Ecological Restoration and Its Effects on a Regional Climate: The Source Region of the Yellow River, China

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ABSTRACT: The source region of the Yellow River, China, experienced degradation during the 1980s and 1990s, but effective ecological restoration projects have restored the alpine grassland ecosystem. The local government has taken action to restore the grassland area since 1996. Remote sensing monitoring results show an initial restoration of this alpine grassland ecosystem with the structural transformation of land cover from 2000 to 2009 as low- and high-coverage grassland recovered. From 2000 to 2009, the low-coverage grassland area expanded by over 25% and the bare soil area decreased by approximately 15%. To examine the relationship between ecological structure and function, surface temperature ($T_s$) and evapotranspiration (ET) levels were estimated to study the dynamics of the hydro-heat pattern. The results show a turning point in approximately the year 2000 from a declining ET to a rising ET, eventually reaching the 1990 level of approximately 1.5 cm/day. We conclude that grassland coverage expansion has improved the regional hydrologic cycle as a consequence of ecological restoration. Thus, we suggest that long-term restoration and monitoring efforts would help maintain the climatic adjustment functions of this alpine grassland ecosystem.

■ INTRODUCTION

Because of climate change and human interference, many ecosystems in the world are experiencing an accelerated degradation,1–3 especially for sensitive alpine and mountain grassland ecosystems.1–6 China has a large population and rapid economic growth and is now realizing the urgent obligation to save degrading land, specifically in the western area. The alpine grassland–wetland ecosystem in the source region of the Yellow River is located in the northeastern boundary of the Tibetan Plateau, which has vast and diverse grasslands and many lakes. It provides irreplaceable ecological services for both the local and downstream areas.7

Natural and human factors played different roles during the stages when the source region experienced ecological degradation and restoration. Between the 1980s and 2000s, the grassland in the source region of the Yellow River experienced two stages, degradation and restoration, which could be attributed to both natural and anthropogenic factors (Table 1). Before and during the 1980s, water and grassland resources in the source region were abundant enough to support the local husbandry.8 On the other hand, overgrazing and extensive pasturing gradually caused the decline in the quality of the grassland. In addition, a continuous drought made the grasslands unlikely to recover by natural means, with some zones beginning the process of desertification.9,10 Meanwhile, glacier thawing and landslides, together with the effects of wind and river flows, caused surface soil erosion, leading to a severe decrease in grass coverage and landscape fragmentation.11 Since the 1990s, human interference from transportation and mining in the region has increased under the national plan of the Western Development.8 Human activities have disturbed the living conditions of wildlife and exiled some large carnivores.12 The local original food chain almost collapsed.13 Rodents were the dominant consumers of the vegetation and exponentially grew in the 1990s, severely threatening the grassland resources.14–16 In 1996, the central and local government of China decided to implement a series of ecological conservation and protection projects to restore the grassland ecosystem in the source region.17 These projects

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ET at a large scale and has a much lower cost and higher space to assess the behavior of ET and its relationship to the few studies have estimated ET at a large scale in a continuous but a few identified indirect effects of land surface succession, with respect to the ecosystem vegetation and the regional climate as a whole. As a result of the impact from climate change, the hydrologic cycle requires particular attention as the fundamental support of local primary productivity. Evapotranspiration (ET) links the groundwater to atmospheric water and has been assumed to be one of the most important factors in the hydrologic cycle. Many previous studies about ET in the source region of the Yellow River showed climate change either through meteorological observation or soil humidity measurements, but few studies have estimated ET at a large scale in a continuous space to assess the behavior of ET and its relationship to the land surface structure. Remote sensing retrieval helps estimate ET at a large scale and has a much lower cost and higher efficiency than conventional ground observation methods. From calculation of the energy balance of the land surface and obtaining heat flux patterns using satellite and meteorological data, ET can be then estimated at a level of each pixel of the regional map.

Numerous studies on land ecosystem and regional climate feedback mechanisms have been conducted worldwide. From the early 1980s to the early 1990s, with remote sensing approaches not yet widely applied for LUCC and meteorological observation, researchers employed experimental observation data and numerical simulations to visualize regional hydrologic cycles and their dynamic patterns to conduct and verify feedback theories. These studies, which were typically conducted in the field, generated fairly limited results with respect to spatial resolution, and mainly forest ecosystems were examined. From the mid-1990s to the present, remote sensing methods have become more common as a reliable and efficient way to generate LUCC and hydro-heat data in a spatially explicit manner, and feedback theory verification and refinement methods have become more efficient and comprehensive through the use of more specified statistical analysis tools. Human interference with LUCC and consequent effects on regional climates have become a key concern. The biological and physical processes affecting land surfaces have been more widely discussed to elucidate the underlying mechanisms of regional climatic systems based on field observations and spatial retrieval methods for various ecosystems.

Because we now understand how land cover and ET patterns have changed at the ground level in recent years, interactions between LUCC and hydrologic cycles in the source region of the Yellow River can be more thoroughly examined. We examined LUCC trends in the source region of the Yellow River for 1990–2009. Surface temperature (T_s) and ET levels were retrieved using remote sensing data and land surface energy balance models, which were used to denote surface energy and hydrological conditions. With the LUCC, T_s and ET results, we describe the effects of ecological restoration on the regional climate of the study area. Our study contributes findings on alpine grassland–wetland ecosystems that further substantiate theories on the interactions between terrestrial ecosystems and regional climatic factors in response to ecological restoration; these findings will be of use for comparisons to projects with similar spatiotemporal dimensions and methodologies.

## Materials and Methods

**Study Area.** The study area was determined to be the core component in the source region of the Yellow River shown in the Landsat-5 Thematic Mapper (TM) image. The area lies between 33° 45' and 35° 26' N and between 96° 54' and 99° 12' E; it covers a total area of approximately 30,625 km^2^ (Figure 1). The altitude of the region is higher than 3800 m on average. The area slopes downward from southwest to northeast, ranging from a combined landform of low mountains to smooth plateaus.

**Identification of Land Cover Changes.** The remote sensing data consisted of five scenes of Landsat-5 TM images (30 × 30 m resolution) of the study area acquired on the following dates: August 30, 1990, July 24, 1994, August 9, 2000, July 25, 2006, and July 17, 2009. We obtained the data from the Global Land Cover Facility (GLCF) (http://glcf.umd.edu/). The land covers of the images from 1990 to 2009 were classified into five types by applying the method of maximum likelihood in ERDAS IMAGINE 2011. To set the interpretation criterion for classification, we defined land with no vegetation, construction areas, and sands as bare soil, grass coverage less than 30% as low-coverage grassland, grass coverage between 30 and 70% as middle-coverage grassland, grass coverage more than 70% as high-coverage grassland, and lakes and rivers as water bodies. The 230 Global Positioning System (GPS)-sampled points were taken during the fieldwork in 2011 and 2012 in total, including 83 for training and 147 for validating, respectively, in the classification criteria that were marked indicatively on the map of the study area (Figure 1) (see Tables

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Table 1. Natural and Human Factors Influencing the Source Region of the Yellow River during the Period from the 1980s to 2010s
A confusion matrix and Kappa statistics were used to make an accuracy assessment, which showed that the final result of the classification was acceptable (see Table S-3 of the Supporting Information).

Retrieval of Vegetation Conditions, T_s, and ET Patterns. Satellite-derived vegetation indices, such as the normalized difference vegetation index (NDVI), have been closely associated with primary vegetation production. NDVI is defined as follows:

$$\text{NDVI} = \frac{r_{\text{NIR}} - r_{\text{red}}}{r_{\text{NIR}} + r_{\text{red}}}$$

where $r_{\text{NIR}}$ and $r_{\text{red}}$ represent surface reflectance levels averaged over wavelength ranges of infrared and visible infrared regions of the spectrum, respectively. NDVI values and trends were used to denote vegetation degradation or restoration trends based on LUC data.

Regional climate indicators regarding surface energy and water budget levels were examined using the same set of Landsat-5 TM images. $T_s$ was calculated as an indicator of surface energy conditions based on the following formula:35,36

$$T_s = \frac{K_2}{\ln(K_1 \epsilon/L_0 + 1)}$$

(1)

where $K_1 = 607.76 \times 10^6 \text{ W cm}^{-2} \text{ sr}^{-1} \mu m^{-1}$, $K_2 = 1260.56 \times 10^6 \text{ W cm}^{-2} \text{ sr}^{-1} \mu m^{-1}$, with $K_1$ and $K_2$ being radiation constants for Landsat-5 images, $L_0$ is the spectral radiance of band 6 in Landsat-5 images, and $\epsilon$ is the atmospheric emissivity level determined on the basis of the NDVI.

We measured the value adding product (VAP) of plain areas in the atmospheric correction (ATCOR2) module platform of the ERDAS 2011 remote sensing processing software to retrieve ET (cm/day) data for the region. Principles of the product are based on the following surface energy balance equations:37

$$R_n = H + G + LE$$

(2)

$$\text{ET} = \frac{\text{LE}}{286}$$

(3)

where the terms denote components of net radiation ($R_n$, W m$^{-2}$), sensible heat flux ($H$, W m$^{-2}$), ground heat flux ($G$, W m$^{-2}$), and latent heat flux ($LE$, W m$^{-2}$). The modeling method involved two main tasks: (1) calculating the radiation balance based on remote sensing pixel reflectance levels and (2) calculating the heat balance using field knowledge that includes surface vegetation and meteorological conditions (see Table S-4 and Figure S-1 of the Supporting Information).

Comparisons to Meteorological and Hydrological Records. To compare the estimated results with meteorological and hydrological observations, air temperature ($^\circ$C), water balance (mm), and runoff (mm) variations during the summers (June–September) of 1990–2009 for the study area were also recorded. The water balance was defined as the difference between precipitation (mm) and evaporation (mm) levels. Because the moving average is typically used with time series data to smooth out short-term fluctuations and reflect longer term trends, we calculated the moving average to visualize observation trends by creating a series of water balance and runoff averages for the full data set. The original meteorological data were provided by the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/) as observed at the meteorological station of Madoi County, and runoff data were provided by the hydrological station of Huangheyan in Qinghai, shown in Figure 1. To validate $T_s$ and ET values estimated via remote sensing and values estimated based on observations, we compared interpolated data of

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observed spatial air temperature and ET with the estimated values. The process and results are described in Figure S-2 of the Supporting Information.

**Statistical Analysis.** Among the key variables, we focused on albedo ($\alpha$) and the NDVI. $\alpha$ reflects the roughness of the land surface and is related to vegetation conditions. The NDVI is used to quantify ground vegetation. $\alpha$, NDVI, $T_v$, and ET values retrieved from the raster-based results were extracted from pixels of different land cover types and then used to perform the correlation analysis in SPSS 13.0 (SPSS, Inc. Chicago, IL). Pairs of variables (e.g., NDVI−$\alpha$, $\alpha$−$T_v$, $T_v$−ET, and ET−NDVI) were selected on the basis of cause−effect vegetation and regional climate processes, which were closely associated with feedback loop pathways. In addition, $\alpha$, NDVI, $T_v$, and ET trends from 1990 to 2009 were observed according to different land cover patterns. The correlations among $\alpha$, NDVI, $T_v$, and ET and corresponding trends are

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**Figure 3.** (a) $T_v$ changes and annual air temperature changes shown by the curve and linear regression. (b) ET changes and annual water balance and runoff variations in the summers of 1990–2009 for the study area shown as three-period moving average (Mavg.) curves.
anticipated to reveal interactions between surface structures and regional hydro-heat processes.

**RESULTS**

**Grassland Degradation and Recovery.** Regional land cover changes showed patterns of grassland degradation and recovery in the summers of 1990−2009 (Figure 2). The proportion of high-coverage grassland expanded gradually from approximately 27% in 1990 to greater than 30% in 2009. Low-coverage grassland areas increased rapidly after 2000, accounting for the largest proportion of land (39%). In addition, proportions of the other two land cover types, middle-coverage grassland and bare soils, decreased from 21 to 12% and from 26 to 11%, respectively. Water body coverage levels remained constant at a level of 8% for the entire period. These trends denote land cover changes after approximately 2000.

**Hydro-heat Patterns and Regional Climate Change.** $T_s$ presents a spatial pattern with higher values of approximately 297.5 K in the north and lower values of approximately 293.2 K in the south (Figure 3a). For different land covers, $T_s$ values are sorted in ascending order (high-, middle-, and low-coverage grasslands and bare soils). In the study area, average summer air temperatures increased by almost 2 °C over the past 20 years (Figure 3a). In general, $T_s$ values of the study area for the summers of 1990−2009 follow observed regional warming trends. We also found that the $T_s$ values of bare soil and low- and middle-coverage grassland areas appeared to decrease from 2006 to 2009 (Figure 4).

ET levels were lower, at approximately 0.85 cm/day, in the north and higher, at approximately 1.75 cm/day, in the south (Figure 3b). ET values were highest in the water bodies, and areas surrounding wetlands also exhibited higher ET values of approximately 1.55 cm/day. The ET values for the other types of land cover were ranked in the following ascending order: bare soils and low-, middle-, and high-coverage grasslands. Sandy riverbank areas generated very low ET values of approximately 0.37 cm/day. The ET value for all of the land cover types initially declined from 1990 to 2000 and then increased to 1990 levels. In grasslands and bare soils, ET levels reached approximately 1.5 cm/day in 1990 and decreased to approximately 1.0 cm/day in approximately 2000, denoting an ET turning point. Thereafter, grassland and bare soil ET levels returned to approximately 1.5 cm/day in 2006 and 2009 (Figures 3b and 4). Meteorological records for the summers of 1990−2009 show that the water balance level reached its lowest value in 1996, and the region has since returned to higher moisture levels.

**Correlation between Key Variables and α and NDVI Trends.** The correlation analysis results show how associations between the key variables form the regional climate feedback loop (Figure 4). Pearson linear coefficients are underlined and added to each pair. In 1990, 1994, and 2000, all pairs were significantly correlated, with the exception of the $\alpha$−$T_s$ pair. The scatter graphs show that NDVI was negatively related to $\alpha$, $T_s$ was negatively related to ET, and ET was positively related to NDVI, although the relationship between $\alpha$ and $T_s$ remains unclear. In 1990, the $\alpha$−$T_s$ pair exhibited an insignificantly negative relation, whereas the 2006 and 2009 results generally showed a positive numerical relationship between the two variables. Apart from the hydro-heat pattern changes of $T_s$ and ET noted above, $\alpha$ and NDVI trends were extracted on the basis of different land cover types, revealing that $\alpha$ reached a maximum value in 1994 and that NDVI initially declined but increased after 1994, denoting the start of the restoration phase.

**DISCUSSION**

**Consequences of Ecosystem Degradation.** As an inland plateau grassland–wetland ecosystem, changes in the land
cover structure in this study area are related to the temperature and hydrologic patterns of this region. From 1990 to 2000, as grassland areas degraded while bare soils expanded, albedo levels of the land surface reached peak level in 1994. At the same time, surface temperatures increased continuously, partly because of global warming but also because of a reduction in evaporative cooling. On the basis of $T_s$ spatial patterns, the surface heating effects on bare soils of the northern area became more pronounced, reflecting patterns similar to those of the urban heat island effect. This regional surface temperature change is attributable to several factors, such as elevation, radiation, surface reflectivity, precipitation, and evaporation. However, quantitative attributes of these factors were not examined in this study. The correlation analysis of the key variables showed an association between vegetation and hydro-heat environments of the study area based on the retrieved spatial data, although these data are too limited to fully reflect causality in the ecological degradation and restoration feedback loop. Temporal dimension variable change trends show that the $\alpha$ and NDVI turning point occurred in 1994 and that ET has increased since 2000, and this could be interpreted as a delayed response to improved vegetation conditions.

**Ecosystem Restoration Effects.** According to references and local policy documents, humans began to play a positive role in the regional feedback process and attempted to control degradation trends in the study area beginning in 1996. The government planned ecological conservation and restoration projects and has implemented these projects from 1996 to the present. These projects have aimed to improve primary productivity levels and ecosystem self-control capacities to maintain healthy grasslands in the source region. These improved vegetation conditions may stabilize surface temperatures and increase soil moisture and ET levels, as shown in relevant observations. Runoff levels in the area have increased since 2000, and this trend has been significantly correlated with precipitation patterns. In the present study, comparisons between annual water balance and runoff variations show a decline in ET until 2000 (Figure 3b), suggesting that runoff and ET patterns interacted closely in the hydrologic cycle.

**Regional Climate Feedback Mechanisms of the Terrestrial Ecosystem.** Previous studies on interactions between the land surface and hydroclimatic conditions have mainly employed methods and tools, such as satellite cloud images, cloud frequency analyses, canopy microclimatology sensors, and meteorological observations, to examine and define cloud formation feedback effects. Most of these studies examined forest ecosystems with less of a focus on alpine grassland ecosystems. Still, micro-to-macro process analyses presented in previous studies suggest the presence of regional climate feedback mechanisms; ET improvements via vegetation recovery helped increase humidity levels, in turn increasing boundary convection and local precipitation levels.

In the neighboring Qinghai–Tibet Plateau source region, which is similar to the study area, recent observations and studies have shown a positive correlation between ET and humidity as well as a general increase in precipitation and runoff levels over the last 5–10 years. Although causal inferences between restored vegetation levels and improved hydrological conditions in the study area remain unclear based on existing results, we expect to reveal such mechanisms in greater depth with the use of more observations and experiments on alpine grassland ecosystems. We conclude that lower ET trends led to lower air moisture levels, inhibiting cloud formation and local precipitation. It is assumed that drought conditions inhibit vegetation growth, potentially accelerating grassland degradation further, as shown in Figure 5.

**Coupling System of the Atmospheric and Terrestrial Hydrocycle.** According to principles of modern hydro-climatology, the atmosphere serves as a climatic frame and drives energy flows and water vapor transportation patterns. Subsystems of the atmosphere and terrestrial ecosystems were coupled to form a complete hydrocycle system. Dividing the hydrocycle system into two branches [the atmospheric hydrocycle (AHC) and terrestrial hydrocycle (THC)] helped reveal global climate patterns.

The dominant factors of AHC mainly include atmospheric circulation and energy flux trends in patterns of circulation. Atmospheric circulation models primarily determine biomes at the continental scale and strongly affect the construction and succession of ecosystems, influencing global land cover structures. THC involves terrestrial–atmosphere interface processes, wherein the atmosphere interacts with geographical, hydrological, and biological processes driven by key factors to support the development of ecosystems, as shown in our study. Key factors include surface energy flux, water availability, and groundwater balance. ET plays a dominant role in THC, because ET is driven by radiation and relies on the transformation of groundwater into atmospheric water vapor, which is widely related to soil and vegetation processes. As part of the land cover structure, vegetation determines the speed and means through which groundwater and precipitation move from the land surface to the atmosphere. In turn, studies have shown that THC plays a key role in climate systems through its involvement in the hydrologic cycle.

To situate this analysis of long-term AHC impacts within processes of ecological restoration, it is also essential to understand this phenomenon and to make predictions. Observations show that the Asian monsoon has been less active over the last 20 years, resulting in the drying and warming of the Qinghai–Tibet Plateau. Drought conditions may continue over a long period of time. Therefore, long-term and advanced ecological restoration and monitoring efforts are
essential. Although previous climate change studies have presented global climate models and have discussed energy use strategies that mitigate global warming, few works have examined regional THC processes to assess or manage regional climatic and hydrological changes. Few climate policy studies have determined the net impact of biophysical changes resulting from land use pattern changes. Our work in the source region of the Yellow River serves as an initial attempt to explore the feasibility of applying innovative methodologies to address gaps in knowledge and to evaluate ecological restoration strategies in future studies.

**ASSOCIATED CONTENT**

Supporting Information
Classification criterions of the study area and the accuracy assessment for the land cover classification, detailed methods for the calculation models of ATCOR2, and validation of the estimated results with meteorological data. The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/es505985q.

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**Notes**
The authors declare no competing financial interest.

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