion to make it easier for the reader to understand (and to avoid re-browsing the methods section).

We have explained all the variables in the discussion to make it easier to understand.

P1541L7-8: Discuss why this result was "as expected in such an arid region".

The greenness of desert vegetation during the growing season is mostly dependent on precipitation. We have added citations about that result in section 4.

13. *P1541L17-28: Discuss these and further studies in the context of your findings rather than just listing them.*

We have revised the content and discussed the similar studies this in the section 4 as mentioned in comment 1 and comment 12.

14. *P1541L28-29: Elaborate on the "larger regional setting".*

Previous studies mainly focus on vegetation in the irrigated oasis regions. "Our results set these vegetation changes into a larger regional setting. We have expanded the discussion to better explain the context.

15. *Fig. 1a: Language issue: "Climatology Precipitation. Please reword.*

Thank you for pointing out. We will reverse the words to Precipitation Climatology.

Fig. 1c: Please indicate where this part of the basin is located in Fig. 1b.

Fig.1c occupies the northern part of the basin delineated by the heavy dark line in Fig.1b. Given the confusion we used a heavier dark line in Fig.1b. Thank you.

16. *Fig. 4: Scale issue: Values for fI appear to be much smaller than values of the other graphs, yet fI is in the range of 16-19%, whereas the other graphs range between 2 and 5%.*

Good point. We have adjusted the axis scale. Thank you.

17. *Fig. 8: I assume that GPCC rainfall was used XP? Also, refer to Fig. S2 for other sources of rainfall observations.*

Yes. X_P refers to contribution of precipitation (GPCC) in Fig. 9 and from other sources of precipitation in the old Fig.S2 (new Fig. S4).

Technical comments

18. P1532L24: "non-mountain regions" . . . flatlands?

Yes, we modified the sentence as per the reviewer's suggestion.

19. Fig. 3: In the legend, use the same line style as for the graphs (dotted, dashed, etc.).

Agreed. We have redrawn the graph (new Fig. 4).

20. Fig. 4, caption: What does the number 3 in "(fD, 3 left scale)" refer to?

It was a typo. We have corrected it.

21. Fig. 8: Typo in "vegetaion".

We have corrected the typo.

Response to Anonymous Comments by Referee 2

Referee comments in Italics

1. *"Attribution of satellite observed vegetation trends in a hyper-arid region of the Heihe River Basin, Central Asia" by Wang et al. used satellite based vegetation index and rainfall data to differentiate climate vs. human activity impact on vegetation greening up in an arid region in China. This is a very interesting study and the research is carefully conducted. I generally support a publication of this manuscript but the following two comments should be considered during the revision stage.*

We thank the reviewer for the positive comments.

2. *First, the separation of irrigation and non-irrigation is a key step in this study. According to the authors, they used NDVI of 0.1 as a cutoff value to differentiate these two areas (Page 1535 Line 10-15). How to validate the 0.1 threshold? This needs elaboration and validation. Furthermore, the authors mentioned that it's difficult to distinguish agricultural vegetation from native vegetation. I was wondering whether harvesting time would be useful here. For example, if there's a common harvesting period in this region, the authors could do an analysis after harvesting and use spectral difference in the crop residuals and natural vegetation to distinguish them.*

Thank you. See response to comment 7 in the response to referee 1 above. Briefly we have incorporated the threshold analysis into the revision (Section 2.3 and 3.2.3).

Second, the authors used an analytic framework to demonstrate their method foundation, which is very helpful. At the same time, I think it would be useful to comment on the uncertainty in the method in terms of both their analytic framework and datasets used. For example, the spatial resolution of MODIS and rainfall data are not the same, is there any consequence?

Very good point. The rainfall data were used to show that the greenness measured over the desert made sense in terms of rainfall. Otherwise the rainfall is not used in the attribution. On the other hand, the runoff data is central to being able to use the method to predict the irrigation area. We have added the uncertainty analysis about the MODIS data (section 4), the analytic method (section 3.2.3), and precipitation data (section 4).Thank you.

Response to Anonymous Comments by Referee 3

Referee comments in Italics

General comments

1. *This study demonstrated one approach how to identify and quantify the factors for the satellite observed 'greening' trends during 2000-2012 over a region within the Heihe River Basin in northern China. The study of this kind is very important and definitely needed, particularly for the water resource management and policy development. The content of this study suits the audience of HESS well. This manuscript is well written and the structure is generally well designed. However, there are a few major issues that need to be addressed before considering for publication in HESS.*

We thank the reviewer for the positive comments.

Major issues

2. *One highlight of the MODIS observation (10+ years) is to provide a spatial distribution of long-term trends in land surface vegetation status. The authors should present a few spatial maps in this manuscript, e.g. spatial map of annual average NDVI over the growing season, and spatial map of annual change in NDVI during 2000-2012. Apart from the change in mean NDVI, it is probably a good idea to add the spatial map of averaged annual max NDVI and change in annual max NDVI during 2000-2012.*

Thank you. We already presented the maps of the mean growing season vegetation cover and its trend in (the now) Fig. 5. The spatial pattern looks reasonable. As to the annual maximum NDVI, we have added a graph in the supporting material (Fig. S2) considering the mean of growing season is more reasonable to represent the annual vegetation cover.

3. *Over the hyper-arid regions, satellite based NDVI products always have higher uncertainty. The authors may would like to add some discussion in this regard.*

We agree that it is hard to evaluate vegetation cover in a hyper-arid region. However, we have used the high resolution MODIS database and we avoid noise from snow/ice by only using growing season vegetation cover. We have added more about data uncertainty in the discussion section.

4. *The spatial map of annual precipitation change rate is also missing from the current manuscript. It is necessary to present and compare these spatial maps from various precipitation datasets and also with spatial map of annual NDVI change. The authors only presented the time series of precipitation over the entire study area. The spatial pattern match is also very important in the study to identify the contribution of climate change (e.g. precipitation) to the observed change. Otherwise, the 'correct' results may come from the 'wrong' reasons.*

Good idea. We have added the requested maps from GPCC in sub-panels of (the new) Fig. 4. For other data sources, we supplied a supporting material in Fig. S1.

The authors identified that the increasing precipitation and irrigation as the primary reasons for the observed ’greening’ trends. But the irrigation is highly dependent on the increasing river runoff which is largely a contribution from the surrounding mountain regions. The audience may be wondering whether this increasing irrigation trend is sustainable or not. I suggest to add one paragraph to discuss the possible reasons for the increasing river runoff from surrounding regions, e.g. precipitation increase, temperature increase leading to more snow melt, or both combined, or something else.

Agreed. We were unable to separate the runoff into a rainfall + change in storage (e.g. melting glaciers) time series because the rainfall data over the mountains regions are simply inadequate at this stage. As to the reasons of increased runoff, we have referred to in the introduction section (P3, Line2-7) and added commentary in the discussion section(P13, Line16-22 in the new version).

Attribution of satellite observed vegetation trends in a hyper-arid region of the Heihe River Basin, Central Asia

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Abstract

Terrestrial vegetation dynamics are closely influenced by both climate ~~change~~ and by direct human activities that modify land use and/or land cover (LULCC). Both can change over time in a monotonic way and it can be difficult to separate the effects of climate change from LULCC on vegetation. Here we attempt to attribute ~~the~~ trends in the ~~of~~ fractional green vegetation cover to ~~climate change~~climate variability and to human activity in Ejina region, a hyper-arid landlocked region in northwest China. This region is dominated by extensive deserts with relatively small areas of irrigation located along the major water courses as is typical throughout much of Central Asia. Variations of fractional vegetation cover from 2000 to 2012 were determined using Moderate Resolution Imaging Spectroradiometer (MODIS) vegetation index data with 250m spatial resolution over 16-day intervals. We found that the fractional vegetation cover in this hyper-arid region is very low, but that the mean growing season vegetation cover has increased from 3.4% in 2000 to 4.5% in 2012. The largest contribution to the overall greening was due to changes in green vegetation cover of the extensive desert areas with a smaller contribution due to changes in the area of irrigated land. Comprehensive analysis with different precipitation data sources found that the greening of

the desert was associated with increases in regional precipitation. We further report ~~found~~ that the area of land irrigated each year could be predicted using the ~~was mostly dependent on the~~ runoff gauged one year earlier. Taken together, water availability both from precipitation in the desert and runoff inflow for the irrigation agricultural lands can explain at least 52% of the total variance in regional vegetation cover from 2000 to 2010. The results demonstrate that it is possible to separate the satellite-observed changes in green vegetation cover into components due to climate and due to human modifications. Such results inform management ~~can supply~~ on the implications for water allocation between oases in middle and lower reaches and for water management in the Ejina oasis.

1 Introduction

Terrestrial vegetation plays a key role in energy, water and biogeochemical cycles and changes in vegetation can also significantly influence atmospheric processes (Pielke et al., 1998; Gerten et al., 2004). Monitoring of terrestrial vegetation dynamics therefore underpins efforts to better understand the feedbacks between vegetation and the atmosphere (Bonan et al., 2003; Bounoua et al., 2010; Angelini et al., 2011). In particular, the Normalized Difference Vegetation Index (NDVI) derived from satellite observations of red and near-infrared reflectance has proven useful in assessing vegetation dynamics from regional to global scales (Tucker, 1979; Box et al., 1989; Fensholt et al., 2013).

Greening trends have been detected on global (Myneni et al., 1997; Nemani et al., 2003; Donohue et al., 2013; Fensholt et al., 2013) and regional (Fang et al., 2004; Herrmann et al., 2005; Donohue et al., 2009) scales but attribution of those trends in terms of the underlying biophysical and socio-economic causes remains a difficult task. The central challenge is that vegetation can change for a myriad of reasons including changes in the local climate (e.g., rainfall, radiation, temperature, humidity, etc.) (Myneni et al., 1997; Goetz et al., 2005; Donohue et al., 2009), biogeochemistry (e.g., atmospheric CO_2, nutrient deposition, etc.) (Lim et al., 2004; Bond et al., 2003; Donohue et al., 2013; Dirnböck et al., 2014), ecological processes (e.g. long term successional recovery from disturbance, fire dynamics, disease, etc.) (Thonicke et al., 2001; Bond et al., 2003) and via direct anthropogenic activity (e.g., land use change, irrigation, agriculture, etc.) (Hutchinson et al., 2000; Thonicke et al., 2001). One approach to handle this complexity is to use regional knowledge to constrain the problem.

In terms of the attribution of regional vegetation trends, Central Asia presents a unique challenge. The region is hyper-arid with annual precipitation in many areas often less than 50 mm with hot summers and cold winters. What is of particular interest throughout Central Asia is the presence of many localised regions of irrigated agriculture that often support relatively large local populations. Those irrigation communities are usually located at oases that receive an annual input of water in the form of runoff from surrounding mountains. Much of the outflow from the mountains is recent precipitation (snow-melt) but a further complication of recent years is that glacier melt has augmented the snow melt and increased inflow of water to many oases throughout Central Asia (Yao et al., 2004; Lioubimtseva and Henebry, 2009; Rahimov, 2009; Unger-Shayesteh et al., 2013). Time series of NDVI satellite imagery generally show greening trends over Central Asia ~~, especially before 2000~~ (Fang et al., 2004; Mohammat et al., 2013). However, in terms of overall water resources management it is important to understand what caused the ~~whether an~~ overall greening (or browning) trend. For example, did it arise ~~arose~~ because of an expansion (or contraction) of the area being irrigated, or ~~. A~~alternatively, the irrigated area might have remained more or less constant and any large scale greening (or browning) trend in vegetation might be related to subtle yet detectable changes in vegetation cover in the extensive deserts in Central Asia. The management implications are quite different for those two scenarios and require a clear separation of these sources of variation.

In this paper, we investigate satellite observed (MODIS) vegetation trends (NDVI) in a hyper-arid region of the Heihe River Basin located in northwest China. The aim of this study is to test whether it is possible to separate the vegetation trends in a small relatively well studied basin into ~~a~~ components due to climate and due to ~~variability related greening (browning) of the deserts and a second component due to~~ changes in irrigation. We anticipate that the method might be widely applicable throughout Central Asia.

2 Data and Methods

2.1 Study Area

We examined part of the landlocked Heihe River Basin in northwest China (40°20'-42°40'N, 97°30'-101°45'E) (Fig. 1). Our study area occupies the downstream (northern) part of the basin (Fig. 1b) and is serviced by the regional centre, Ejina, which currently has a population of around 30,000 (http://www.geohive.com/cntry/cn-15.aspx). The hydro-climate of this predominantly desert environment is extreme. As an indication, at Ejina, the mean annual temperature is around 8°C but day-time excursions in the summer reach 42°C whilst night-time temperatures drop to -36°C during winter (Zhang et al., 2011). The mean annual precipitation over the extensive flatlands~~non-mountain regions~~ is typically less than 50 mm (Fig. 1a) while the mean annual pan evaporation is typically around 3500 mm (Jin et al., 2010; Jia et al., 2011; Wang et al., 2013). Agriculture is only possible via irrigation that is located immediately adjacent to the Heihe River (Fig. 1c). The study area (~80,000 km^2) is located with the broader Gobi desert and also hosts the second largest area of *Populus euphratica* and *Haloxylon ammondendron* forests in China. The basin is generally considered to be the main eco-barrier in northern China (Fu et al., 2007; Qin et al., 2012).

The Heihe River (Fig. 1b) is the second longest inland river in China and is the sole river flowing through the Ejina region (Guo et al., 2009). This river originates in the Qilian Mountains. After reaching the mountain outlet at the Yingluoxia hydrological gauge station (Fig.1b), it flows through several oases (Zhangye, Gaotai, Dingxin, Ejina) before terminating at the East and West Juyan Lakes. Zhengyixia station is located downstream of those main oases, where the most water was consumed for agriculture. The discharge at Zhengyixia typically peaks around September each year while the growing season extends from April to October (Fig. 2~~a~~). Consequently, the irrigated crops in the northern parts of the basin use irrigation water that was discharged from the mountains some 6 months earlier.

The river discharge from the mountain regions showed increase trend in past decades. Annual discharge observed at Yingluoxia site increased to 15.7×10^8 m^3 in the 1990s from around 14.4×10^8 m^3 in the 1960s (Fig. 2b). However, the discharge observed at Zhengyixia station located at the place after the river flowing ~~throw~~ through the oases decreased from around 10.5×10^8 m^3 in the 1960s to around 7.5×10^8 m^3 in the 1990s. The increasing water withdrawal in the upper and middle reaches since the 1960s was associated with increased irrigation (and associated industrial development and urbanization) that made significant reduction in river flows to the downstream oases and accelerated desertification in the northern parts of the basin (Guo et al., 2009; Jin et al., 2010). This phenomenon resulted in the drying-up of East Juyan Lake in 1992 and the drying-up of West Juyan Lake even earlier (Guo et al., 2009).

To restore the ecosystem of the downstream Heihe basin the Ecological Water Conveyance Project (EWCP) was launched by the Chinese Government. Water use has been regulated (reduced) since around the year 2000 in the middle parts of the basin thereby delivering more water to the terminal lakes in the northern extremities of the basin~~parts~~ (Zhang et al., 2011).

In the past decade (2000-2009) the average flow at Zhengyixia has increased to levels (about 10.5×10^8 m^3) not seen ~~much~~ since the 1960s (Zhang et al., 2011; Qin et al., 2012). One ~~Th~~aim was to reduce ~~is extra water has restored~~ degradation of the ecological environment in the northern extremities. Since 2000, an increase in native vegetation growth and species diversity has been attributed to increased groundwater recharge from the increased flows making their way into the northern parts of the basin (Jin et al., 2010; Jia et al., 2011).

In summary the basin is a classic source-sink system with water sourced (via snow- and glacier-melt) in the humid mountains in the south that subsequently flows northwards to terminal sinks at the East and West Juyan lakes. With that background we note that many studies have reported trends in vegetation in particular subregions of the basin (Jin et al., 2010; Jia et al., 2011; Wang et al., 2011) but there has yet to be a comprehensive assessment of vegetation trends in the study area. A basin-wide assessment that is useful for hydrologic management requires separation of the overall vegetation trend into a component due to irrigation and a component due to changes in the desert vegetation. That is the aim of the current study.

2.2 MODIS Satellite Observations

Moderate Resolution Imaging Spectroradiometer (MODIS) Terra Vegetation Indices (MOD13Q1) data were acquired from the National Aeronautics and Space Administration (NASA) Earth Observing System Data and Information System (http://reverb.echo.nasa.gov) with spatial resolution of 250 m and temporal resolution of 16 days between April 2000 and December 2012. We ~~initially~~ used the Savitzky-Golay filter (Chen et al., 2004) to minimise noise in the NDVI series prior to further processing. Exploratory analysis highlighted anomalously low NDVI values during many of the winter months that coincided with snow/ice cover. To avoid those anomalous values we restricted the time series to cover the seven month growing season (April-October).~~–~~

2.3 Identifying the Irrigated Areas

The irrigation regions of interest are restricted to the immediate vicinity of the Heihe River (within the dashed line in Fig. 1c). Within that zone, irrigation is usually supplied by the extraction of groundwater and it is very difficult to distinguish agricultural vegetation from native vegetation that is drawing upon groundwater reserves in the satellite imagery. From the point of view of water resource management, b~~However, b~~oth vegetation types use the same groundwater resources and we ~~make ~~made no distinction between them. That enabled us to use a simple threshold approach to identify the vegetated ~~ion ~~areas of interest because they have much higher green vegetation cover during the April-October growing season.

To identify the irrigated ~~ose ~~area~~s~~ we ~~first ~~created a composite image for each year (2000-2012) showing the maximum NDVI recorded during the April-October growing period. We first estimated the mean of the maximum NDVI over adjacent desert regions and found an NDVI of 0.0996 (±~~ xx~~0.024). On that basis we initially defined the irrigated areas as being within the river zone (Fig. 1c) and having an annual maximum NDVI greater than 0.10. To test that threshold we used field surveys showing that irrigated vegetation (that includes native vegetation accessing groundwater) can exist up to a kilometre from the main east river channel in a central part of the basin since the water conveyance project was launched (Guo et al., 2009). We varied the NDVI threshold (0.08, 0.10, 0.12; see Fig. 3) and visually estimated the lateral extent of the vegetation from the river channel. At a threshold of 0.08, the implied irrigation area extended further than 1 km from the main channel while at a threshold of 0.10 the extent was some 200-1000 m and close to field survey results (Guo et al., 2009). When the NDVI threshold was set at 0.12, the irrigated area was (incorrectly) shown to be discontinuous (Fig. 3). With that result we were confident that a threshold of 0.10 would correctly identify irrigated areas as defined. That ~~e ~~threshold was used to classify the basin land cover into two classes, desert and irrigation, for each year of the period 2000-2012.

2.4 Converting NDVI to Fractional Vegetation Cover

Fractional Vegetation Cover (f_V) was computed from NDVI (V) using a simple linear scaling (Carlson and Ripley, 1997):

$$f_V = \left(V - V_{\min}\right) / \left(V_{\max} - V_{\min}\right) \tag{1}$$

where $V_{\min}$ and $V_{\max}$ represent zero green vegetation cover (i.e., bare soil, $f_V = 0$) and complete vegetation cover~~foliage cover~~ ($f_V = 1$) respectively. We assume that there are regions of bare soil (e.g., desert) and of complete vegetation cover~~foliage cover~~ (e.g., irrigated agriculture) in the study area of sufficient size relative to the MODIS spatial resolution (250 m) to define the limits of our scaling. To identify those limits we first composited the annual (April-October) maximum V image into a single maximum V image for the entire 13 year (2000-2012) study period. We then conducted a detailed examination of the desert regions and identified an

NDVI threshold of 0.05 that was equated to bare ground ($f_V = 0$). To identify the upper limit we investigated small regions of agricultural crops in the maximum composite and identified an NDVI threshold of 0.65 that was equated to full cover ($f_V = 1$). Those thresholds were used (in Eq. 1) to re-scale the NDVI data into fractional vegetation cover~~foliage cover~~ with values outside the range set to the respective limits.

2.5 Attribution of Vegetation Changes

With the region split into two land cover types, the regional fractional vegetation cover (f_V) is determined by fractional vegetation coverage of the irrigated (f_I) and non-irrigated (f_D) areas and the respective areas (A_I , A_D) for each year,

$$f_V = \frac{A_I * f_I + A_D * f_D}{A_I + A_D} \qquad (2a)$$

Defining the area fractions $A_I^* \left(= \frac{A_I}{A_I + A_D} \right)$ and $A_D^* \left(= \frac{A_D}{A_I + A_D} \right)$ with ~~–~~ $A_I^* + A_D^* = 1$, we ~~can~~ rewrite Eq. (2a) as,

$$f_V = A_I^* * f_I + A_D^* * f_D \qquad (\cancel{3}2b)$$

The full differential df_V is:

$$df_V = \frac{\partial f_V}{\partial f_I} df_I + \frac{\partial f_V}{\partial A_I^*} dA_I^* + \frac{\partial f_V}{\partial f_D} df_D + \frac{\partial f_V}{\partial A_D^*} dA_D^*$$

$$= A_I^* \, df_I + f_I \, dA_I^* + A_D^* \, df_D + f_D \, dA_D^* \qquad (\cancel{4}3)$$

The relative change in f_V is given by,

$$\frac{df_V}{f_V} = \frac{A_I^* f_I}{f_V} \frac{df_I}{f_I} + \frac{f_I}{f_V} dA_I^* + \frac{A_D^* f_D}{f_V} \frac{df_D}{f_D} + \frac{f_D}{f_V} dA_D^* = X_{fI} + X_{AI} + X_{fD} + X_{AD} \qquad (\cancel{5}4)$$

where the various X terms on the right hand side denote the total change in f_V due to changes in the greenness (X_{fI}, X_{fD}) and fractional area (X_{AI}, X_{AD}).

2.6 Estimates of Water Availability

The vegetation trends are ultimately compared to estimates of trends in water availability over the desert and in the irrigation area. We used the monthly discharge gauged at Zhengyixia (Fig. 1b) as a measure of the inflow available for irrigation in Ejina. Over the desert parts of the region, precipitation represents the only input of water. To estimate water availability via precipitation we used three gridded databases (0.5°×0.5°, monthly, 2000-2010) from the Global Precipitation Climatology Centre (GPCC) (Schneider et al., 2008), Climatic Research Unit (CRU) TS 3.10 (Harris et al., 2013), and the Climate Prediction Center (CPC) (Chen et al., 2002). We also averaged the data from two local meteorological sites (Ejina, Dingxin; see Fig. 1b) as a further check on the gridded databases. Initial analysis showed that precipitation (*P*) was generally a little higher in the CRU database (but with similar inter-annual variability) while the other two remaining databases gave ~~almost identical~~similar spatial pattern, variability and trend~~ results~~ (Fig. 4 and Fig. S1~~3~~). We were most familiar with the GPCC database following previous work (Sun et al., 2012) and subsequently adopted the GPCC database as the precipitation record for the study ~~area~~area (Fig. 4b, c). Note that final interpretations and our conclusions are not sensitive to the choice of precipitation database and we also present the complete analysis using the other spatial databases (CRU, Sites, and CPC) in the supporting material.

3 Results

3.1 Vegetation Trends

The fractional vegetation cover f_V in this hyper-arid region is very low, with mean growing season f_V of about 3-4%. The oases systems are clearly distinguished by the much higher vegetation cover (Fig. 5~~4~~a and Fig. S2a). Over the 13 year period (2000-2012) the mean growing season fractional vegetation cover~~foliage cover~~ (f_V) ~~showed ~~showed an increase trend overall, especially in the irrigated oasis (Fig. 5b). So did the annual maximal fractional vegetation cover (Fig. S2). The mean annual fractional vegetation for the whole region increased ~~a more or less ~~stead~~y~~ily ~~increase ~~starting at about 3.2% in 2000 and rising to around to 4.5% in 2012 (Fig. 5~~4b~~c). Fractional vegetation cover in both the desert and irrigated regions also increased and more or less tracked the increase in f_V.

The mean growing season fractional vegetation cover~~foliage cover~~ in the extensive desert regions (f_D) more or less tracked the changes in the regional total (f_V). The area classified as irrigated only occupies around 3% of total study area with a relatively high growing season average vegetation cover f_I of around 17%. Over the 2000-2012 period, the fractional irrigation area (A_I^*) showed a steady increase (from 3% to 4%) and the mean growing season fractional vegetation cover~~foliage cover~~ (f_I) also increased from around 16% to 18%.

3.2 Sensitivity Analysis and Trend Attribution

3.2.1 Sensitivity

After substituting the relevant numerical values (f_V = 0.039, f_I = 0.174, A_I^* = 0.033, f_D = 0.035, A_D^* = 0.967) derived from the mean growing season (2000-2012) into Eq. (~~5~~4), the relative change in f_V is,

$$\frac{df_V}{f_V} = 0.15\frac{df_I}{f_I} + 4.45dA_I^* + 0.85\frac{df_D}{f_D} + 0.88dA_D^* \qquad (\cancel{6}5)$$

The coefficients in equation ~~6~~ 5 denote the different ~~sensitivity~~ sensitivities to change in the overall regional vegetation cover. From that equation we infer that the relative change in fractional green vegetation is most sensitive to variations in the fractional irrigation area~~The most sensitive factor is relative variations in the fractional irrigated area~~ (A_I^*). Note that regional vegetation cover is also a factor of around six (= 0.85/0.15) times more sensitive to variations in greenness over the desert than over the irrigated regions because the desert land cover type dominates the total area.

3.2.2 Trend Attribution

From 2000 to 2012, the regional f_V increased by ~ 25%. In terms of the underlying components, the causes of those changes varied from year to year (Fig. 6~~5~~) but the largest contribution was generally due to changes in f_D (see X_{fD} in Fig. ~~5~~6~~5~~) with a smaller contribution due to changes in A_I^* (X_{AI} in Fig. 6~~5~~). Variations in the remaining terms (X_{fI}, X_{AD}) had little impact on trends in the overall regional vegetation cover.

3.2.3 Uncertainty Analysis

The major source of uncertainty in our results relates to the NDVI threshold used to distinguish the irrigated and desert regions (Section 2.3, Fig. 3). To evaluate the robustness of our results we also calculated the relative change in fractional vegetation cover using five different NDVI thresholds (0.08, 0.09, 0.10, 0.11, 0.12; Table 1). Those results show that while the numerical value of the sensitivity coefficients does change, the overall conclusion that regional vegetation cover is most sensitive to changes in irrigation area remains unchanged. Similarly, the attribution results for different thresholds show that most of the change in regional vegetation cover remained due to changes in desert greenness and in the area of irrigation.

3.3 Predicting Regional Vegetation Cover Based on Water Availability

The earlier results (Sections 3.2.2, ~~and~~ 3.2.3) show that the regional vegetation cover trend mainly depends on fractional vegetation cover over the extensive desert regions and the area of the irrigated lands. With that result, we approximate Eq. (~~5~~4) as,

$$\frac{df_V}{f_V} \sim \frac{f_I}{f_V} dA_I^* + \frac{A_D^*}{f_V} df_D \qquad (\cancel{7}6)$$

In this region the area of land irrigated each year is dependent on the inflow at an earlier time while greenness in the desert areas is dependent on precipitation. To test that we use the 12 month GPCC precipitation estimate to the end of the growing season (previous November-October) to estimate the growing season desert vegetation cover. The results ~~when using GPCC precipitation~~ show a positive relationship ($p<0.05$, Fig. 7~~6~~) and imply that the desert vegetation cover increases by 0.017% for each additional mm of annual P. (The analysis based on other precipitation databases (CRU, Sites, and CPC) is included in the supporting materials (Fig. ~~S1~~ S3 and Table S1~~)~~).

We sought a similar predictive relation between the total runoff (R) in the previous calendar year at Zhengyixia and the fractional irrigated area (A_I^*) (Fig. 8~~7~~). The results ~~(Fig. 7)~~ reveal a strong positive relationship ($p = 0.002$) where an increase in inflow at Zhengyixia of 1×10^8 m^3 will increase the fractional area of irrigation by around 0.1%.

The results allow us to modify the earlier expression by replacing dA_I^* with $\alpha\, dR$ (Fig. ~~7~~8~~5~~) and df_D with $-\beta\, dP$ (Fig. ~~6~~7) respectively,

$$\frac{df_V}{f_V} \sim \frac{f_I}{f_V} \alpha\, dR + \frac{A_D^*}{f_V} \beta\, dP \qquad (\cancel{8}7)$$

Expressing that in a relative form we have,

$$\frac{df_V}{f_V} \sim \frac{f_I}{f_V} \alpha R \frac{dR}{R} + \frac{A_D^*}{f_V} \beta P \frac{dP}{P}$$

Taking the long term mean annual values (f_I =0.17, f_V = 0.038, R = 9.67, P = 47.5~~4~~, A_D^* = 0.97) and the empirical coefficients (α = 0.0011, Fig. ~~7~~8; β = 0.00017, Fig. ~~6~~7) we have,

$$\frac{df_V}{f_V} \sim 0.05 \frac{dR}{R} + 0.21 \frac{dP}{P} = X_R + X_P \qquad (\cancel{9}8)$$

The empirically based equation predicts that a 1% variation in runoff would leads to a 0.05% variation in f_V whilst a 1% variation in precipitation would increase f_V by 0.21%. Finally we use the runoff and precipitation data to estimate the relative changes in regional vegetation cover. The overall result shows that the model developed here accounts for *c.* ~~at least~~ 52% of the total variance in regional vegetation cover (Fig. ~~9~~8). It varied from 45%-62% depending on different precipitation databases (Fig. S4).

4 Discussions

In this study, we focused on ~~an~~a hyper-arid oasis-desert system where agricultural crops (artificial oasis) and groundwater-fed native ~~vegetation~~vegetation (natural oasis) that occupy some 4% of the entire region are concentrated along the Heihe River. As is well known, it is very hard to evaluate sparse desert vegetation cover in hyper-arid regions at a regional scale owing to coarse spatial and spectral resolution (Fensholt and Proud, 2012). However, the high resolution The MODIS sensor has ~~contains~~ spectral bands that are specifically designed for vegetation monitoring and ~~.~~ MODIS-based vegetation indices ~~indicies index~~ are known to perform~~ed~~ well ~~with higher fidelity and presented sensitivities~~ in discriminating vegetation differences in both sparsely, and densely, ~~and dense~~ vegetated ~~ion~~ areas (Huete et al., 2002). Therefore, a vegetation index from MODIS with 250m spatial resolution is likely to be ~~more~~ appropriate for monitoring of fragmented landscapes of drylands, e.g. Central Asia (Dubovyk et al., 2013) and provides a potentially useful ~~valid~~ data source to evaluate regional vegetation change.

We found it necessary to restrict our analysis to the ~~Also, we have used~~ growing season to avoid ~~vegetation cover to avoid~~ noise apparently caused by ~~from~~ snow and ice. With that pre-processing, our ~~.~~

~~The~~ results showed that the mean growing season fractional vegetation cover (f_V) in Ejina showed a steady increase from ~ ~~starting at about~~ 3.2% in 2000 and rising to ~ ~~around to~~ 4.5% in 2012. The key question is what caused this change; the general climate variability ~~of~~or human-induced land use changes relating to irrigation? ~~In addition to the reasons for this change related to regional climate variability, also related to human activities within the oasis being restricted by water availability.~~

We were able to identify the crops and green native vegetation along the river using ~~from~~ the elevated NDVI signal during the April-October growing season~~. Each year we identified those regions~~ but we were unable to separate the crops from the native vegetation using the MODIS NDVI satellite data. With that, the entire region was split into two land cover types, denoted here as desert and irrigation oasis (that includes native vegetation along the river) for each year. Desert ~~a~~is distinguished from irrigated lands using a simple maximal NDVI threshold (Fig. 3).

Regional vegetation cover depends on both the desert and irrigated vegetation cover and their area fractions. Regional vegetation cover in the downstream of the Heihe River Basin (2000-2012) is ~~was~~ highly sensitive to variations in the area of irrigated land (Eq. ~~6~~5). Over the whole period we found that the contributions to regional vegetation cover change due to changes in irrigated vegetation cover (f_I) and the area fraction (A_I^*) were 7.8% and 20.5% respectively, whilst changes in the non-irrigated vegetation cover (f_D) and area fraction (A_D^*) accounted for 75.8%, and -4.1% respectively. Uncertainty analysis indicated ~~analysis indicates~~ that the fractional changes were not especially sensitive to the assumed NDVI threshold that was used to delineate desert from irrigated lands (Table 1). With that, our final result was that the relative vegetation change over the basin was most sensitive to changes in greenness of desert vegetation (~75%, Table 1) and in the area of irrigation (~21%, Table 1). The remaining terms (greenness of irrigated vegetation, area of desert) could be ignored. ~~contribution is steady with varied thresholds. This result implies that we need only consider variations in~~ ~~f_D~~ ~~and in~~ ~~A_I^*~~ ~~to account for most of the changes in regional vegetation cover.~~

~~eatfractional vegetation cover in the extensive desert regions the fractional irrigation area In all, the method includes both analytic and approximate ways~~

~~The ecological vegetation change of inland river basins in China is closely related to water conditions that are mainly subject to human activity and climate change (Yu and~~

~~Wang, 2013). Desert vegetation is characterised by large spatial and temporal variability influenced by aridity stress with scarcity, discrete, and largely unpredictable precipitation inputs (D'Odorico and Porporato, 2006; Ma and Frank, 2006; Bhuiyan, 2008). Precipitation observation over arid region is scarce. Although the grid data with spatial resolution of 1 degree may overlook some details, it still can supply a reference at some extent. Therefore, as expected,~~

To be able to prognostically estimate changes in relative vegetation cover we sought empirical relations between desert greenness and precipitation (Fig. 7) and between the extent of irrigation and runoff in the previous year (Fig. 8). Gridded databases ~~grid data sets~~ supplied a useful way to ~~understand~~estimate the precipitation and its spatial distribution. Therefore, as expected, vegetation cover in the non-irrigated f_D was strongly related to scarcity, discrete annual precipitation in such an arid region (Fig. 6) (Bhuiyan, 2008; D'Odorico and Porporato, 2006). The underlying basis of that latter relation would be complex and would involve a lag because (i) farmers may anticipate future planting areas based on runoff from the previous year/s, and (ii) the runoff recharges the local groundwater that is subsequently used by the local population (for irrigation) and by the native oasis vegetation. The lagged relation between runoff and the area of irrigation may provide a useful empirical basis for forecasting and confirms the importance of managing the human impact to achieve targeted improvements in the regional ecology.– For the lower reaches, that empirical relation ~~it~~ can be used to estimate ~~manage~~ water use based on the previous runoff.

It is difficult to discriminate the effects of climate change and of human activities on regional vegetation change in arid regions (Zhou et al., 2013). In northwest –China, previous work has suggested that precipitation is the most important factor~~s~~ (Ma and Frank, 2006) while other studies concluded ~~and some indicated~~ that climate factors only played a small role with the major cause of regional vegetation change being caused agricultural activities (Kong et al., 2010; Zhou et al., 2013). The results varied with time and space. Most of the studies are limited to qualitative distinctions (Dai et al., 2011), model estimation (Zhang et al., 2011; Zhou et al., 2013), and regression and residual approximation (Wang et al., 2012). To resolve those differences we used a formal analytic framework to attribute the change of regional vegetation cover. The separation and attribution between extensive desert regions and irrigation area supplied a useful way to quantify the vegetation contributions from land use changes relating to irrigation~~human activities~~ and climate variability.

The reason why we can use this method in this ecologically delicate and highly concerned area is that the most human activities focus on the irrigated oasis that accounts for 3% - 5% of the total area. It is a typical oasis-desert landscape that dominates Central Asia with widespread irrigation oases.

~~A number of studies have previously evaluated the ecological environment in Ejina since the Ecological Water Conveyance Project (EWCP) was launched in 2000. Some earlier work Research methods have been diverse and includes, for example, questionnaire surveys and group discussions (Wang et al., 2013), eco-hydrological field-based investigations (Guo et al., 2009; Wang et al., 2011; Zhang et al., 2011), monitoring by satellite remote sensing (Jin et al., 2010; Jia et al., 2011; Zhang et al., 2011) and by model simulations (Xi et al., 2010). Those studies revealed that more water is now available for the natural environment with plant growth extending up to 1000 m from the Heihe River (Guo et al., 2009). In addition, the regional water table has risen in many parts of the Ejina Basin (Zhao et al., 2009; Wang et al., 2011). Native vegetation in most (~ 80 %) of the oasis regions has shown an increasing trend in the last decade (Zhang et al., 2011) in response to the increasing availability of water. Our results set these earlier studies vegetation changes into a larger regional setting. of whole lower reaches and we showed that the changes in irrigated oasis related EWCO have a large impacted on the regional vegetation cover.~~

~~The downstream parts of Heihe River basin studied here are typical of the oasis-desert landscape that dominates Central Asia with widespread irrigation.~~ In this system, the allocation of water resources is critical in achieving a balance among different oases as well as between human water appropriation for irrigation and ecological conservation. The overuse water in the upper and middle reaches associated with increased irrigation made significant reduction in river flows to the downstream oases and accelerated desertification. A similar over use of water for irrigation also happened in the Aral Sea. The water withdrawal for agricultural ~~irrigation~~ expansion (e.g. from about 4.5 Mha in 1960 to almost 7.9 Mha by 1999) led to a dramatic shrinkage of the Aral Sea that has attracted the attention of the international scientific community over the last few decades (Micklin, 1988; Whish-Wilson, 2002; Lioubimtseva et al., 2005). In the last few decades, the runoff from mountains showed an increase trend with more precipitation and warmer climate (Unger-Shayesteh et al., 2013; Wang et al., 2013). However, ~~R~~rational distribution and sustainable management of water resources is still a long-term and arduous task. Our results suggest that it is possible to use remotely sensed data to provide practical support in assessing the ecological status of irrigation regions that surround most Central Asian rivers.

5 Conclusions

We found that the regional fractional vegetation cover f_V in the downstream parts of the greater Heihe River basin increased by 25% from 2000 to 2012. The largest contribution was due to a slight greening of the desert regions that was consistent with increased precipitation over the period. The other main contribution to the regional trend was an expansion of irrigated areas ~~ion~~ (including native vegetation dependent on groundwater) along the Heihe River that was found to be dependent on the runoff in the previous year. In conclusion, water availability both from precipitation and runoff can explain around 52% of the total variance in regional vegetation cover over the period in this extremely arid environment. This study showed that it is feasible to separate the variations in regional vegetation cover that are due to changes in the climate from those due to changes in human activities given appropriate regional context.

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Table 1 Sensitivity and attribution uncertainty with varied NDVI thresholds to define irrigated and non-irrigated region (mean annual fractional vegetation for the whole region f_V, irrigated oasis f_I and desert f_D, fractional area of irrigation A_I^* and desert A_D^*; And their attribution X_{fI}, X_{AI}, X_{fD}, X_{AD})

NDVI Threshold	Sensitivity	Attribution			
		X_{fI}	X_{AI}	X_{fD}	X_{AD}
0.08	$\frac{df_V}{f_V}=0.18\frac{df_I}{f_I}+2.97dA_I^*+0.82\frac{df_D}{f_D}+0.88dA_D^*$	14.0%	16.8%	74.1%	-5.0%
0.09	$\frac{df_V}{f_V}=0.16\frac{df_I}{f_I}+3.76dA_I^*+0.84\frac{df_D}{f_D}+0.88dA_D^*$	9.5%	19.4%	75.6%	-4.5%
0.1	$\frac{df_V}{f_V}=0.15\frac{df_I}{f_I}+4.45dA_I^*+0.85\frac{df_D}{f_D}+0.88dA_D^*$	7.8%	20.5%	75.8%	-4.1%
0.11	$\frac{df_V}{f_V}=0.14\frac{df_I}{f_I}+4.99dA_I^*+0.86\frac{df_D}{f_D}+0.89dA_D^*$	7.6%	20.3%	75.7%	-3.6%
0.12	$\frac{df_V}{f_V}=0.13\frac{df_I}{f_I}+5.42dA_I^*+0.87\frac{df_D}{f_D}+0.89dA_D^*$	7.3%	19.4%	76.4%	-3.2%

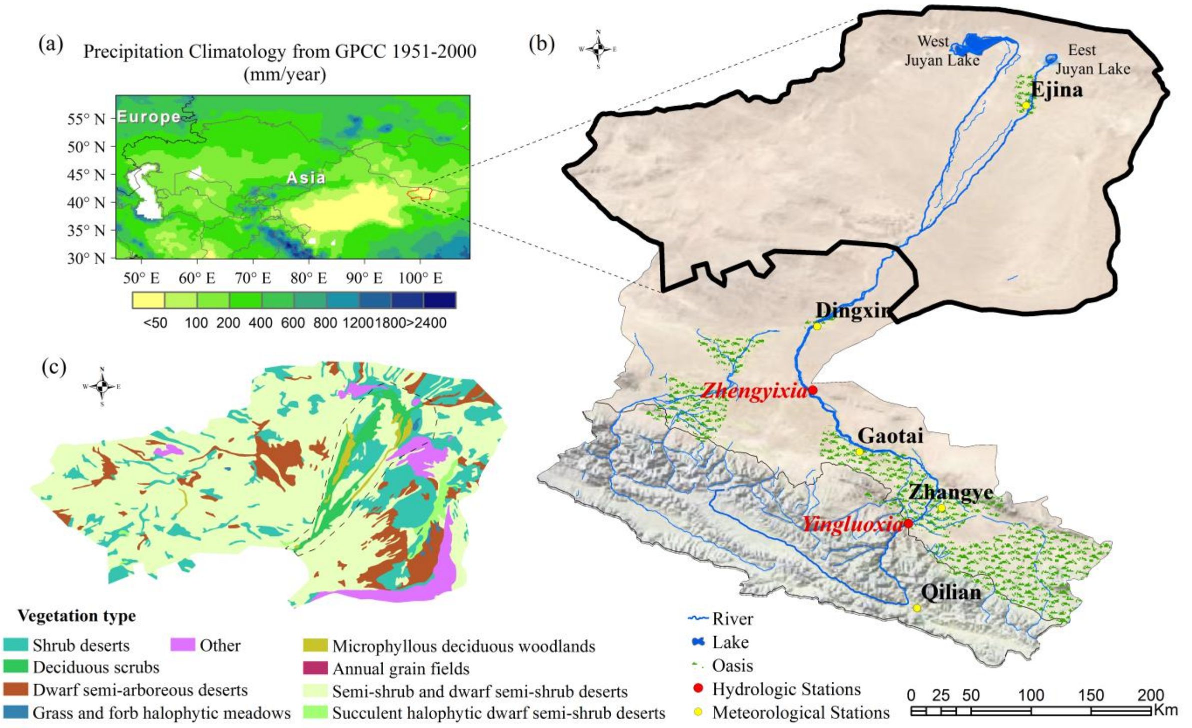

Fig. 1 Details of the study area. (a) Regional setting and the mean annual precipitation (1951-2000). (b) Landscape of Heihe River Basin with location of meteorological and hydrologic observation sites. (c) Vegetation Map of lower Heihe river basin where the dashed line denotes the bounds of the possible irrigation area.

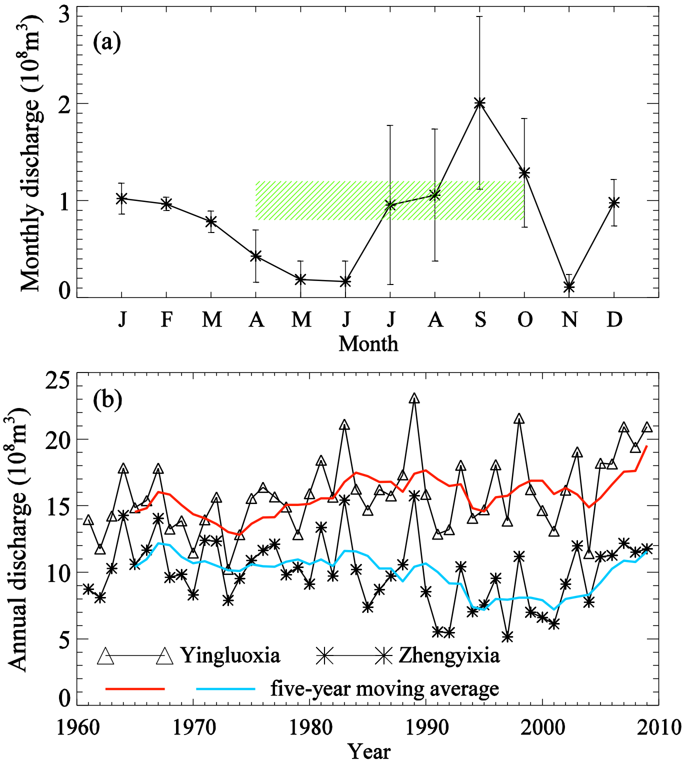

Fig. 2 River flows in the Heihe River basin. (a) Mean monthly river discharge (bars indicate standard deviation) of Heihe River (2000-2009) at Zhengyixia station in relation to the growing season (diagonal stripes). (b) Annual discharge of Heihe River (1961-2009) at Yingluoxia and Zhengyixia stations

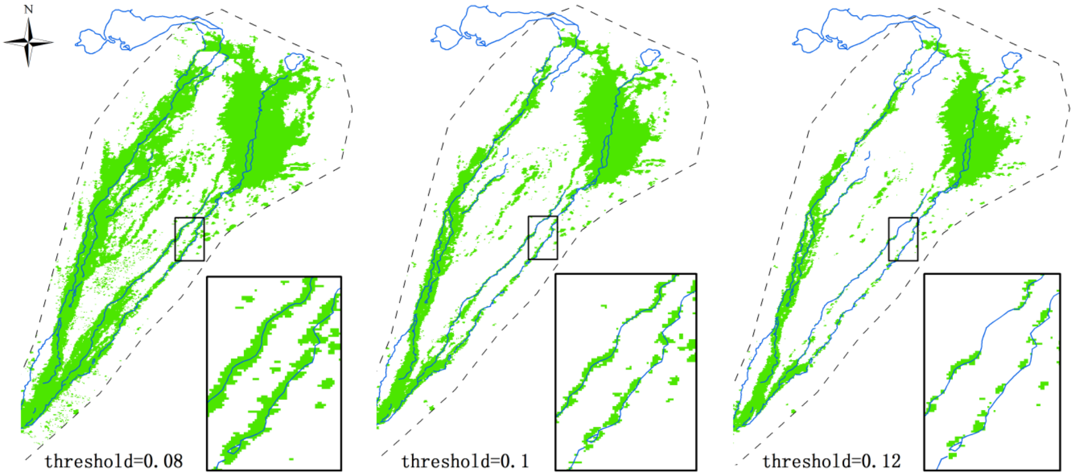

Fig. 3 Irrigated areas derived using different NDVI thresholds

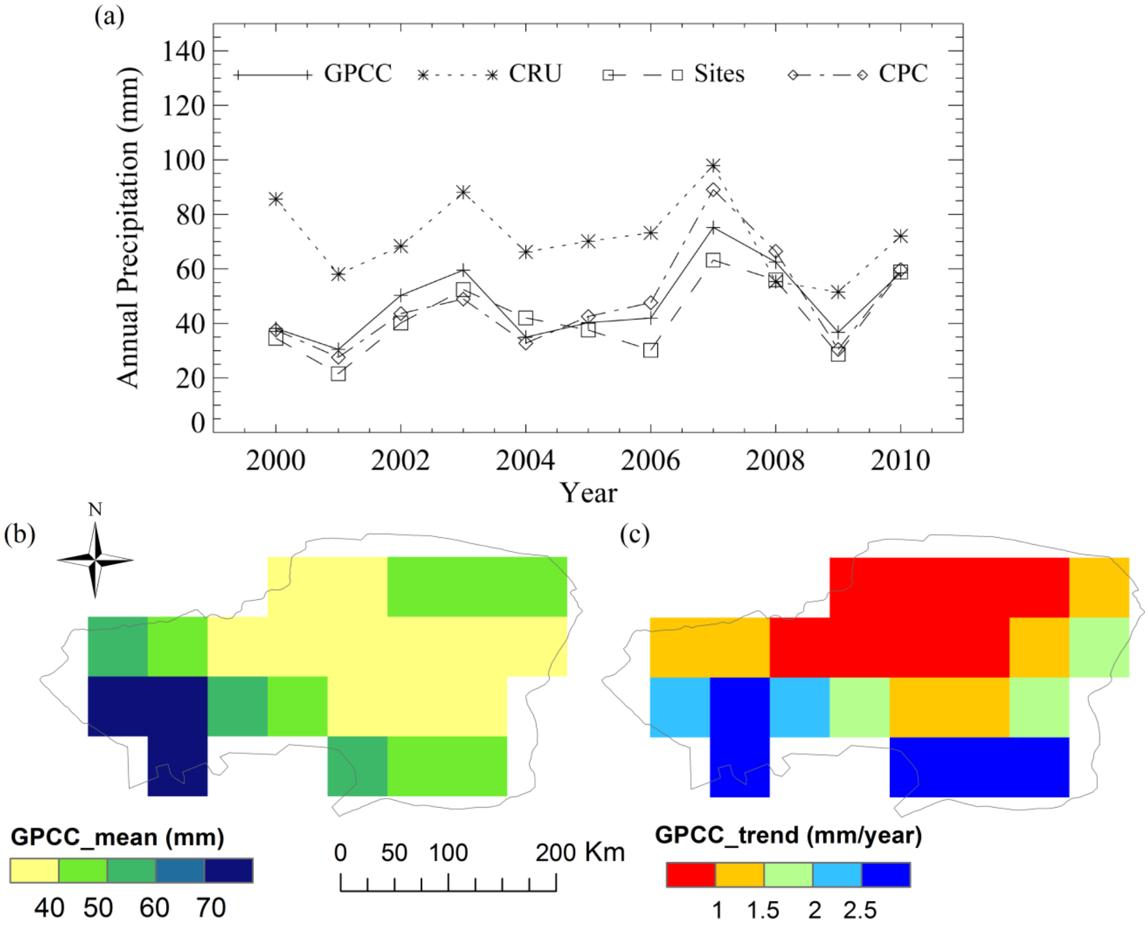

Fig. 4~~3~~ Spatial-temporal change of precipitation for the study area. (a) Annual precipitation ~~for the study area as~~ per four different data sources (as indicated~~).~~); (b) Mean annual precipitation from GPCC, and (c) the trend from 2000 to 2010.

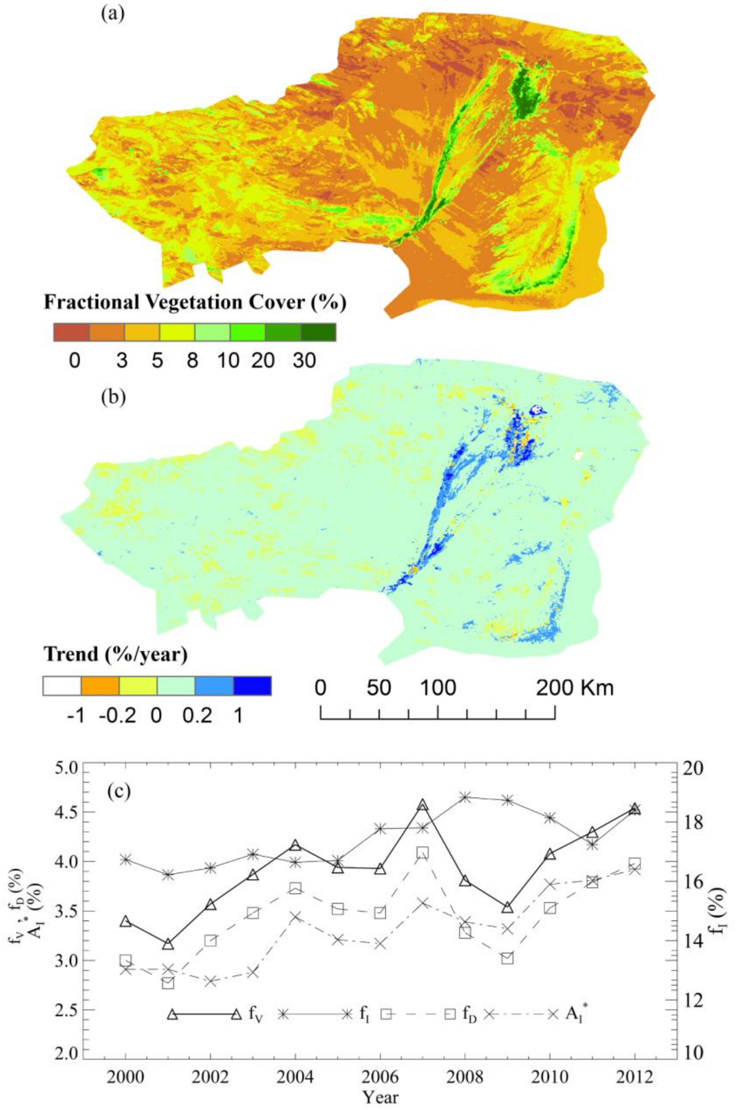

Fig. 5~~4~~ Spatial-temporal change of the ~~G~~growing season (April-October) mean annual fractional vegetation cover (2000-2012).(a) Spatial pattern of growing season (April-October) mean annual fractional vegetation cover; (b) Spatial trend of growing season (April-October) mean annual fractional vegetation cover (2000-2012); (c) Trends in the growing season (April-October) mean annual fractional vegetation for the whole region (f_V, left scale), desert (f_D, left scale) and irrigated (f_I, right scale) land cover classes, and for the fractional area of irrigation (A_I^* , left scale).

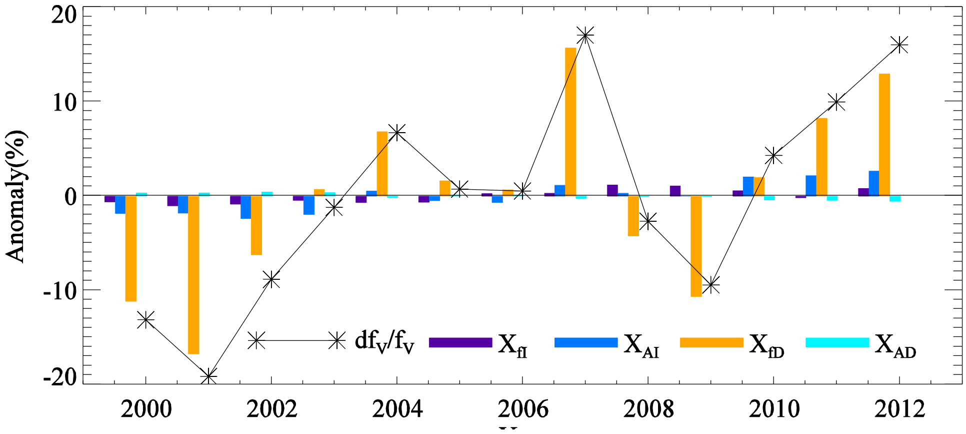

Fig.~~5~~ 6 Annual changes in relative vegetation cover (df_V/f_V) and the underlying components from mean annual fractional vegetation for the desert (X_{fD}) and ~~,~~ for the irrigated (X_{fI}) regions along with changes due to ~~, and for~~ changes in the the fractional area of desert (X_{AD}) and irrigated ~~ion~~ (X_{AI},) regions.~~and desert (X_{AD}).~~

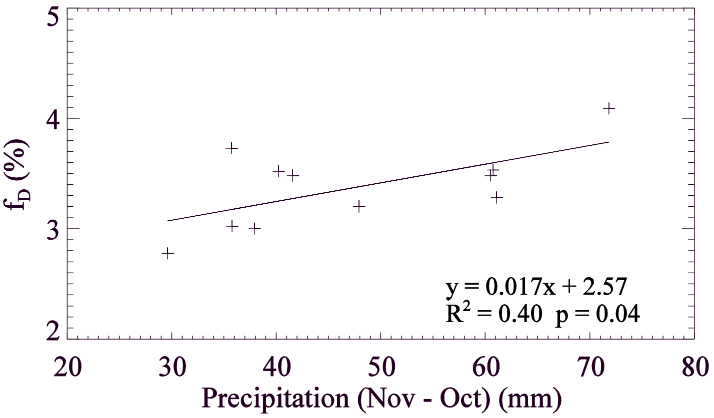

Fig. 7~~6~~. Relationship between growing season desert vegetation cover (f_D) and annual precipitation (per GPCC database 2000-2010).

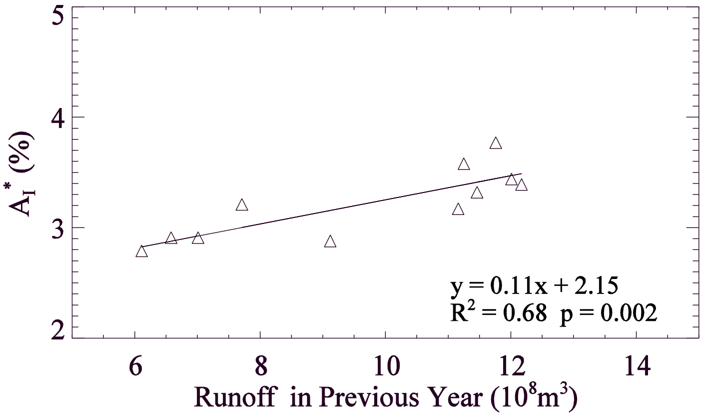

Fig. ~~7~~ 8 Relationship between fractional irrigated area A_I^* and runoff at Zhengyixia from the previous year 2000-2010.

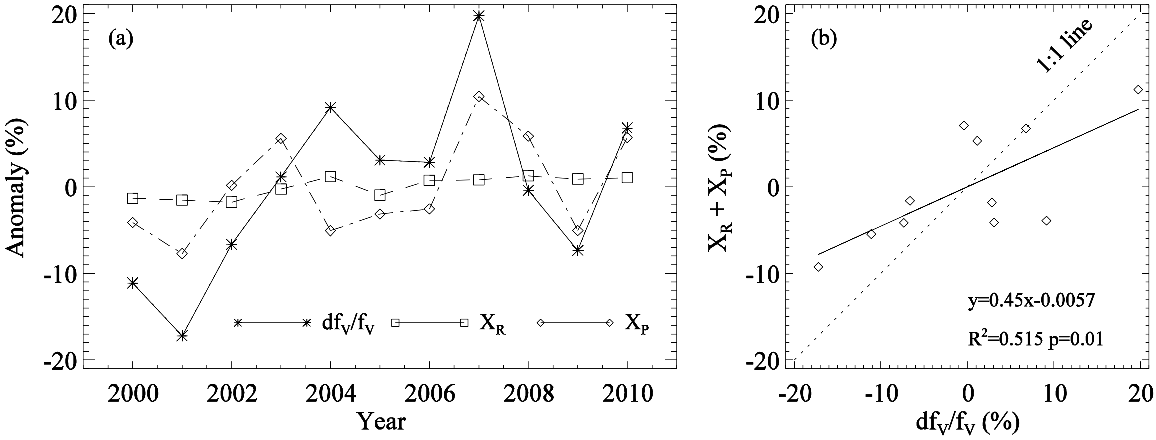

Fig.~~8~~ 9 Relation between regional vegetation cover and water availability. (a) Relative variations, and (b) the observed annual changes in relative vegetation cover (df_V/f_V) versus predicted changes from water availability of runoff (X_R) and precipitation (X_P).

Supporting material

Table S1 Statistics (e.g., R^2, significance level (p), and the slope of the linear regression) between desert vegetation cover f_D and regional precipitation variations from different sources

	GPCC	CRU	SITES	CPC
R^2	0.40	0.37	0.49	0.51
p	0.04	0.05	0.02	0.01
Slope	0.017	0.015	0.018	0.014

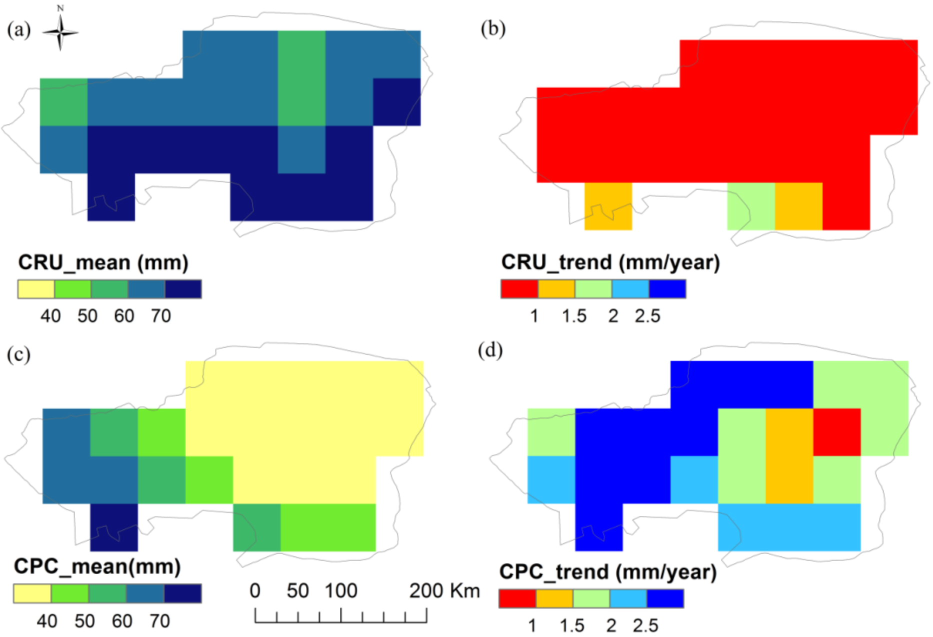

Fig. S1 Spatial~~-temporal~~ pattern and change of precipitation for the study area from different sources. (a) Mean annual precipitation from CRU~~Annual precipitation per four different data sources (as indicated)~~. (b) spatial trend of precipitation from CRU 2000-2010~~Mean annual precipitation from GPCC, and~~ (c) Mean annual precipitation from CPC. (d) spatial trend of precipitation from CPC 2000-2010~~the trend from 2000 to 2010~~.

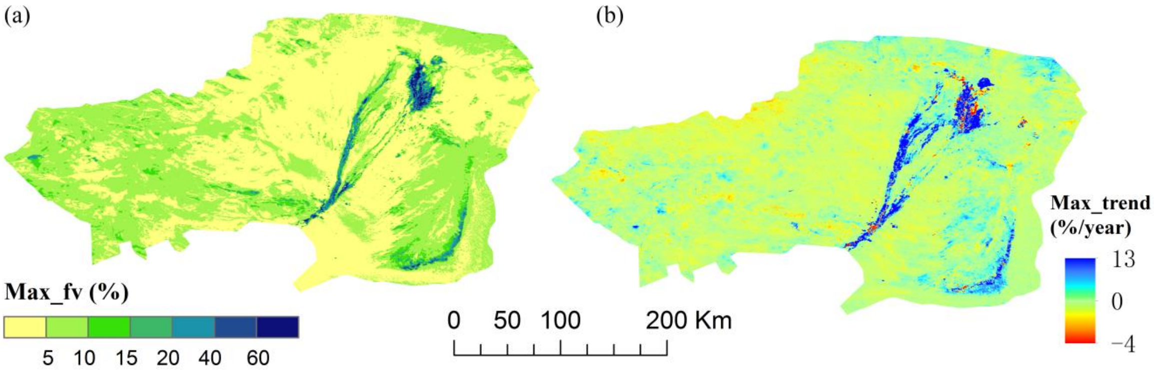

Fig. S2 Spatial of annual maximal fraction vegetation cover (a) Averaged annual max fraction vegetation cover (Max_fv) and (b) change in annual max NDVI during 2000-2012

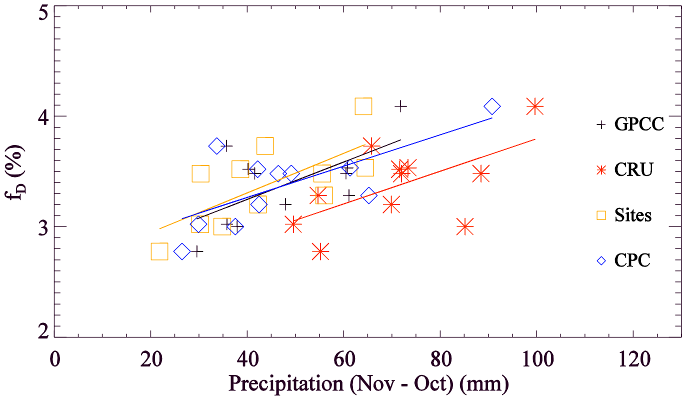

Fig. ~~S1~~S3~~.—~~ Relationship between desert vegetation cover f_D and regional precipitation from different data sets

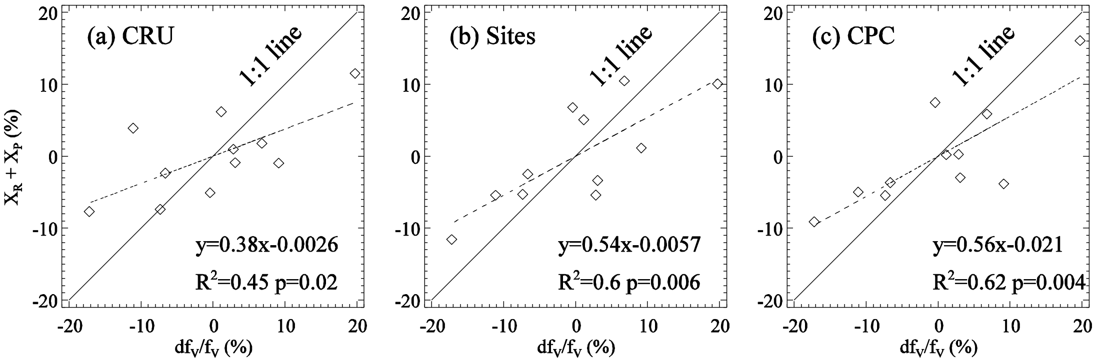

Fig.~~S2~~S4~~.~~ The observed annual changes in relative vegetation cover (df_V/f_V) versus predicted changes from water availability of runoff (X_R) and precipitation (X_P) in relative vegetation cover with different percipitation data sources.