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Ecological restoration intensifies evapotranspiration in the Kubuqi Desert

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ABSTRACT

Afforestation combats desertification and improves the ecological environment but leads to huge consumption of water resources. Understanding how ecological restoration affects the regional water balance is important for scientific desertification management. Using remote sensing satellite images and meteorological data, we analyzed the impacts of ecological restoration on water resources in the Kubuqi Desert during 1986–2017. Human activities accounted for 60.14% of the desertification reversal: annual average NDVI increased by 94%, the severe desertification area decreased by 30%, and the non-desertification area increased threefold. Vegetation restoration accounted for 70.96% of the evapotranspiration increase of 5.17 mm·yr^{-1}. However, precipitation could not support the increased water demand, which relied on replenishment from groundwater and Yellow River diversion. Therefore, to ensure water security in the Kubuqi, species that use less water should be used in future ecological restoration, and decision-makers should carefully consider the huge water consumption cost of ecological restoration.

1. Introduction

In many regions, desertification is a critical factor leading to the degradation of ecosystems because it leads to erosion of land resources, damages to soil quality, and dust storms, and because it seriously restricts local economic development and human livelihoods (Symeonakis et al., 2016; Guo et al., 2017). Currently, about one-quarter of the global land area, or more than 3.6 × 10^7 km^2, is undergoing desertification. Desertification is therefore regarded as one of the most serious global eco-environmental and socioeconomic issues (Wang et al., 2012). Afforestation is an essential measure to protect soil resources, improve the regional environment, and combat desertification (Lamb et al., 2005; Chazdon, 2008; Cao et al., 2020). To reverse land degradation, many ecological restoration projects have been launched around the world, such as the American Roosevelt Shelterbelt Project, the Green Dam Project of the Five Countries in Northern Africa, and the Great Stalin Plan for the Transformation of Nature. These projects have effectively improved regional ecological environments (Liu et al., 2020). However, such large-scale ecological projects inevitably affect the regional water balance, thereby potentially causing water demand conflicts between ecosystems and socioeconomic systems, which are more intense in water-limited areas (Feng et al., 2016; Zhao et al., 2021). Because of water resources limitations, various ecological problems, including the creation of newly desertified areas, tree death, and reductions of water reserves have arisen in some areas (Bala et al., 2007; Cao, 2008; Wang and Cao, 2011; Xu, 2011). Therefore, the appropriateness of large-scale ecological restoration in arid and semi-arid regions is still a controversial topic (Wang et al., 2010; Zhang et al., 2018; Zhou et al., 2021), and it is imperative to systematically evaluate the effects of ecological restoration, especially in such regions.

Evapotranspiration (ET) is one of the most complex and critical parts of hydrological and energy cycles in terrestrial surface systems. On a global scale, more than 60% of precipitation over land returns to the atmosphere as ET (Jung et al., 2010), and in arid and semi-arid regions, where precipitation is the main source of moisture (Feng et al., 2016), ET can exceed 80% of precipitation (Liu and Yang, 2010). Thus, the dynamics of ET profoundly affects ecosystems and human well-being in arid and semi-arid regions (Zhang et al., 2015). Changes in climate and vegetation covers can alter the proportions of runoff and ET following precipitation, thus affecting the water balance in a region, and studies have confirmed that human activities (e.g., afforestation, deforestation) can greatly increase the uncertainty of water distribution processes.

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Revegetation can increase surface ET, reduce runoff, and decrease soil moisture availability (Duan et al., 2016), thus exacerbating water scarcity in water-limited areas (Feng et al., 2016; Bai et al., 2020; Bentley and Coomes, 2020). Moreover, when precipitation cannot support the water demand by vegetation, excessive consumption of deep soil moisture by planted forests can lead to soil drying and ecological degradation (Cao et al., 2011). However, some studies have also pointed out that vegetation cover, by increasing precipitation, can help to maintain the stability of terrestrial water storage (Branch and Wulfmeyer, 2019). Therefore, analyses of the spatial and temporal patterns of ET as influenced by climate and human activities are important for understanding and predicting the hydrological cycle in arid and semiarid regions, as well as for exploring the complex interactive feedback mechanisms of climate-vegetation-hydrological processes.

The Kubuqi Desert (hereafter, the Kubuqi) is one of the most successful areas of ecological restoration and desertification reversal in China. At the Fifth Kubuqi International Desert Forum, the United Nations Environment Programme (UNEP) and the United Nations Convention to Combat Desertification recommended the successful environmental management experience in the Kubuqi as a model for desertification control (Li, 2015; Wang et al., 2019). The Kubuqi is the seventh largest desert in China and the main source of sand and dust affecting air quality in Inner Mongolia, Beijing, and surrounding areas. Historically, climate change, combined with human activities such as over-cultivation and grazing, has driven the continued desertification in the Kubuqi and surrounding areas (Guo et al., 2017). To improve the ecological environment and reduce desertification, local governments and private companies have launched large-scale ecological restoration projects in the Kubuqi (Wang et al., 2019). For example, large numbers of fast-growing forests, including commercial forests, were planted in the Kubuqi starting in 1988 (Wang et al., 2018), and several ecological projects, such as the Three Norths Shelter Forest Program, the Beijing and Tianjin Sand Source Control Project, and the Grain for Green Project, have been implemented there since 1999 (Feng et al., 2016; Wang et al., 2018; Zhao et al., 2021). All of these activities have contributed to the recovery of vegetation and the reversal of desertification in the region (Liu et al., 2020; Zhao et al., 2021). The total reforestation area had reached 1361 km^2 by 2014 (Elion Resource Company of China, 2016; Wang et al., 2019), and the continued implementation of ecological restoration projects has effectively controlled desertification in the Kubuqi. However, although the ecological restoration of the Kubuqi is a world-renowned achievement, the dynamics of desertification and its quantitative relationships with different drivers (human activities, climate change, etc.) are still poorly understood, and little is known about the impact of large-scale afforestation activities on the water balance in this desert region (Guo et al., 2017). Moreover, whether the experience of ecological restoration in the Kubuqi means that similar projects are suitable for the control of desertification in other arid and semi-arid areas needs to be confirmed by more scientific studies. Given these considerations, a systematic assessment of the actual effects of ecological restoration in the Kubuqi is needed.

Therefore, in this study, we analyzed the spatial and temporal dynamics of vegetation and eco-hydrological processes during the ecological restoration of the Kubuqi from 1986 to 2017, with the aim of addressing two scientific questions: (1) what were the spatial and temporal dynamics of ecological restoration in the Kubuqi? and (2) what were the effects of ecological restoration measures on the regional water balance?

2. Materials and methods

2.1. Study area

The Kubuqi Desert (39°15′–40°45′N and 107°00′–111°30′E), in the southern part of the Hetao Basin on the southern bank of the Yellow River, covers an area of about 1.8×10^4 km^2 at elevations from 1200 to 1400 m and is one of the large deserts near the Loess Plateau, China (Fig. 1). It has a temperate continental climate, during 1969–2018, the annual mean temperature in the region ranges from 5.75 °C to 8.85 °C, and rainfall in the region ranges from 119.6 to 403.2 mm following a west to east trend, with about 80% of the precipitation concentrated in summer (July to September). Soils in the area are mainly arenosol. The dominant plant species in areas of fixed and semi-fixed sand are *Artemisia ordosica*, *Salix psammophila*, and *Caragana korshinskii*. Along the north margin of the Kubuqi along the South bank of the Yellow River, shelter forests combinations such as *Pinus sylvestris*, *Salix matsudana*, *Salix psammophila* and *Elaeagnus angustifolia* L. are used to stabilize shifting sands. Also vegetation such as *C. korshinskii*, *Salix psammophila* and *Glycyrrhiza uralensis* are widely used in the ecological restoration of Kubuqi (UNEP, 2015), which effectively promotes the vegetation cover of Kubuqi.

2.2. Data sources and preprocessing

Landsat images (TM, ETM+, and OLI, 30-m spatial resolution) from 1986 to 2017 (path/row: 127/32, 128/32, 129/32; http://landsat.usgs.gov) were used. Synthesized ET data (1000 - m spatial resolution, https://doi.org/10.7910/DVN/ZGOUED), PLM_V2 ET data (500 - m spatial resolution, https://doi.org/10.1016/j.rse.2018.12.031), MOD16A2 ET data (500 - m spatial resolution, https://doi.org/10.5067/MODIS/MOD16A2.006), SEBAL ET data (1000 - m spatial resolution, https://doi.org/10.5281/zenodo.4243988, https://doi.org/10.5281/zenodo.4896147) and soil moisture data from ERA5_LAND for soil depths of 0–289 cm (0.1 degrees spatial resolution, https://cds.climate.copernicus.eu/) were used. Previous studies have confirmed that the quality of these data are stable (Guo et al., 2017; Deng et al., 2020; Liu et al., 2020; Yu et al., 2020). All of the above data can be downloaded free of charge from the GEE platform.

Google Earth Engine (GEE) is a cloud-based integration platform that can process massive amounts of data online and improve data processing efficiency (Gorelick et al., 2017; Zhou et al., 2021). GEE has already been widely used in various research areas such as land-use change, global surface water change, and crop yield estimation (Hansen et al., 2013; Lobell et al., 2015; Pekel et al., 2016). In this study, we used GEE to calculate the Normalized Difference Vegetation Index (NDVI) and the land surface albedo, after preprocessing (e.g., de-clouding of Landsat data).

2.3. Data analysis

2.3.1. Quantitative assessment of ecological restoration in the Kubuqi from 1986 to 2017

The Desertification Divided Index (DDI) is a multi-dimensional indicator with obvious biophysical characteristics that reflects desertification changes, water energy status, and vegetation cover. Smaller DDI values indicate a lower vegetation cover and higher albedo, which correspond to higher desertification levels. DDI was calculated as follows:

$$DDI = k \times \text{NDVI-Albedo} \tag{1}$$

where Albedo is the land surface albedo, and *k* is the inverse of the slope of a straight line fitted to the NDVI–Albedo relationship. Due to the influence of sensors and imaging time, the same degree of desertification has different DDI values in different periods. Previous studies indicated that DDI values of similar land types show greater similarity, and reclassification of DDI values (*Re-* DDI) using the natural breakpoint (Jenks) classification system is the most stable method to perform desertification time series analysis (Wei et al., 2018; Liu et al., 2020). Therefore, based on *Re*-DDI values, areas of the Kubuqi were classified into five categories: severe desertification, high desertification, moderate desertification, slight desertification, and non-desertification (for

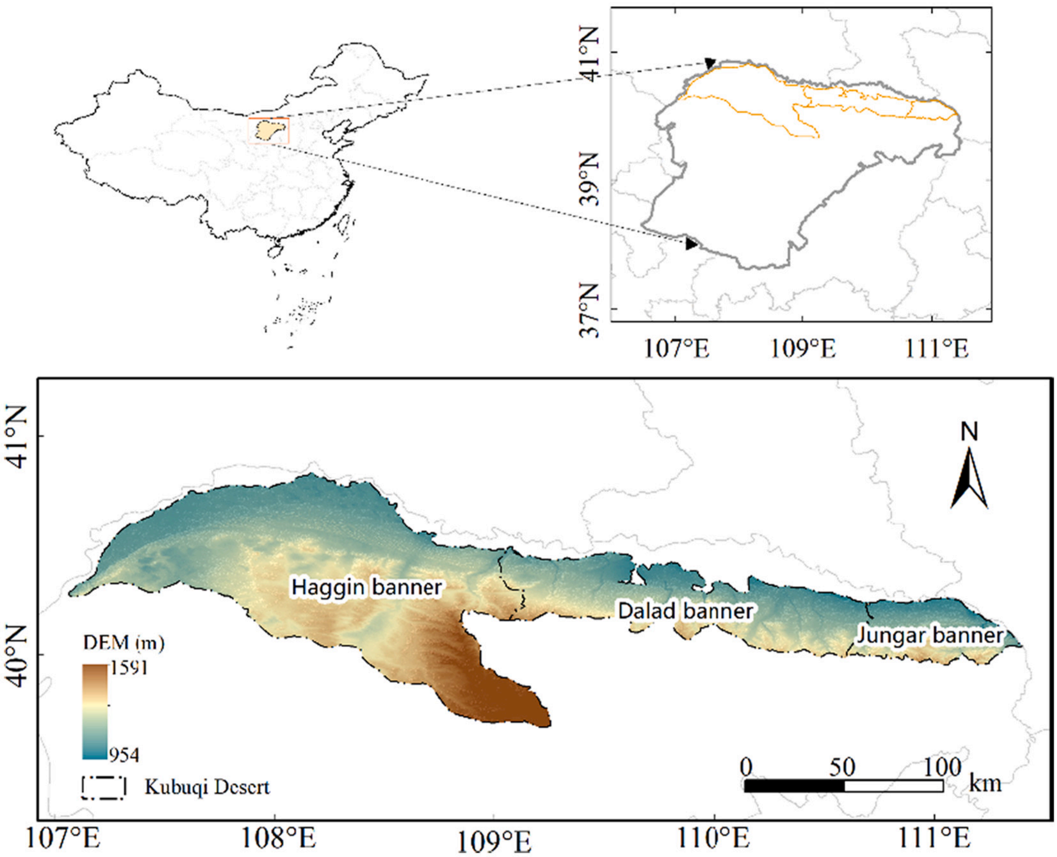

Fig. 1. The geographic location of the study area.

details, see Liu et al., 2020).

NDVI was calculated as follows:

$$NDVI = (NIR - RED)/(NIR + RED) \tag{2}$$

where *NIR* and *RED* are the near-infrared and red bands of the multi-spectral data, respectively.

We calculated Albedo using the following empirical formulas developed for Landsat imagery (Liang, 2001):

$$\text{Albedo}(TM/ETM+) = 0.356\rho_1 + 0.130\rho_3 + 0.373\rho_4 + 0.085\rho_5 + 0.072\rho_7 - 0.0018 \tag{3}$$

$$\text{Albedo}(OLI) = 0.356\rho_2 + 0.130\rho_4 + 0.373\rho_5 + 0.085\rho_6 + 0.072\rho_7 - 0.0018 \tag{4}$$

where ρ_1, ρ_2, ρ_3, ρ_4, ρ_5, ρ_6, and ρ_7 are the spectral reflectances of the corresponding Landsat bands (TM, ETM+, and OLI).

The Desertification Grade Index (DGI), which is also based on the natural breakpoint (Jenks) classification system, was then used to quantify the desertification trend within the whole Kubuqi:

$$DGI = (S_{sl} + 2S_m + 3S_h + 4S_{se})/S_a \tag{5}$$

where S_{sl}, S_m, S_h, and S_{se} are areas of slight, moderate, high, and severe desertification, respectively, within the Kubuqi, and S_a is the total area of the Kubuqi. Thus, the DGI value can range from 0 to 4, with higher values indicating more severe desertification.

2.3.2. Analysis of the factors driving ecological restoration

Climate change and human activities are important drivers that affect vegetation recovery. Growing season precipitation (GP, $P < 0.1$) and average spring temperature (ST, $P < 0.01$), which were significantly correlated with NDVI in the correlation analysis, were selected to represent climate change indicators. Then, partial differential equations were used to quantify the relative contribution of the drivers to ecological restoration. Initially, partial differential equations were initially used widely mainly in hydrological dynamics studies (Yang and Yang, 2012), but later studies suggested that the method also performed well for analysis of the factors driving vegetation restoration (Zhang et al., 2016a). The following partial differential equation was used:

$$\frac{dNDVI}{dt} = \varepsilon_1 \times \left(\frac{dGP}{dt}\right) + \varepsilon_2 \times \left(\frac{dST}{dt}\right) + UF = \left(\frac{\partial NDVI}{\partial GP}\right) \times \left(\frac{dGP}{dt}\right) + \left(\frac{\partial NDVI}{\partial ST}\right) \times \left(\frac{dST}{dt}\right) + UF \tag{6}$$

where t is the total number of years; $\varepsilon_1 \times \left(\frac{dGP}{dt}\right)$ and $\varepsilon_2 \times \left(\frac{dST}{dt}\right)$ represent the relative contribution of growing season precipitation and spring temperature to NDVI, respectively; and *UF* represents the residual contribution, after the contribution of climate factors, to NDVI. Here, *UF* is used to represent the relative contribution of human activities.

2.3.3. Analysis of the factors driving ET

Owing to the small area of cultivated croplands in the area, the impact of irrigated croplands on ET can be neglected; therefore, we attributed the ET dynamics to tree planting and climate change. We used principal component analysis (PCA) and multiple regression analysis to quantify the relative contributions of the drivers of ET change at different grid scales. Because of the strong correlation among climate factors, we used PCA to obtain a comprehensive climate indicator (Bro and Smilde, 2014). The detailed process is as follows: First, correlation analysis was used to identify the climate factors with the highest correlation to ET; in this study, four climate factors were selected (average temperature, spring temperature, growing season precipitation, and autumn precipitation). Second, PCA was used to calculate the composite climate indicators at grid scale. Finally, the composite climate indicator obtained from the PCA for each grid was used in the driving factor analysis to calculate the relative contribution of climate to ET in each grid. In order to extract the maximum important information from the climate factors, the cumulative variance contribution was set to 85% in this study. Generally, an extracted principal component is considered to well reflect the characteristics of all factors when its contribution to the variance is at least 70%; therefore, the composite climate index values obtained can be considered to reflect information on all climate factors. PCA was not required to obtain a composite indicator of human activities because only one indicator (NDVI) of vegetation restoration was used. Its relative contribution at grid scales was calculated as follows:

$$\mathrm{Con}_i = \frac{|SCV_i|}{\sum_1^i \left|SCV_i\right|} \times 100\% \tag{7}$$

where variable *i* is NDVI or composite climate index values in our study, Con_i is the contribution of variable i to ET (%), and $|SCVi|$ is the absolute value of the standard regression coefficient of variable *i*.

2.3.4. Analysis of the water balance in the Kubuqi from 1986 to 2017

The area water dynamics was calculated as follows (Feng et al., 2016):

$$\Delta W = PPT\text{-}ET - (R_{out}\text{-}R_{in})\text{-}\Delta SM\text{-}\Delta RW \tag{8}$$

where PPT, R_{out}, R_{in}, ΔSM, and ΔRW are annual precipitation (mm), outflow, inflow, change in soil moisture, and change in river – reservoir water storage, respectively. $\Delta W > 0$ means that the water supply is sufficient for ecological water consumption, whereas $\Delta W < 0$ means there is a water deficit. Thus, if $\Delta W < 0$, precipitation alone cannot support the ecological water demand and supplementation by groundwater or water diversion is required. Because there are no large reservoirs in the area, ΔRW was set to zero in the calculation. Ten seasonal rivers (known as the "Ten Kongduis") cross the Kubuqi, but their water dynamics have negligible impact on the water balance at whole-desert scale (Yao et al., 2018); therefore, (R_{out} – R_{in}) was also set to zero in the calculation.

Matlab 2020 (https://www.mathworks.com) was used for statistical tests and calculations, and Arcgis 10.7 (http://www.esri.com/software/arcgis) and python were used for figure drawing.

3. Results

3.1. The ecological restoration process in the Kubuqi from 1986 to 2017

The examination of the trend and trend significance of the NDVI time series at grid scales across the whole desert from 1986 to 2017 (Fig. 2c, d) indicated that most of the Kubuqi (94.71%) experienced an obvious greening trend (i.e., an NDVI increase), and 76.83% of the greened area became significantly green. On whole-desert scale, the annual NDVI time series increased by 94% from 1986 to 2017 to 0.12, at a rate, obtained by fitting a linear regression model to the time series, of 0.004 yr^{-1}. The degree of greening was spatially heterogeneous; it tended to be high in the east and low in the northwest. We quantified the contribution of human activities and climate change to vegetation greening (NDVI increase) (see materials and methods), and the results indicate that human activities were the main driving factor for NDVI increase (60.14%).

The DGI and classified DDI results indicated that desertification in the Kubuqi was gradually reversed from 1986 to 2017, and the DDI spatial pattern was generally consistent with the NDVI pattern (Figs. 2a, b, 3). Overall, the change in DGI showed a fluctuating downward trend at a rate of 0.0156 yr^{-1}, with a significant 30% decrease in the severe desertification area and a significant threefold increase in the non-desertified area. The relative areas of moderate and slight

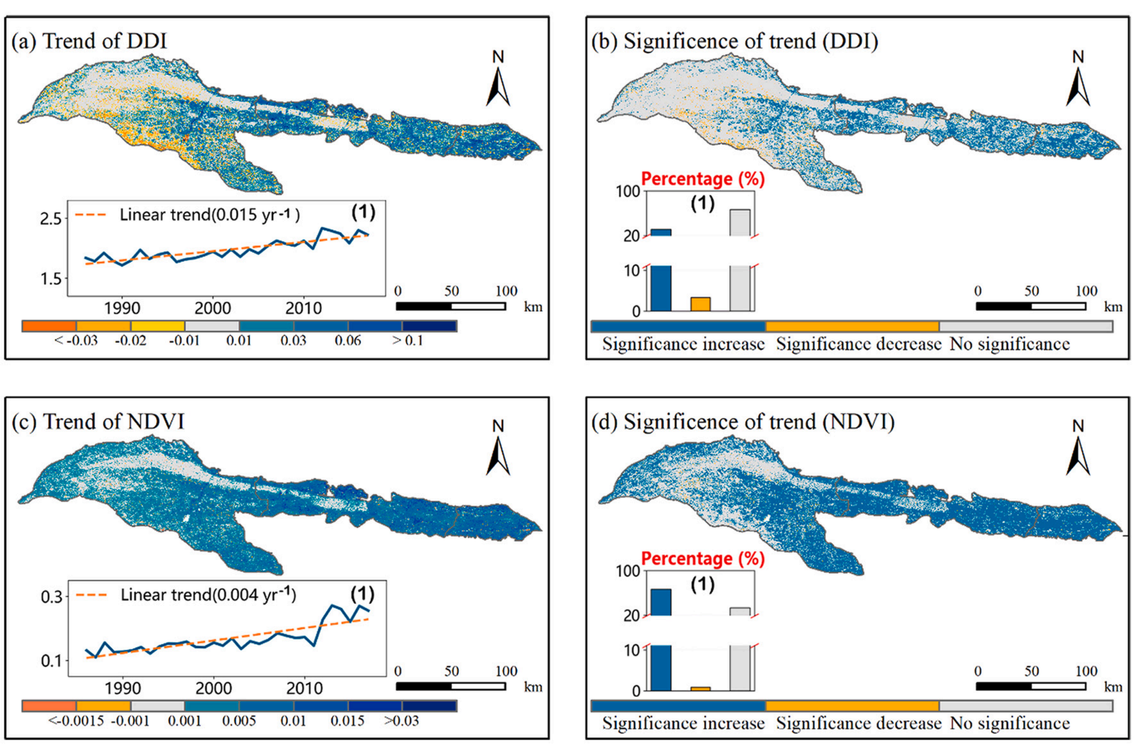

Fig. 2. The linear trend (a, c) and the significance test (b, d) for annual (1986–2017) *Re*-DDI and NDVI; the trend of mean annual Re-DDI and NDVI (a-1, c-1); the percentage of significance test (b-1, d-1). The Mann-Kendall test was used to test the significance of the trend at the 5% significance level ($P < 0.05$).

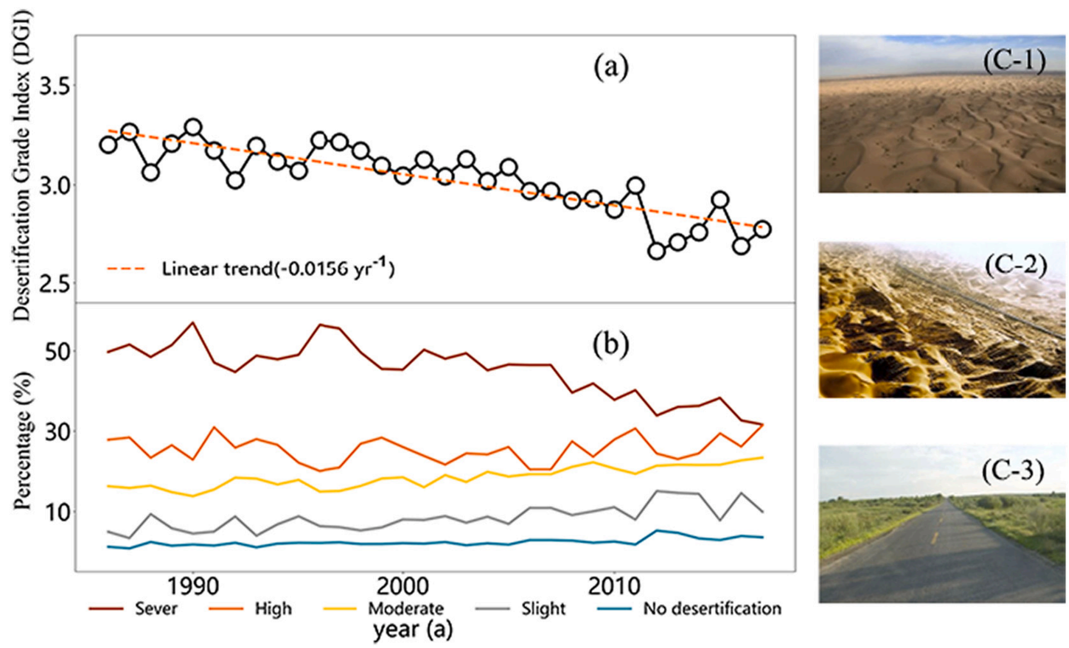

Fig. 3. The trend in desertification (a), the proportion of desertification area within each grade (b), and the transition of ecological restoration processes (c-1, 2, 3; according to (UNEP, 2015)):1988 (original state), 1990s (Ecological restoration by shelterbelt and chequerboard plantation), and 2012 (green stable state) in the Kubuqi desert. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

desertification increased, whereas the relative area of high desertification fluctuated, but less than the severe desertification area.

3.2. *Ecological restoration impacts on the water balance in the Kubuqi*

In the Kubuqi, ecological restoration has driven a reversal of desertification but has also greatly increased the ecological water demand: 95% of the total area of the desert showed a significant increase in ET. Overall, ET increased at a rate of 5.17 mm·yr^{-1} from 1986 to 2017 (Fig. 4a). However, it is worth noting that the change in ET over the 32 years was not continuous. When the start of the ecological policy in 1999, ET increased significantly and reached a first peak in 2003. During 2000–2017, mean ET increased by 91.91 mm compared to the mean value during 1988–1999 (101.49 mm), and the spatial distribution of ET trends was similar to that of NDVI.

In contrast to the obvious changes in ET, the overall changes in annual mean precipitation and soil moisture in the Kubuqi during 1986–2017 were not significant (Fig. 4c–1, 4e–1). Precipitation showed a slight increasing linear trend of 0.80 mm/ yr, and soil moisture showed a slight decreasing linear trend of −0.0187% yr^{-1}. These results imply that the significant increase in ET was at the cost of groundwater depletion.

We quantified the relative contributions of NDVI and climate change to ET, and the results indicated that NDVI was the dominant driver of ET dynamics in the desert scale (contribution 70.96%) (Fig. 5). Further analysis revealed that in areas where NDVI showed no significant chang, the contribution of NDVI to ET was only 33.46%, while the contribution increased to 69.00% in vegetation restoration areas.

To clarify the impact of the increase in ET on groundwater resources, we used the water balance eq. (8) to quantify the area water dynamics. The results indicated that, in general, ΔW showed a significant decreasing trend (-8.8×10^7 m^3 yr^{-1}), and water depletion was first observed in the area in 2005 and tended to gradually increase thereafter (Fig. 6). The annual water deficit was 9.2×10^8 m^3, 4.1×10^6 m^3, and 3.6×10^8 m in 2005, 2011, and 2014, respectively. These results indicate that precipitation alone was insufficient to satisfy the huge ecological water demand of the whole desert, and additional depletion of groundwater and ecological water diversion was required to maintain the ecological restoration achievements.

4. Discussion

4.1. *Ecological restoration projects were the dominant factor in the ecological restoration of the Kubuqi*

Ecological restoration projects played an integral role in vegetation recovery and ecosystem restoration of the Kubuqi. Afforestation during 1986–2017 significantly increased the greenness of the Kubuqi, a result consistent with the findings of Yu et al. (2020). Our quantification of the contributions of climate change and human activities to NDVI indicated that human activities accounted for 60.14% of the vegetation dynamics, making them the dominant factor in vegetation recovery in the Kubuqi. This result could be anticipated because previous studies have reported that human activities (especially ecological policies) play a non-negligible role in vegetation dynamics, particularly in China (Chen et al., 2019; Zhang et al., 2016b; Zhou et al., 2021). The Chinese government has made large financial investments in ecological restoration projects over the past 30 years (Guo et al., 2017), and billions of trees have been planted to drive the greening trend in China (Piao et al., 2015; Chen et al., 2019). The Kubuqi is a priority area for implementing ecological restoration projects, and a series of such projects were launched in succession: the Return of Cultivated Land to Forests Project in 1999, the Beijing and the Tianjin Sand Source Control Project in 2002, and the Grain for Green Project in 2003. Consistent with the results of our study, these ecological restoration project have profoundly affected vegetation restoration in the Kubuqi (Guo et al., 2017). In contrast, climate change has played a smaller role in vegetation restoration (Zhou et al., 2021), and the impacts of climate factors have strong spatial and temporal heterogeneity. In the Kubuqi, moreover, temperature and precipitation showed only small changes during 1986–2017. Therefore, the long-term trends of climate elements could not sufficiently explain the dynamic ecological restoration processes in the Kubuqi (Guo et al., 2017).

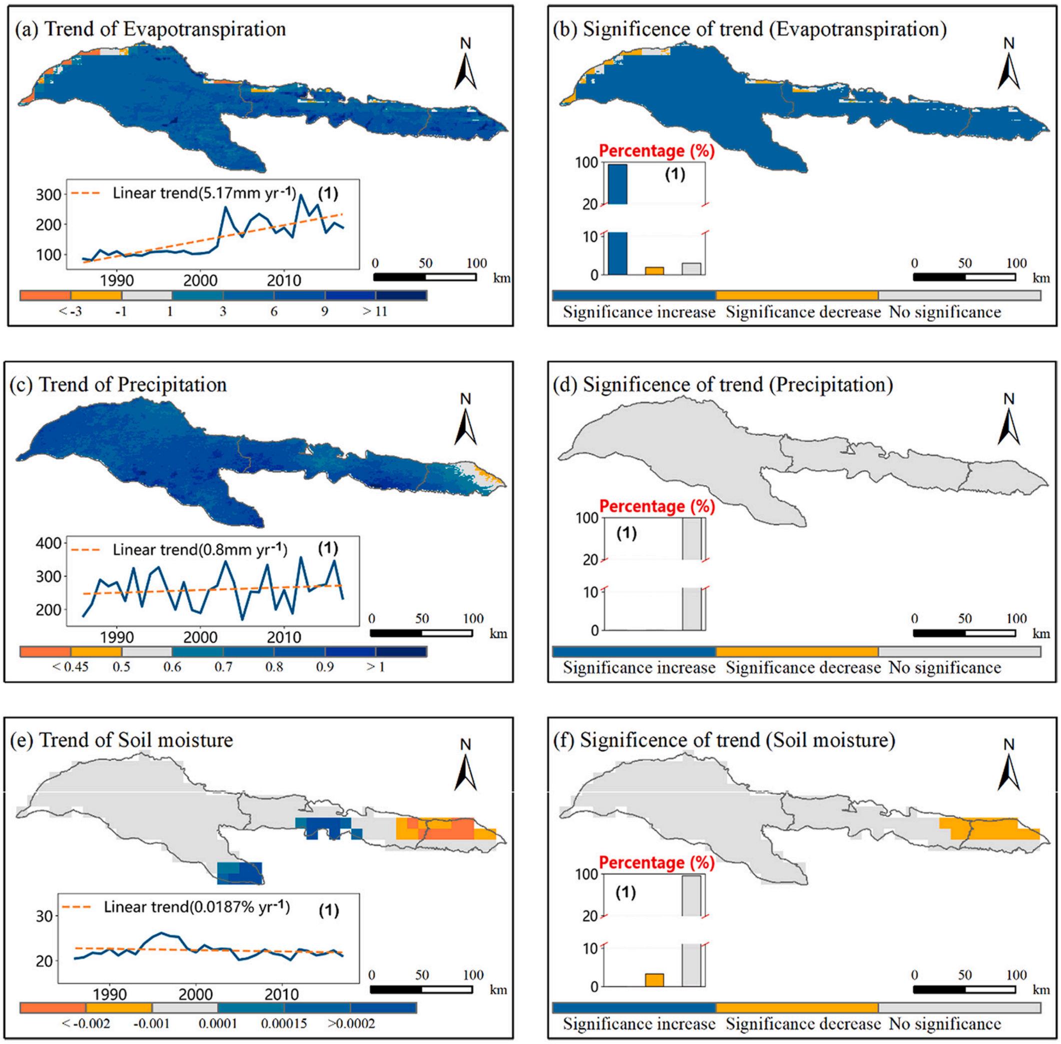

Fig. 4. The linear trend (a, c, e) and the significance test (b, d, f) for annual (1986–2017) ET, PPT, and SM; the trend of mean annual ET, PPT, and SM (a-1, c-1, e-1); the percentage of significance test (b-1, d-1, f-1). The Mann-Kendall test was used to test the significance of the trend at the 5% significance level ($P < 0.05$).

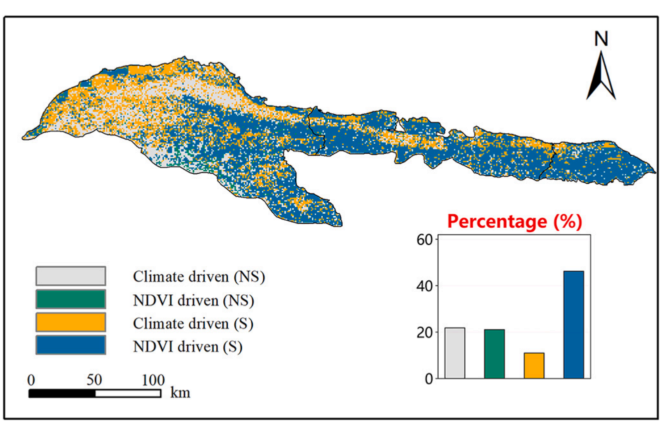

Fig. 5. The relative roles of NDVI and climate on ET dynamics for 1986–2017; NS and S indicate no significant change and significant change in NDVI, respectively.

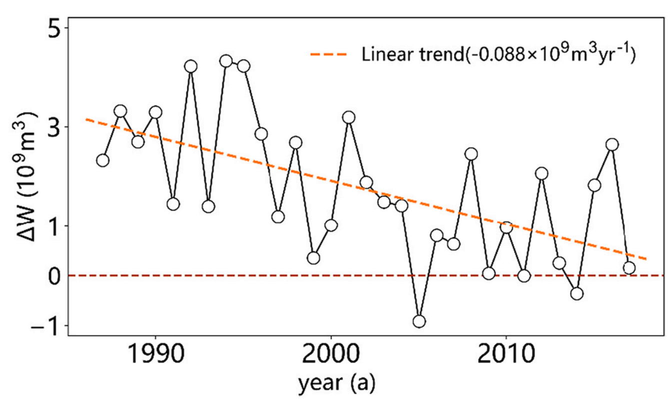

Fig. 6. Water balance characteristics in Kubuqi desert (1986–2017).

4.2. Ecological restoration was the dominant factor in ET dynamics

During 1986–1999, ET showed a relatively gentle trend in the Kubuqi, but after the implementation of the ecological restoration project, ET increased significantly and reached a first peak in 2003. This result is consistent with the ET dynamics in the Loess Plateau region reported by Jin et al. (2017) When we quantified the relative contributions of vegetation and climate change to ET dynamics, we found that NDVI was the dominant factor driving ET dynamics (contribution 70.96%). Further, in areas where NDVI showed no significant change, it accounted only for 33.43% of the ET change, whereas it accounted for as much as 69.00% of the ET change in vegetation restoration areas (Fig. 5). This result indicates that vegetation restoration was the dominant factor in the ET dynamics, and that huge water consumption during ecological restoration means that vegetation restoration probably exacerbates water allocation conflicts in the Kubuqi. In past decades, people have feared that large-scale tree planting would lead to water shortages (Jin et al., 2017), and, unfortunately, negative effects (death or poor growth of trees) of afforestation have already been observed in some parts of northern China (Zhang et al., 2018; Cao et al., 2021). For example, afforestation in the Loess Plateau has increased soil desiccation (Chen et al., 2008; Wang et al., 2010) and has caused the flow of many rivers to decrease (Wang et al., 2016). Therefore, the water-carrying capacity of water-limited areas should be carefully considered in the planning and implementation of ecological restoration projects; for example, trees that require more water should be replaced as far as possible with native vegetation or shrubs that require less water (Feng et al., 2016; Jia et al., 2017). Admittedly, ET products based on different theories probably have some differences in the value and trend (Nagler et al., 2005; Anderson et al., 2007; Senay et al., 2013), which may have some influence on our results. Therefore, we compared four different ET datasets, and found that Synthesized dataset (used in this study) has the longest time series, which is beneficial for researching the dynamic characteristics of ET at long time scales. In addition, the ET of Synthesized dataset is between PML_V2 and MOD16A2, which is closer to their means, and the ET of each dataset showed the same dynamic trend in the Kubuqi, which confirmed the reliability of our findings (Fig. S1).

4.3. The limits of the Kubuqi ecological restoration model

Currently, the role of vegetation in water conservation in dryland areas is controversial (Ma et al., 2013; Cao et al., 2020; Zhang and Wei, 2021). Vegetation can increase surface roughness, improve soil porosity and hydraulic conductivity, and promote an increased soil water content (Ilstedt et al., 2007; Jia et al., 2017), but the fact that continuous greening is at the expense of water consumption cannot be ignored (Zhao et al., 2021). Water consumption by the fast-growing species commonly used for afforestation is often huge, and their roots often penetrate deeper than those of native vegetation. Thus, when water depletion is excessive, the groundwater table may fall to a depth not reached by the roots of native vegetation, thereby seriously reducing water security locally (Wang and Cao, 2011; Xu, 2011; Cao et al., 2020). In our results, soil moisture showed a decreasing trend in the Kubuqi during 1986–2017, and water deficits have occurred intermittently since 2005. Thus, increased infiltration of precipitation was offset by depletion of groundwater by vegetation (Bai et al., 2019), and this water depletion tended to increase gradually during 1986–2017. Therefore, precipitation alone cannot support the huge ecological water demand of the Kubuqi, and additional depletion of groundwater and water diversion will be required to maintain the current ecological restoration achievements (Guo et al., 2017; Zhang et al., 2017). Although groundwater storage in the Kubuqi is abundant, groundwater levels have in fact been declining in recent decades (Guo et al., 2017). Importantly, continuous replenishment from the Yellow River and abundant groundwater can explain the successful ecological restoration in the Kubuqi, compared with other drylands and desert areas where such superior water resources may not be available. Therefore, directly replicating the ecological restoration model of the Kubuqi in such areas may be too aggressive, and potentially have worrisome results.

5. Conclusions

We investigated ecological restoration and its effects on the regional water balance in the Kubuqi Desert during 1986–2017. The results showed that ~77% of the area of the Kubuqi Desert experienced significant greening, and NDVI increased at a rate of 0.004 /yr. The main driving factor for the reversal of desertification was human activities (contribution 60.14%). With ecological restoration, the water demand of vegetation increased significantly, and ET increased at a rate of 5.17 mm/yr; this increase in vegetation was the main contributor to the significant increase in interannual ET variations in the Kubuqi (70.96%). We discovered that precipitation cannot support the huge water consumption demands of ecological restoration; therefore, maintenance of the ecological restoration results depends on additional replenishment from groundwater and the Yellow River. For this reason, it is important to closely monitor groundwater conditions and tree survival rates, and to plant trees that consume relatively little water. Further, planners and decision-makers, learning from the experience of ecological restoration in the Kubuqi, must carefully consider the high cost of huge water consumption to develop reasonable and sustainable ecological restoration projects.

CRediT authorship contribution statement

Peng Chen: Conceptualization, Methodology, Formal analysis, Writing - original draft. **Shuai Wang:** Conceptualization, Funding acquisition, Supervision, Writing - review & editing. **Shuang Song:** Conceptualization, Methodology. **Yijia Wang:** Conceptualization, Methodology. **Yaping Wang:** Methodology, Data curation. **Dexin Gao:** Methodology. **Zidong Li:** Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoleng.2021.106504.

References

Anderson, M.C., Norman, J.M., Mecikalski, J.R., Otkin, J.A., Kustas, W.P., 2007. A climatological study of evapotranspiration and moisture stress across the continental United States based on thermal remote sensing: 1. Model formulation. J. Geophys. Res.-Atmos. 112. https://doi.org/10.1029/2006JD007506.

Bai, M., Mo, X., Liu, S., Hu, S., 2019. Contributions of climate change and vegetation greening to evapotranspiration trend in a typical hilly-gully basin on the Loess Plateau, China. Sci. Total Environ. 657, 325–339. https://doi.org/10.1016/j.scitotenv.2018.11.360.

Bai, P., Liu, X., Zhang, Y., Liu, C., 2020. Assessing the impacts of vegetation greenness change on evapotranspiration and water yield in China. Water Resour. Res. 56 https://doi.org/10.1029/2019WR027019 e2019WR027019.

Bala, G., Caldeira, K., Wickett, M., Phillips, T.J., Lobell, D.B., Delire, C., Mirin, A., 2007. Combined climate and carbon-cycle effects of large-scale deforestation. Proc. Natl. Acad. Sci. 104, 6550–6555. https://doi.org/10.1073/pnas.0608998104. National Academy of Sciences.

Bentley, L., Coomes, D.A., 2020. Partial river flow recovery with forest age is rare in the decades following establishment. Glob. Chang. Biol. 26, 1458–1473. https://doi.org/10.1111/gcb.14954.

Branch, O., Wulfmeyer, V., 2019. Deliberate enhancement of rainfall using desert plantations. Proc. Natl. Acad. Sci. 116, 18841–18847. https://doi.org/10.1073/pnas.1904754116. National Academy of Sciences.

Bro, R., Smilde, A.K., 2014. Principal component analysis. Anal. Methods 6, 2812–2831. https://doi.org/10.1002/9781119674757.ch11. The Royal Society of Chemistry.

Cao, S., 2008. Why large-scale afforestation efforts in China have failed to Solve the desertification problem. Environ. Sci. Technol. 42, 1826–1831. https://doi.org/10.1021/es0870597. American Chemical Society.

Cao, S., Chen, L., Shankman, D., Wang, C., Wang, X., Zhang, H., 2011. Excessive reliance on afforestation in China's arid and semi-arid regions: Lessons in ecological restoration. Earth Sci. Rev. 104, 240–245. https://doi.org/10.1016/j.earscirev.2010.11.002.

Cao, S., Suo, X., Xia, C., 2020. Payoff from afforestation under the Three-North Shelter Forest program. J. Clean. Prod. 256, 120461 https://doi.org/10.1016/j.jclepro.2020.120461.

Cao, S., Liu, Z., Li, W., Xian, J., 2021. Balancing ecological conservation with socioeconomic development. Ambio. https://doi.org/10.1007/s13280-020-01448-z.

Chazdon, R.L., 2008. Beyond deforestation: restoring forests and ecosystem services on degraded lands. Science 320, 1458–1460. https://doi.org/10.1126/science.1155365. American Association for the Advancement of Science.

Chen, H., Shao, M., Li, Y., 2008. Soil desiccation in the Loess Plateau of China. Geoderma 143, 91–100. https://doi.org/10.1016/j.geoderma.2007.10.013.

Chen, C., Park, T., Wang, X., Piao, S., Xu, B., Chaturvedi, R.K., Fuchs, R., Brovkin, V., et al., 2019. China and India lead in greening of the world through land-use management. Nat. Sustain. 2, 122–129. https://doi.org/10.1038/s41893-019-0220-7. Nature Publishing Group.

Deng, Y., Wang, S., Bai, X., Luo, G., Wu, L., Chen, F., Wang, J., Li, C., et al., 2020. Vegetation greening intensified soil drying in some semi-arid and arid areas of the world. Agric. For. Meteorol. 292–293, 108103 https://doi.org/10.1016/j.agrformet.2020.108103.

Duan, L., Huang, M., Zhang, L., 2016. Differences in hydrological responses for different vegetation types on a steep slope on the Loess Plateau, China. J. Hydrol. 537, 356–366. https://doi.org/10.1016/j.jhydrol.2016.03.057.

Elion Resource Company of China., 2016. Personal Communication.

Feng, X., Fu, B., Piao, S., Wang, S., Ciais, P., Zeng, Z., Lü, Y., Zeng, Y., et al., 2016. Revegetation in China's Loess Plateau is approaching sustainable water resource limits. Nat. Clim. Chang. 6, 1019–1022. https://doi.org/10.1038/NCLIMATE3092. Nature Publishing Group.

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., Moore, R., 2017. Google Earth Engine: Planetary-scale geospatial analysis for everyone. Remote Sens. Environ. 202, 18–27. https://doi.org/10.1016/j.rse.2017.06.031. Big Remotely Sensed Data: Tools, Applications and Experiences.

Guo, Q., Fu, B., Shi, P., Cudahy, T., Zhang, J., Xu, H., 2017. Satellite monitoring the spatial-temporal dynamics of desertification in response to climate change and human activities across the Ordos Plateau, China. Remote Sens. 9, 525. https://doi.org/10.3390/rs9060525. Multidisciplinary Digital Publishing Institute.

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., et al., 2013. High-resolution global maps of 21st-century forest cover change. Science 342, 850–853. https://doi.org/10.1126/science.1244693. American Association for the Advancement of Science.

Ilstedt, U., Malmer, A., Verbeeten, E., Murdiyarso, D., 2007. The effect of afforestation on water infiltration in the tropics: a systematic review and meta-analysis. For. Ecol. Manag. 251, 45–51. https://doi.org/10.1016/j.foreco.2007.06.014. Planted Forests and Water.

Jia, X., Shao, M., Zhu, Y., Luo, Y., 2017. Soil moisture decline due to afforestation across the Loess Plateau, China. J. Hydrol. 546, 113–122. https://doi.org/10.1016/j.jhydrol.2017.01.011.

Jin, Z., Liang, W., Yang, Y., Zhang, W., Yan, J., Chen, X., Li, S., Mo, X., 2017. Separating vegetation greening and climate change controls on evapotranspiration trend over the Loess Plateau. Sci. Rep. 7, 8191. https://doi.org/10.1038/s41598-017-08477-x. Nature Publishing Group.

Jung, M., Reichstein, M., Ciais, P., Seneviratne, S.I., Sheffield, J., Goulden, M.L., Bonan, G., Cescatti, A., et al., 2010. Recent decline in the global land evapotranspiration trend due to limited moisture supply. Nature 467, 951–954. https://doi.org/10.1038/nature09396. Nature Publishing Group.

Lamb, D., Erskine, P.D., Parrotta, J.A., 2005. Restoration of degraded tropical forest landscapes. Science 310, 1628–1632. https://doi.org/10.1126/science.1111773. American Association for the Advancement of Science.

Li, W., 2015. Building Consensus Kubuqi International Desert Forum. China Today 9, 47–49.

Liang, S., 2001. Narrowband to broadband conversions of land surface albedo I: Algorithms. Remote Sens. Environ. 76, 213–238. https://doi.org/10.1016/S0034-4257(00)00205-4.

Liu, Q., Yang, Z., 2010. Quantitative estimation of the impact of climate change on actual evapotranspiration in the Yellow River Basin, China. J. Hydrol. 395, 226–234. https://doi.org/10.1016/j.jhydrol.2010.10.031.

Liu, Q., Zhang, Q., Yan, Y., Zhang, X., Niu, J., Svenning, J.-C., 2020. Ecological restoration is the dominant driver of the recent reversal of desertification in the Mu Us Desert (China). J. Clean. Prod. 268, 122241 https://doi.org/10.1016/j.jclepro.2020.122241.

Lobell, D.B., Thau, D., Seifert, C., Engle, E., Little, B., 2015. A scalable satellite-based crop yield mapper. Remote Sens. Environ. 164, 324–333. https://doi.org/10.1016/j.rse.2015.04.021.

Ma, H., Lv, Y., Li, H., 2013. Complexity of ecological restoration in China. Ecol. Eng. 52, 75–78. https://doi.org/10.1016/j.ecoleng.2012.12.093.

Nagler, P.L., Cleverly, J., Glenn, E., Lampkin, D., Huete, A., Wan, Z., 2005. Predicting riparian evapotranspiration from MODIS vegetation indices and meteorological data. Remote Sens. Environ. 94, 17–30. https://doi.org/10.1016/j.rse.2004.08.009.

Pekel, J.-F., Cottam, A., Gorelick, N., Belward, A.S., 2016. High-resolution mapping of global surface water and its long-term changes. Nature 540, 418–422. https://doi.org/10.1038/nature20584. Nature Publishing Group.

Piao, S., Yin, G., Tan, J., Cheng, L., Huang, M., Li, Y., Liu, R., Mao, J., et al., 2015. Detection and attribution of vegetation greening trend in China over the last 30 years. Glob. Chang. Biol. 21, 1601–1609. https://doi.org/10.1111/gcb.12795.

Senay, G.B., Bohms, S., Singh, R.K., Gowda, P.H., Velpuri, N.M., Alemu, H., Verdin, J.P., 2013. Operational Evapotranspiration Mapping using Remote Sensing and Weather Datasets: a New Parameterization for the SSEB Approach. JAWRA J. Am. W. Resour. Assoc. 49, 577–591. https://doi.org/10.1111/jawr.12057.

Symeonakis, E., Karathanasis, N., Koukoulas, S., Panagopoulos, G., 2016. Monitoring Sensitivity to Land Degradation and Desertification with the Environmentally Sensitive Area Index: The Case of Lesvos Island.

UNEP, 2015. Review of the Kubuqi Ecological Restoration Project: A Desert Green Economy Pilot Initiative. United Nations Environment Programme (UNEP).

Wang, Y., Cao, S., 2011. Carbon Sequestration May have negative Impacts on Ecosystem Health. Environ. Sci. Technol. 45, 1759–1760. https://doi.org/10.1021/es200042s. American Chemical Society.

Wang, X.M., Zhang, C.X., Hasi, E., Dong, Z.B., 2010. Has the three Norths Forest Shelterbelt Program solved the desertification and dust storm problems in arid and semiarid China? J. Arid Environ. 74, 13–22. https://doi.org/10.1016/j.jaridenv.2009.08.001.

Wang, T., Yan, C.Z., Song, X., Xie, J.L., 2012. Monitoring recent trends in the area of aeolian desertified land using Landsat images in China's Xinjiang region. ISPRS J. Photogramm. Remote Sens. 68, 184–190. https://doi.org/10.1016/j.isprsjprs.2012.01.001.

Wang, S., Fu, B., Piao, S., Lü, Y., Ciais, P., Feng, X., Wang, Y., 2016. Reduced sediment transport in the Yellow River due to anthropogenic changes. Nat. Geosci. 9, 38–41. https://doi.org/10.1038/ngeo2602. Nature Publishing Group.

Wang, L., Lee, X., Schultz, N., Chen, S., Wei, Z., Fu, C., Gao, Y., Yang, Y., et al., 2018. Response of Surface Temperature to Afforestation in the Kubuqi Desert, Inner Mongolia. J. Geophys. Res.-Atmos. 123, 948–964. https://doi.org/10.1002/2017jd027522.

Wang, L., Lee, X., Feng, D., Fu, C., Wei, Z., Yang, Y., Yin, Y., Luo, Y., et al., 2019. Impact of large-scale afforestation on surface temperature: a case study in the Kubuqi Desert, inner mongolia based on the WRF model. Forests 10, 368. https://doi.org/10.3390/f10050368. Multidisciplinary Digital Publishing Institute.

Wei, H., Wang, J., Cheng, K., Li, G., Ochir, A., Davaasuren, D., Chonokhuu, S., 2018. Desertification information extraction based on feature space combinations on the Mongolian Plateau. Remote Sens. 10, 1614. https://doi.org/10.3390/rs10101614. Multidisciplinary Digital Publishing Institute.

Xu, J., 2011. China's new forests aren't as green as they seem. Nature 477, 371. https://doi.org/10.1038/477371a.

Yang, H., Yang, D., 2012. Climatic factors influencing changing pan evaporation across China from 1961 to 2001. J. Hydrol. 414–415, 184–193. https://doi.org/10.1016/j.jhydrol.2011.10.043.

Yao, H., Shi, C., Gu, Z., 2018. Impacts of climate change and human activities on water discharge and sediment load of ten tributaries (the Ten Kongduis) of the upper Yellow River. Arid Land Geogr. 41, 472–479.

Yu, X., Zhuo, Y., Liu, H., Wang, Q., Wen, L., Li, Z., Liang, C., Wang, L., 2020. Degree of desertification based on normalized landscape index of sandy lands in inner Mongolia. China Glob. Ecol. Conserv. 23, e01132 https://doi.org/10.1016/j.gecco.2020.e01132.

Zhang, M., Wei, X., 2021. Deforestation, forestation, and water supply. Science 371, 990–991. https://doi.org/10.1126/science.abe7821. American Association for the Advancement of Science.

Zhang, K., Kimball, J.S., Nemani, R.R., Running, S.W., Hong, Y., Gourley, J.J., Yu, Z., 2015. Vegetation greening and climate change promote multidecadal rises of global land evapotranspiration. Sci. Rep. 5, 15956. https://doi.org/10.1038/srep15956. Nature Publishing Group.

Zhang, Yao, Peng, C., Li, W., Tian, L., Zhu, Q., Chen, H., Fang, X., Zhang, G., et al., 2016a. Multiple afforestation programs accelerate the greenness in the 'three North' region of China from 1982 to 2013. Ecol. Indic. 61, 404–412. https://doi.org/10.1016/j.ecolind.2015.09.041.

Zhang, Ying, Zhang, C., Wang, Z., Chen, Y., Gang, C., An, R., Li, J., 2016b. Vegetation dynamics and its driving forces from climate change and human activities in the Three-River Source Region, China from 1982 to 2012. Sci. Total Environ. 563–564, 210–220. https://doi.org/10.1016/j.scitotenv.2016.03.223.

Zhang, J., Ding, Z., Luo, M., 2017. Risk analysis of water scarcity in artificial woodlands of semi-arid and arid China. Land Use Policy 63, 324–330. https://doi.org/10.1016/j.landusepol.2017.02.008.

Zhang, S., Yang, D., Yang, Y., Piao, S., Yang, H., Lei, H., Fu, B., 2018. Excessive Afforestation and Soil Drying on China's Loess Plateau. J. Geophys. Res. Biogeosci. 123, 923–935. https://doi.org/10.1002/2017JG004038.

Zhao, M., Zhang, J., Velicogna, I., Liang, C., Li, Z., 2021. Ecological restoration impact on total terrestrial water storage. Nat. Sustain. 4, 56–62. https://doi.org/10.1038/s41893-020-00600-7. Nature Publishing Group.

Zhou, Y., Fu, D., Lu, C., Xu, X., Tang, Q., 2021. Positive effects of ecological restoration policies on the vegetation dynamics in a typical ecologically vulnerable area of China. Ecol. Eng. 159, 106087 https://doi.org/10.1016/j.ecoleng.2020.106087.