Relating historical vegetation cover to aridity index patterns in the greater desert region of northern China: Implications to planned and existing restoration projects

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**Abstract.** Desert regions of northern China have always been the most severely affected by climate change, especially in terms of their ecological integrity and social sustainable development. Assessments of dryness in both space and time are central to the development of adaptation strategies to climate change. Earlier studies have identified long-term patterns of dryness in northern China, but these studies have usually been of limited value to land-management planning as they ignore local-to-regional-scale climate features. To identify potential cause-and-effect relationship between aridity and vegetation cover, changes in aridity index (AI) and vegetation cover were tracked with the assistance of a chronological series of surfaces based on the mapping of normalized difference vegetation index (NDVI) and AI and convergent cross mapping. By tracking regional-scale variation in precipitation, air temperature, AI from 1961-2013 (53 years), and vegetation cover dynamics from 1982-2013 (32 years), we show that precipitation increased in approximately 70% of the greater desert region, including in the Ulanbuh, Tengger, Badain Jaran, Qaidam, Kumtag, Gurbantunggut, and Taklimakan Deserts. This increase was statistically strongest for the Gurbantunggut (*p* < 0.01) and Taklimakan Deserts (*p* < 0.1). Predictably, air temperature rose in nearly all deserts (*p* < 0.01) at approximately 2.5 times greater than the global rate. Changes in AI paralleled those of precipitation (low AI, denoting hyper-arid conditions), except for the Tengger Desert. Increasing AI (i.e., wetting) was statistically strongest for the Gurbantunggut (*p* < 0.01), Qaidam (*p* < 0.05), and Taklimakan Deserts (*p* < 0.05). Vegetation growth largely improved in oases of the western desert region and Mu Us Desert over the 1982-2013 period (*p* < 0.1). For the most part, aridity had a measureable control on NDVI (*p* < 0.05), with no indication of vegetation feedback at an 8-km resolution. The wetting trend observed in the western desert region (increasing AI) improved ecological conditions of the region by increasing NDVI. In contrast, continued drying in the eastern desert regions (decreasing AI) had caused NDVI to decrease. Future planning of restoration projects should ideally take into account drying/wetting trends currently being observed and projected for northern China.

# 1 Introduction

In recent decades, countless studies have demonstrated the indisputable fact of climate change (IPCC, 2013) and its impacts on water resources (Raghavan et al., 2012; Deng et al., 2015; [Pumo](http://www.sciencedirect.com/science/article/pii/S0048969715309256) et al., 2016), ecological environment (Chen et al., 2013; Yang et al., 2015), human settlement ([Dumenu](http://www.sciencedirect.com/science/article/pii/S1462901115300939) and [Obeng](http://www.sciencedirect.com/science/article/pii/S1462901115300939), 2016), and human health (Moore et al., 2008; Abaya et al., 2011; Wu et al., 2016). Continued global climate change in desert regions of the world may have a profound impact by accelerating hydrological processes and by increasing the unpredictability of related eco-hydrometeorological variables (Gan, 2000; Ma et al., 2004; Jentsch and Beierkuhnlein, 2008), possibly leading to a re-definition of desert-dryness patterns globally.

Desert regions of northern (N) China cover nearly one-fifth of the country’s land area. Drylands have always been the most severely affected by changes in climate (Fullen and Mitchell, 1994; Liu and Diamond, 2005; Wang et al., 2013). Extended periods of dryness can alter local-to-regional biogeochemical cycles and key ecosystem functions and services and, in the process, enhance regional desertification ([Delgado-Baquerizo](http://www.nature.com/nature/journal/v502/n7473/abs/nature12670.html#auth-1) et al., 2013). Knowledge regarding drying and wetting trends regionally is critical for proper planning and management of land and state resources, including their allocation and deployment, to ensure the sustainable development of vulnerable desert environments.

Previous studies have indicated that increasing precipitation and subsequent wetting in northwest (NW) China during the past 50 years represents a major climate signal anticipated to persists into the future (Wang et al., 2007; Xu et al., 2010; Huo et al., 2013; Li et al., 2013 and 2016). Some drylands in northern (N) China have been reported to have undergone some expansion in the last 50 years with their boundaries extending eastward to NE China by about 2° of longitude and southward to the middle-to-lower reaches of the Yellow River by about 1° of latitude (Li et al., 2015). This expansion has led to water scarcity and land degradation in many parts of the region. Differences in wetting and drying patterns across China are clearly not uniform, potentially condemning many existing and planned re-vegetation projects in N China to failure.

Earlier studies addressing the variation and long-term patterns of aridity in N China are generally unsuitable for ecological-restoration-project planning because of their coarse spatiotemporal resolutions. Precipitation, air temperature, and aridity patterns over large areas vary in both space and time as a result of differences in climatic regimes induced by differences in geographic placement, synoptic-scale weather patterns, topography, prevailing wind directions, proximity to sources of moisture, and other controlling features. Spatial variation in related eco-hydrometeorological variables in N China have yet to be investigated at spatial resolutions appropriate for ecological-restoration planning. Under the background of climate change, it is largely undetermined if aridity patterns in N China, particularly at sub-regional scale resolutions (e.g., < 10-km resolution), have changed appreciably over the past 50 years.

To investigate this problem, we analysed the changes in precipitation, air temperature, aridity, and vegetation dynamics in the major deserts of N China. Changes in vegetation cover and aridity (assessed by means of the aridity index, i.e., AI) are tracked with the assistance of a chronological series of surfaces based on the mapping of satellite-based normalized difference vegetation index (NDVI) and AI. The analysis is based on meteorological and NDVI data from 1961-2013 and 1982-2013, respectively. The objectives of the study were to (1) understand the role of regional changes in climate in effecting vegetation-cover dynamics in the greater desert belt region of N China, and (2) relate their likely impact on existing and planned ecological-restoration projects. Our specific aims were to (1) quantify trends in spatiotemporal variation in precipitation and air temperature and reveal pattern changes in surface aridity, and (2) track spatiotemporal changes in vegetation dynamics vis-à-vis plant growth and plant-cover expansion and contraction in corroborating our assessment of climate change impacts in N China.

**2. Materials and methods**

**2.1. Study regions**

Desert regions of N China (75°-125°E longitude, 35°-50°N latitude) cover approximately 172.1 × 104 km2, accounting for about 17.9% of the total land area of China (State Forestry Administration, P.R. China, 2015a). The land area forms a discontinuous arc-shaped desert belt from the western Tarim Basin to western Songnen Plain. It traverses the NW-, N-, and northeast (NE)-regions of China with a length of 4,500 km from east to west and a width of 600 km from south to north, including most of Xinjiang, Inner Mongolia, Ningxia, N Gansu, Hebei, Heilongjiang, Jilin, Liaoning, and a part of Qinghai and Shaanxi provinces (Zhu and Liu, 1981; Li et al., 2013; Li [et al., 2014)](http://link.springer.com/article/10.1007/s11427-014-4633-2#author-details-1). These areas are characterized by different climate types, from hyper-arid (AI < 0.05), arid (0.05 ≤ AI < 0.2), semi-arid (0.2 ≤ AI < 0.5), to dry sub-humid climate types (0.5 ≤ AI < 0.65; Hulme, 1996; Middleton and Thonas, 1997). The deserts span two vegetation zones, namely steppes (grasslands) in the east and temperate deserts in the west of the Helan Mountain Range (106° E longitude). Harsh natural conditions (e.g., drought, wind erosion, sparse vegetation, and infertile soils), combined with anthropogenic activities (e.g., over-grazing by free-ranging sheep and goats, excess land reclamation, and irrational exploitation of water resources), have resulted in serious land degradation and desertification in many parts of these regions. To improve ecological conditions, the Chinese government’s “Grain for Green” program (1999-present) was responsible for re-planting vast areas of N China. By the end of 2014, 15.93 × 104 km2 of N China had been converted into forests and grassland (State Forestry Administration, P.R. China, 2015b).

## 2.2. Data source and processing

By means of desert (Zhu et al., 1980) and sand-covered desert classification maps of China, at a 1:100,000 scale (for data source, refer to [Section](http://www.escience.gov.cn/metdata/page/index.html) 6), we were able to delineate boundaries of twelve major deserts, namely the Hulun Buir, Horqin, Otindag, Hobq, Mu Us, Ulanbuh, Tengger, Badain Jaran, Qaidam, Kumtag, Gurbantunggut, and Taklimakan Deserts (Fig. 1). Time series of mean, minimum, and maximum air temperature, air pressure, wind speed, relative humidity, sunshine hours, and precipitation, spanning from January 01, 1961 to December 31, 2013, were collected from 113 meteorological stations (Fig. 1) through China’s Meteorological Data Sharing Service System ([Section](http://www.escience.gov.cn/metdata/page/index.html) 6). Data related to vegetation growth and coverage was based on 15-day resolution time series of Global Inventory Modeling and Mapping Studies (GIMMS) NDVI, with an original spatial resolution of 8 km (for data source, see [Section](http://www.escience.gov.cn/metdata/page/index.html) 6).

Incomplete meteorological time series were gap-filled with linear regression with complete time series from adjacent meteorological stations serving as independent input. To assess the spatial variation in annual trends in precipitation, air temperature, and AI, spatial interpolation of meteorological data was conducted at a spatial resolution of 8 km [using the thin-plate smoothing spline method of](C:\\Users\\Administrator\\Desktop\\投稿包\\邵艳莹-BG投稿包\\ using the thin-plate smoothing spline method of) Hutchinson (2004; [Section](http://cres.anu.edu.au/) 6) and an 8-km re-sampling of an existing 1-km resolution digital elevation model (DEM) developed by the Heihe Project Data Management Centre ([Section](http://cres.anu.edu.au/) 6). We generated annual composites of NDVI from the 15-day images with the maximum value composite method described in Holben (1986).

## 2.3. Aridity Index

Aridity index (AI) was used as an indicator of dryness in the desert regions of N China. It was calculated from:

, (1)

where *P* is the annual precipitation (mm) and *PET* is the annual potential evapotranspiration (in mm) based on the summation of daily reference evapotranspiration (i.e., , in mm d-1) calculated with the Penman-Monteith equation (Allen et al., 1998), i.e.,

, (2)

where *Rn* and *G* are the net radiation and soil heat flux (in MJ m-2 d-1), *γ* is the psychometric constant (kPa oC-1), is the saturation vapor pressure (kPa), is the actual vapor pressure (kPa), Δ is the slope of the saturation vapor pressure-vs.-air temperature curve (kPa oC-1), *T* is the average daily mean air temperature (oC), and is the mean daily wind speed at a 2-m height above the ground surface (m s-1). Computation of variables in Eq. (2) follow the approaches described by the Food and Agriculture Organization of the United Nations (UN FAO). The main radiation component of Eq. (2) is calculated from:

, (3)

, (4)

(5)

, (6)

where  is the extraterrestrial radiation,  is the incident solar radiation,  is the clear-sky solar radiation,  and  are the net shortwave and longwave radiation (all, in MJ m-2 d-1), *α* is the albedo (*α* = 0.23 for deserts, Warner, 2004), *n* and *N* are the actual and maximum possible sunshine duration (h), *σ* is the Stefan-Boltzmann constant (4.903×10-9 MJ K-4 m-2 d-1),  and are the maximum and minimum absolute temperature (K) during any 24-h period (K), and *a* and *b* are empirical coefficients (i.e., *a* = 0.161 and *b* = 0.614, after Wang et al., 2014). Variables, , and *N* were calculated from solar constant, latitude, elevation, and the number of days in the year following procedures outlined in the UN FAO56 report (Yin et al., 2008).

## 2.4. Mann–Kendall test

To detect changes in precipitation, air temperature, and AI in the twelve deserts, the Mann-Kendall (M-K) non-parametric test was used. For a time series of “n” observations (i.e.,,,…,), the M-K test is based on the S-statistic, which is computed from

, (7)

where

. (8)

When the sample size (n) ≥ 8, the variance of the S-statistics is calculated from

(9)

(Mann, 1945; Kendall, 1975), where “m” is the number of sets having the same value in a time series, and denotes the number of duplicate data in dataset k. The standardized M-K test statistic is defined by

, (10)

where |Z|> signifies a statistically-significant trend. When |Z| > 1.64, statistical significance is determined at a significance level of *p*0.1; whereas |Z| > 1.96 and > 2.576 indicate statistical significance at critical *p*-values of 0.05 and 0.01, respectively. A positive Z-value indicates an ‘upward trend’, whereas a negative value indicates a ‘downward trend’; Z=0 corresponds to a ‘statistically non-detectable trend’. To estimate the actual mean rate-of-change in the data (i.e., trend) we employ localized linear regressions at individual image pixels. By definition, the slope of the regression line equals to the mean rate-of-change in the time series data.

## 2.5. Convergent cross mapping

Convergent cross mapping is a model-free method that detects cause-and-effect relationships and direction of cause-and-effect, and possibly feedback, in dynamic systems (Sugihara et al., 2012). As a general rule, time series are considered causally linked if both time series come from the same dynamic system. Convergent cross mapping (CCM) tests for cause-and-effect by determining the extent historical records in one time series can reliably describe the state in a second time series. The method provides reliable assessments of cause-and-effect even in the presence of system confoundedness (Sugihara et al., 2012). Moreover, CCM involves convergence, a distinct feature of the method that distinguishes cause-and-effect from conventional correlation. Ordinarily, non-causal associations are displayed as horizontal, non-convergent curves of predictive skill (Pearson’s correlation coefficients) between predictions and actual observations as time series record length is increased. Convergent cross mapping in this study is based on analyzing random paired, co-located time series of NDVI and AI with the *multispatialCCM* R-library developed by Clark et al.’s (2015) in prior work. System embedded dimensions and time delay required as input to *multispatialCCM* were generated with the *pdc* library, also coded in R. Secondary analyses were carried out to explore relationships between different variables (e.g., within-oasis production of precipitation vs. NDVI) in the greater desert region.

# 3. Results

## 3.1. Precipitation

Figure 2 provides the annual precipitation from 1961-2013 for the twelve deserts. The results indicate annual fluctuations in precipitation, with an obvious drop in precipitation from east to west. According to the M-K test, precipitation increased for seven of the twelve deserts, namely for the Ulanbuh, Tengger, Badain Jaran, Qaidam, Kumtag, Gurbantunggut, and Taklimakan Deserts. A statistically strong increasing trend was observed for the Gurbantunggut (*p* < 0.01) and the Taklimakan Deserts (*p* < 0.1). In contrast, five of the deserts (i.e., Hulun Buir, Horqin, Otindag, Hobq, and Mu Us) demonstrated declining trends in precipitation. However, these trends were not statistically significant (Table 1).

In addition, slopes in precipitation exhibited increasing trends in seven of the deserts, in order from lowest to highest, Kumtag, Tengger, Badain Jaran, Qaidam, Ulanbuh, Taklimakan, and Gurbantunggut Deserts, with a rate-of-change of 0.05 to 1.21 mm yr-1, and decreasing trends in Hobq, Otindag, Mu Us, Hulun Buir, and Horqin Deserts, with a rate-of-change of -0.17, -0.33, -0.35, -0.54, and -0.88 mm yr-1, respectively (Table 1).

Results of linear regression on annual precipitation at the pixel-level are summarized in Fig. 3. The results show that during the observation period (1961-2013), an increasing trend in precipitation occurred within about 70% of N China, mainly in the western half of the greater desert region, with a particularly strong, statistically significant trend in the northern-half of that region (*p* < 0.05; Fig. 1). Whereas, a decreasing trend, though not statistically significant (i.e., *p* > 0.05), was observed to have occurred in the eastern part of the study area, affecting about 30% of the greater desert region.

## 3.2. Mean air temperature

Time series of annual mean air temperature (1961-2013) for the twelve deserts are also shown in Fig. 2. The M-K tests show that all twelve deserts exhibited a statistically significant upward trend in air temperature (*p* < 0.01; Table 1). Similar trends were detected by linear regression (Table 1). Highest rate of air temperature change was observed to have occurred in the Hobq Desert at 0.082oC yr-1, amounting to about 6.3 times greater than the lowest rate determined for the Ulanbuh Desert (i.e., 0.013oC yr-1). Figure 4 shows the changes in annual mean air temperature over the twelve deserts. Expectedly, 97% of the greater desert region was associated with a distinct rising trend in annual temperature (*p* < 0.05) with the majority of the area observing increases of 0.02-0.04oC yr-1.

## 3.3. Aridity

Time series of annual AI show annual fluctuations, with a clear historical dryness gradient from east to west (Fig. 2). According to M-K tests, the Ulanbuh, Badain Jaran, Qaidam, Kumtag, Gurbantunggut, and Taklimakan Deserts exhibited wetting trends, which were especially strong for the Gurbantunggut (*p* < 0.01), Taklimakan (*p* < 0.05), and Qaidam Deserts (*p* < 0.05). Drying trends observed for the Hulun Buir, Horqin, Otindag, Hobq, Mu Us, and Tengger Deserts were not statistically significant at the critical *p*-value of 0.05 (Table 1).

Results from linear regression supported our earlier trend analysis with a rate-of-change of 0.0006-0.013 per decade. The highest positive rate-of-change in AI was for the Gurbantunggut Desert (0.0013 per decade), and the lowest for the Kumtag Desert (0.00006 per decade). A declining (i.e., drying) trend was detected for the Hulun Buir, Horqin, Otindag, Hobq, Mu Us, and Tengger Deserts with a rate-of-change of -0.00014 to -0.008 per decade.

Overall, the results indicated that AI in more than half of the deserts (63.6%; Fig. 1) exhibited a wetting trend (i.e., increasing AI); this trend, for the most part, was statistically significant. About 36.4% of the affected area exhibited a drying trend (decreasing AI), though not statistically significant (Fig. 5). This suggests that most of the desert belt of N China has experienced some level of wetting. As shown in Fig. 5, the wetting zones were mainly distributed in the western desert region (*p* < 0.05). The higher rates-of-change appear in the NW portion of the belt, with a rate-of-change > 0.005 per decade.

## 3.4 Vegetation dynamics

Spatial distribution of annual mean NDVI from 1982-2013 shows a gradual reduction in vegetation vigor and cover from east to west, with the higher values of NDVI occurring in the oases within the western part of the greater desert region (Fig. 6).

Areas of annual mean NDVI < 0.1 were considered non-vegetated areas and were excluded from analysis. Results of linear regression on NDVI are summarized in Fig. 7. Spatial dynamics of annual NDVI indicate that vegetation growth largely improved in the oases in the western half of the desert belt over the 1982-2013 period (*p* ﹤ 0.1). However, inconsistent trends of annual NDVI (both increasing and decreasing) were scattered throughout the eastern part of the desert region (*p* < 0.1); only the Mu Us Desert showed a statistically significant increase. Three deserts, namely the Hulun Buir, Otindag, and Horqin Deserts, had statistically non-significant results. Greatest changes in spatial patterns in NDVI occurred mainly along the transitional zone between the grassland and desert biomes along the vast east-to-west transect (Fig. 7). Temporal changes in NDVI across the desert belt paralleled changes in local-to-regional climate patterns.

Convergent cross mapping directly related independently-derived estimates of annual vegetation cover (by way of NDVI) to annual changes in aridity index (A causes B; *p* < 0.05). The reverse, i.e., B (changes in NDVI) causes A (changes in AI; Fig. 8), failed to support that local changes in NDVI by land use processes (e.g., over-grazing and land conversion) contributed to an observable change in aridity (*p* = 0.37 and non-convergence of the predictive skill curve of B causes A; Fig. 8), minimizing the possibility of feedback between the two variables at 8-km resolution.

# 4. Discussion

According to global trends, precipitation has generally increased over the Northern Hemisphere at middle to high latitudes, with wet areas becoming wetter and dry areas becoming drier (New et al., [2001](http://onlinelibrary.wiley.com/doi/10.1002/met.284/full#bib138); Dore, 2005). Our results suggest an opposing trend, where dry areas have become wetter and wet areas have become drier, although not statistically supported in all cases. Clearly, these findings emphasize the complexity of short- to long-term spatiotemporal patterns in meteorological/climatological processes in desert regions. According to the IPCC (2013), climatic variability combined with human-induced emission of greenhouse gases has resulted in a global increase of near-surface air temperatures of 0.72oC during the 1951-2012 period, amounting to a 0.01oC yr-1 increase. Our study indicates that the effect of global climate change has resulted in far greater temperature increases in the deserts of N China, averaging to about 0.025oC yr-1 from 1961-2013. This increase was about 2.5 times greater than the global rate. In terms of aridity, our results are consistent with findings previously reported for NW China and semi-arid regions of Inner Mongolia (e.g., Huo et al., 2013; Zhou et al., 2015), albeit expressed at different resolution. Historical trends in NW China differ from the ‘dry gets drier and wet gets wetter’ association that we currently see globally (Melillo et al., 1993; Whitford, 2002; Lioubimtseva, 2004; Herrmann et al., 2005; Donohue et al., 2009).

Precipitation is an important driver of vegetation growth and vigor in drylands (Zhang et al., 2006; Cleland et al., 2007; Xin et al., 2008; Fig. 8). In general, increased precipitation and AI is followed by improvements in vegetation cover (Zhang et al., 2013). Current mean distribution of NDVI illustrates a general decreasing trend from east to west (Fig. 6), largely in conformity with regional precipitation patterns. Elevated air temperatures anticipated with climate change may cause melting of high-elevation glaciers, currently a major source of water in many inland arid areas of NW China (Wang et al., 2008; Sorg et al., 2012; Hua and Wang, 2014; Matin and Bourque, 2015), to accelerate (Zhang et al., 2016), potentially increasing the amount of water available for oasis agriculture and vegetation establishment.

Matin and Bourque (2015) show through their work that vegetation cover dynamics and surface evaporation in the lowland oases of two large endorheic (hydrologically-closed) watersheds of central Gansu (expressed in terms of satellite-based estimates of enhanced vegetation index) was causally related to the production of precipitation in the Qilian Mountains (south of the oases) and precipitation in the mountains was causally related to the seasonal phenology and coverage of oases vegetation, with the former relation providing the stronger control on regional re-cycling of water. Convergent cross mapping of within-oasis production of precipitation through localized convective processes is shown to have no detectable causal relation with NDVI in the oases (i.e., *p* > 0.05 and absence of convergence). This assessment is consistent with the view that in-mountain production of precipitation through orographic-lifting of evaporated water from the oases and surface and shallow sub-surface return flow from the mountains is central to sustaining healthy growing vegetation in the lowland oases (Bourque and Matin, 2012; Matin and Bourque, 2015). Added water resources to the oases in the form of glacial meltwater should help sustain some of these oases for some time into the future, providing that the vegetation cover in the oases (transpiration pump) is not radically altered by urbanization and other forms of land conversion (Bourque and Hassan, 2009). For semi-arid regions of NE China undergoing drying, rising air temperatures may accelerate surface evaporation (Xin et al., 2008; Hao et al., 2012) and cause vegetation vigor and cover to decline, potentially promoting desertification.

Although impacts of precipitation and air temperature on ecosystems are important, ecological processes of ecosystems are largely influenced by their integrated effects (aridity vs. vegetation; Fig. 8). Spatiotemporal patterns of aridity determine the spatial structures and evolution of plant communities (Fernandez-Illescas and Rodriguez-Iturbe, 2004; Oguntunde et al., 2006; McVicar et al., 2007; Jiapaer et al., 2015; Fig. 8) and the process of desertification in arid-to-semi-arid regions (Wang, et al., 2009). As illustrated in Fig.8, annual changes in NDVI are shown to be controlled to a large measure by annual changes in aridity (*p* < 0.05 + convergence). Clearly, the integrity of the vegetation cover assessed at moderate resolutions (i.e., 8-km resolution) is more greatly influenced by changes in mesoscale-to-synoptic scale circulation patterns (Ye et al., 2013) and the delivery of glacial meltwater to the oases in the west (Bourque and Matin, 2012; Matin and Bourque, 2015). Prominence of small-scale land use practices on aridity (e.g., von Hardenberg et al., 2001) and AI, especially those related to over-exploitation and over-grazing (if present), can remain undetected at the current spatial resolution.

The relationship between AI and NDVI at 8-km resolution suggest that patterns of wetting in the western desert region in the past 53 years have led to small improvements in vegetation cover (NDVI; Fig.7) and potentially alleviated planning concerns associated with the sustainable development of existing oases (Zhu et al., 1981). Recent studies have shown that the change from hot-dry to hot-wet conditions have led to an increase in vegetation cover in Xinjiang Province (western part) of NW China (Zhao et al., 2011; Jiapaer et al., 2015). Continued wetting of the western desert region with climate change (Yin et al., 2015) could potentially improve ecological conditions, promote desertification reversal, and reduce reliance on groundwater for crop irrigation. However, vegetation in some scattered areas in the western desert region (denoted by the small red areas in Fig.7) have shown to have undergone some level of decline, notwithstanding improvements in precipitation overall. Discrepancy with regional wetting and vegetation decline is most likely relate to the presence of small-scale re-vegetation projects or prevalence of land use practices associated with resource over-exploitation and over-grazing. Many re-vegetation projects rely on the exploitation of groundwater, which may cause natural vegetation nearby of the projects to decline as a result of insufficient water (Cao, 2008; Cao et al., 2010). Continued drying in the eastern semi-arid region would likely encumber agricultural operations, vegetation re-growth, and ecological restoration in the Hulun Buir, Horqin, Otindag, Hobq, Mu Us, and Tengger Deserts (Fig. 7) for some time into the future (Yin et al., 2015). Many of the conclusions drawn from this analysis are consistent with those reported in Brookshire and Weaver (2015).

Given the massive re-vegetation projects of the past (circa 1999 to the present) and planned re-vegetation projects for the next planning cycle, ending in 2050 (Lal, 2001 and 2004; Feng et al., 2016), it is important to recognize that vegetation-restoration projects may contribute to water shortages that may ultimately lead to their failure, especially in semi-arid areas currently undergoing drying. Therefore, under this backdrop, pattern changes in drying/wetting should be taken into account in balancing re-vegetation projects with the domestic needs for water (Liu and Yang, 2012). This would avoid the excessive restoration of marginally to severely impoverished lands with little possibility of generating ecological and socio-economic benefits. Re-vegetation-project planning should ideally place a greater emphasis on vegetation- and land-area-specific carrying capacities (Bourque et al., 2000) and their future condition as climate, water accessibility, and physiographic conditions evolve with climate change. A “one-fit-all” dryland-restoration strategy is not only expensive, but ecologically flawed.

# 5. Concluding Remarks

We present a new framework in the analysis of climate change and associated trends in aridity and vegetation cover in the greater desert belt of N China. We use convergent cross mapping to investigate the cause-and-effect relationship between aridity and NDVI, as well as other variables. The framework, combined with convergent cross mapping, provides a means to assess historical climate change impacts on vegetation dynamics and ecosystem function and services, important for decision-making. At the spatial resolution of the present study (i.e., 8-km resolution), meteorological aridity is shown to be the most important controlling variable of vegetation cover (NDVI) changes observed, with no indication of feedback. Trend analysis of precipitation, aridity, and NDVI suggest that climatic conditions in the western desert region in the past 53 years has undergone a level of wetting, leading to small improvements in vegetation cover. In contrast, semi-arid areas of the eastern desert region have experienced declining ecological conditions over the same time period. Many of these recent historical trends are projected to continue into the future with further changes in climate.

Our results are critical for adaptation planning and desertification management which can provide guidance to the ecological restoration of deserts in N China. However, promoting sustainable management of re-vegetation projects during the next cycle of restoration-project planning remains a major challenge. We recommend that more information, such as tolerance of vegetation cover in an environment of increasing demand for water by residential, agricultural, and industrial users, be obtained to ensure socio-economic and ecological sustainability of dryland ecosystems. Although, vegetation cover is shown not to affect aridity at the current resolution by feedback mechanisms, we suggest that further work be done to uncover these relationships as over-exploitation of land-surface vegetation and other land use practices may lead to further decline, even in areas where precipitation may be trending upwards.

# 6. Data availability

Time series of mean, minimum, and maximum air temperature, air pressure, wind speed, relative humidity, sunshine hours, and precipitation from January 01, 1961 to December 31, 2013, were obtained from China’s Meteorological Data Sharing Service System (<http://www.escience.gov.cn/metdata/page/index.html>); Global Inventory Modelling and Mapping Studies (GIMMS) NDVI were accessed from <http://ecocast.arc.nasa.gov/data/pub/gimms/3g.v0/>; while the DEM was obtained from the Heihe Project Data Management Centre (<http://heihedata.org/>).

# Author contributions

YQZ and YYS designed the study of the paper; YYS, YQZ, XQW, and CPAB contributed to the ideas, interpretation of the data, and manuscript writing; CPAB employed CCM in a cause-and-effect analysis of precipitation, AI, and NDVI; YYS contributed to data processing and analysis; all authors contributed to the discussion and commented on the manuscript throughout its development.

# Conflicts of Interest

The authors declare no conflict of interest.

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**Figures**

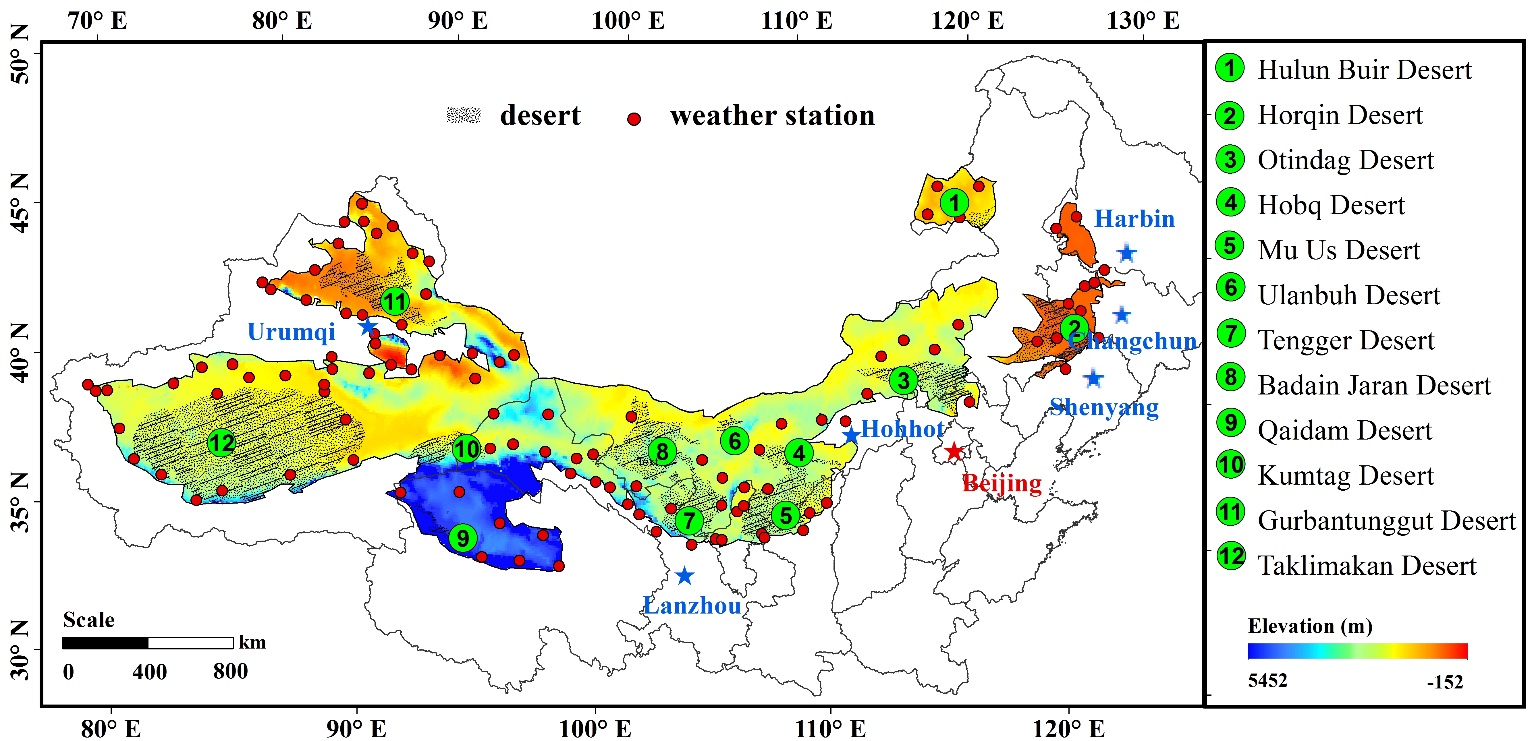
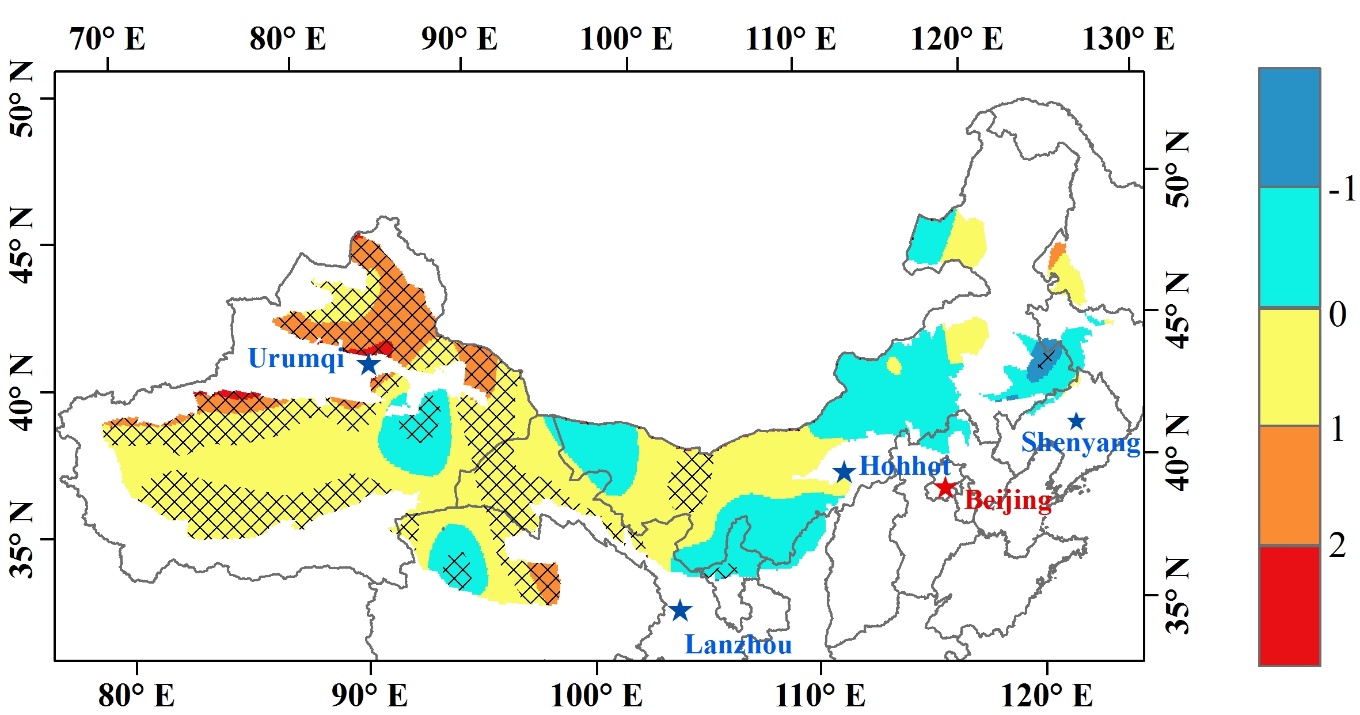


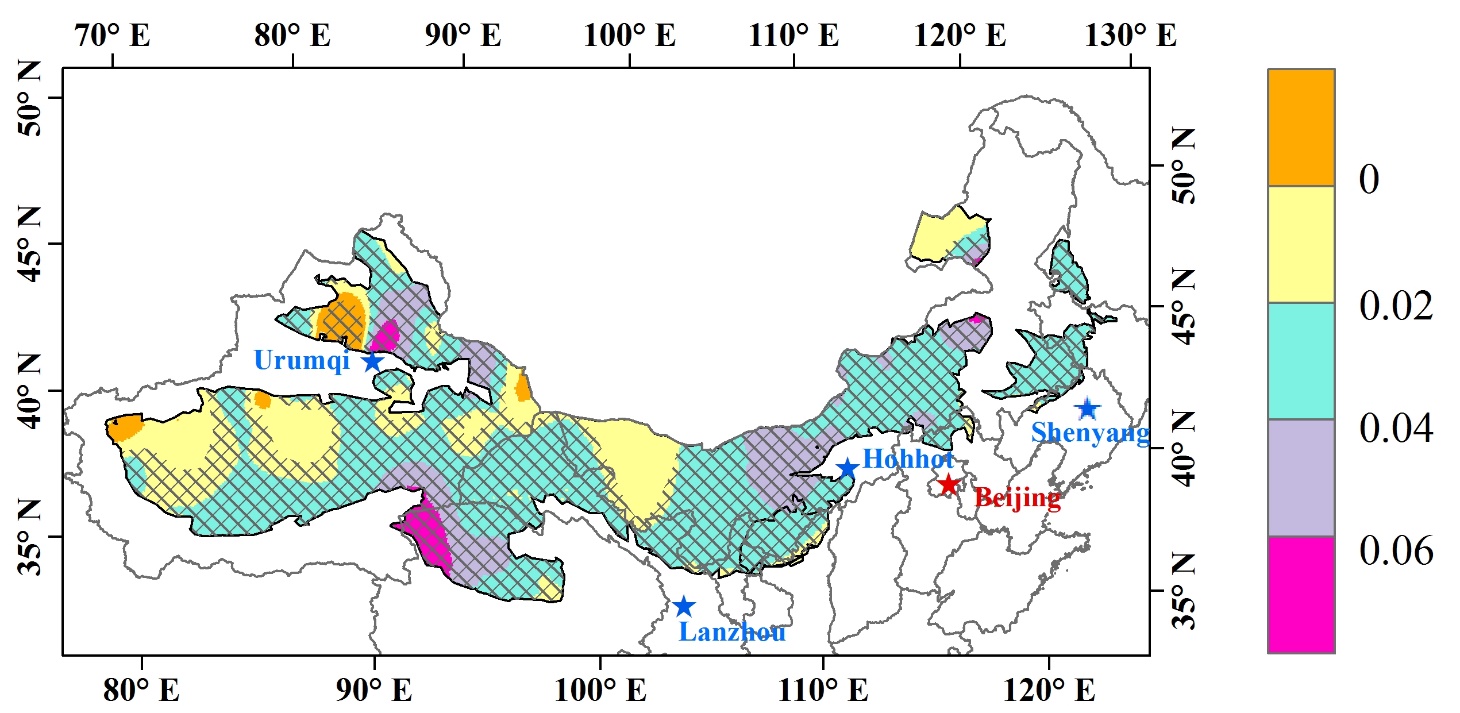
Fig. . Distribution of meteorological stations and major deserts in N China.



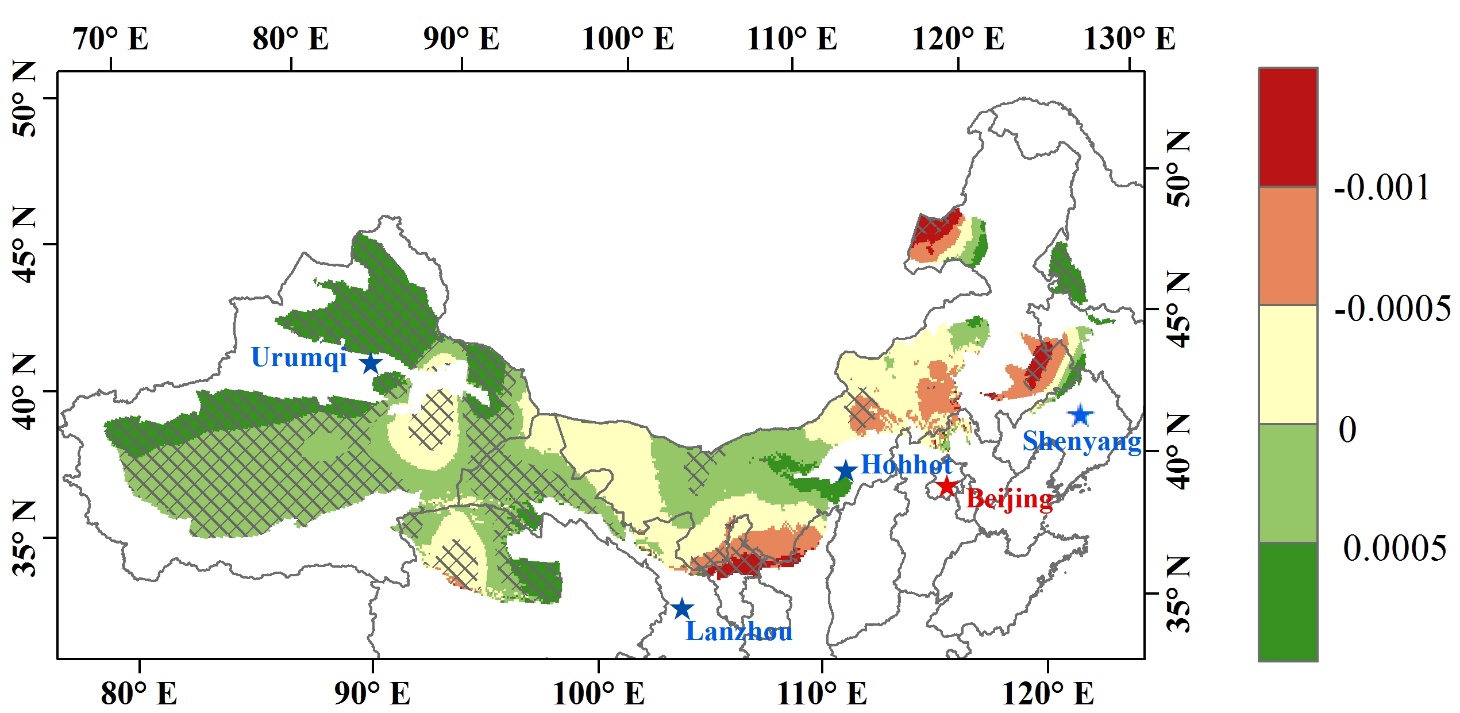
**Fig. 2.** Variation in annual precipitation, mean air temperature, and aridity index from 1961-2013 for the twelve deserts (Fig. 1): (a) Hulun Buir, (b) Horqin, (c) Mu Us, (d) Hobq, (e) Otindag, (f) Badain Jaran, (g) Ulanbuh, (h) Gurbantunggut, (i) Taklimakan, (j) Tengger, (k) Kumtag, and (l) Qaidam Deserts.



**Fig. 3.** Temporal trends in annual precipitation (mm yr-1) over the greater desert belt from 1961-2013 (Fig. 1); trend analysis is based on linear regression. Black crosshatched areas indicate pixels where trends were statistically significant at the critical *p*-value of 0.05.



**Fig. 4.** Temporal trends (1961-2013) in annual mean air temperature (oC yr-1) over the greater desert belt (Fig. 1); trend analysis is based on linear regression. Black crosshatched areas indicate pixels where trends were statistically significant at the critical *p*-value of 0.05.



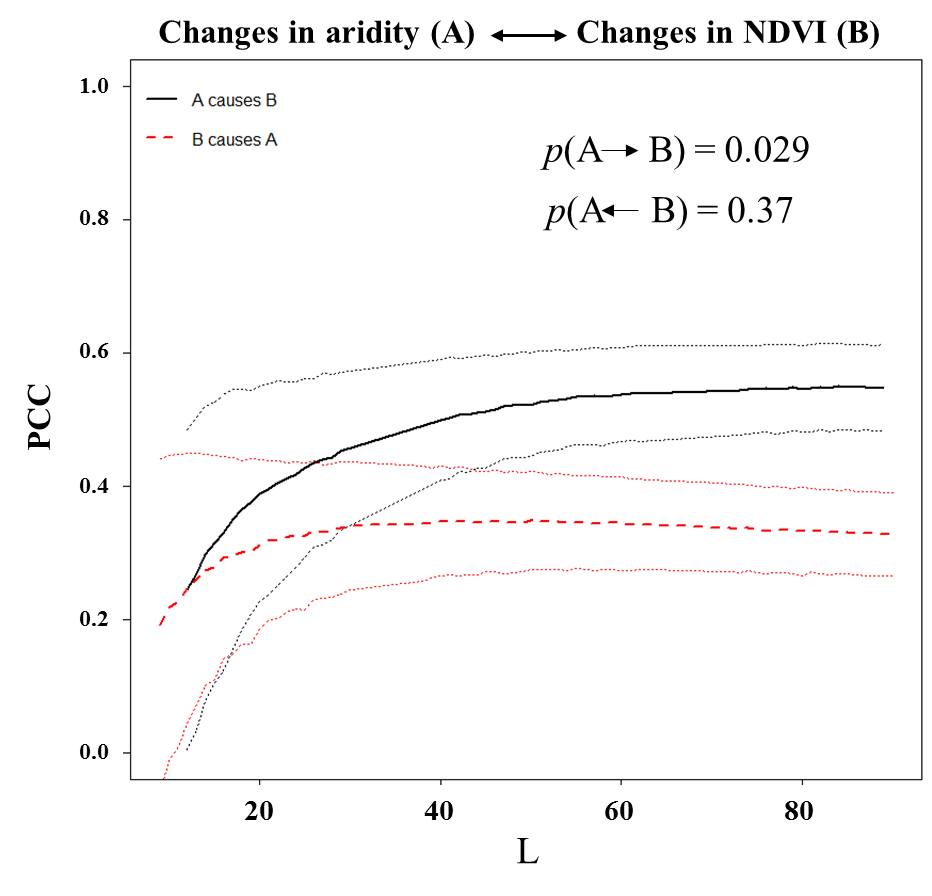
**Fig. 5.** Temporal trends (1961-2013) in annual aridity index (AI) for the greater desert belt (Fig. 1); trend analysis is based on linear regression. Black crosshatched areas indicate pixels where trends were statistically significant at the critical *p*-value of 0.05.



**Fig. 6.** Current NDVI (based on data from 1982-2013) for the greater desert belt of N China. Areas with NDVI < 0.1, appear white.



**Fig. 7.** Temporal trends in annual NDVI (1982-2013) for the greater desert belt (Fig. 1); trend analysis is based on linear regression.



**Fig. 8.** Predictive-skill curves based on Pearson’s correlation coefficients (PCC) for convergent cross mapping (CCM) of aridity and normalized difference vegetation index (AI vs. NDVI) for several random points across the greater desert belt. Dotted lines on both sides of the solid and dashed curves (A causes B, black curve and B causes A, red dashed curve) of predictive skill give the 95% confidence interval estimated from bootstrapping with 5,000 iterations. Cause-and-effect relationship between variables is inferred when convergence is present and PCC at the point of convergence is > 0.0. Analysis is based on an embedded dimension and time delay of 4 and 3, respectively (Sugihara et al., 2012).

**Table**

**Table 1.** Trend analysis based on M-K tests and linear regression for precipitation, temperature, and AI for the

twelve deserts.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Desert** | ***P*** | | ***T*** | | **AI** | |
| **M-K** | **Slope** (mm yr-1) | **M-K** | **Slope**  (mm yr-1) | **M-K** | **Slope**  (yr-1) |
| Hulun Buir | -0.01 | -0.54 | **3.78\*\*** | 0.028 | -0.41 | -0.0008 |
| Horqin | -1.61 | -0.88 | **3.65\*\*** | 0.032 | -0.86 | -0.0005 |
| Otindag | -0.71 | -0.33 | **3.81\*\*** | 0.022 | -0.40 | -0.0002 |
| Hobq | -0.24 | -0.17 | **5.18\*\*** | 0.082 | -0.28 | -0.0003 |
| Mu Us | -0.11 | -0.35 | **2.84\*\*** | 0.025 | -0.15 | -0.0005 |
| Ulanbuh | 0.40 | 0.15 | **2.57\*\*** | 0.013 | 0.41 | 0.0001 |
| Tengger | 0.76 | 0.07 | **4.47\*\*** | 0.047 | -0.26 | -0.000014 |
| Badain Jaran | 0.77 | 0.12 | **4.08\*\*** | 0.044 | 0.68 | 0.00001 |
| Qaidam | 1.03 | 0.13 | **3.66\*\*** | 0.028 | **1.97\*** | 0.0002 |
| Kumtag | 0.84 | 0.05 | **2.91\*\*** | 0.025 | 1.20 | 0.00006 |
| Gurbantunggut | **3.50\*\*** | 1.21 | **4.01\*\*** | 0.036 | **3.54\*\*** | 0.0013 |
| Taklimakan | **1.82**♣ | 0.31 | **4.36\*\*** | 0.039 | **2.14\*** | 0.0003 |

♣ Indicate significance levels of 0.1, \* 0.05; \*\* 0.01.