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Vegetation Restoration in the Loess Plateau Induces Regional Cooling: A Postprint

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Abstract

Ecological restoration projects such as the Grain for Green Program (including afforestation and grassland restoration) on the Loess Plateau have promoted increases in surface vegetation cover, thereby influencing regional climate processes through their effects on heat exchange between the surface and the atmosphere. Based on SPOT satellite-retrieved vegetation cover data, temperature data from 54 ground meteorological stations, and EIN-Interim surface heat flux data for the Loess Plateau during 1998–2000 and 2008–2010, this study employed spatial analysis cross-validation and surface heat balance analysis methods to investigate the relationship between vegetation changes and variations in temperature and surface heat fluxes at the site scale, comparing the initial stage of the Grain for Green Program with conditions a decade later. The results indicate that a decade after the implementation of the Grain for Green Program, the minimum, maximum, and mean temperatures on the Loess Plateau all decreased, with increases in vegetation cover showing a positive spatial correlation with reductions in temperature variables. Simultaneously, increases in vegetation cover also exhibited positive spatial correlations with increases in latent heat flux and decreases in sensible heat flux and atmospheric downward longwave radiation. These results demonstrate that vegetation restoration can produce a cooling effect on regional climate by enhancing surface evapotranspiration, thereby mitigating the impacts of rising temperatures on the Loess Plateau ecosystem.

Full Text

Preamble

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Cooling Effect Induced by Vegetation Restoration on the Loess Plateau

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Abstract

Large-scale re-vegetation through ecological engineering on the Loess Plateau, including the Grain for Green Project (GGP), has substantially impacted heat and energy exchange between the land surface and atmosphere, thereby influencing regional climate. We employed two methods—spatial change cross-checking and surface heat balance analysis—to examine relationships among vegetation change, temperature change, and surface heat flux change during the GGP at the station scale across the Loess Plateau. The 10-day normalized difference vegetation index (NDVI) derived from SPOT data was used to characterize vegetation conditions. Monthly temperature data from 54 weather stations within or near the Loess Plateau described temperature variations, while ERA-Interim surface heat fluxes were analyzed to determine surface thermal conditions. Two stages were compared: the initial stage of GGP (1998–2000, Stage I) and ten years after implementation (2008–2010, Stage II). Minimum, maximum, and mean temperatures were lower in Stage II, and vegetation increase was spatially positively correlated with decreases in all temperature variables. Meanwhile, vegetation increase was spatially positively correlated with latent heat flux increase and with decreases in sensible heat flux and atmospheric downward long-wave radiation. These results indicate that vegetation restoration may lower temperatures through increased surface evapotranspiration, thereby mitigating climate warming effects on the Loess Plateau ecosystem.

Keywords: Loess Plateau; Grain for Green Project (GGP); regional climate; spatial change cross-checking; surface heat balance

Introduction

Vegetation, as the principal component of terrestrial ecosystems, represents a crucial and dynamic part of the climate system [1–2]. Terrestrial vegetation can regulate land-atmosphere water and energy cycles by altering surface albedo and the partitioning of net radiation among sensible heat, latent heat, and ground heat flux [3], or by modifying surface roughness to influence atmospheric dynamic characteristics, thereby affecting surface energy balance and climate characteristics [4]. Numerous studies have explored vegetation impacts on climate at local and regional scales [5–6]. However, because Earth’s surface physical and

biological properties exhibit significant regional variation, vegetation-climate mechanisms may differ across regions. For instance, forests may cause temperature increases in tropical regions but decreases in cold regions [7].

The Loess Plateau is one of China's most climate-sensitive regions, attracting widespread scholarly attention due to its unique natural and climatic conditions and ecological environmental changes [8-9]. To alleviate soil erosion and land degradation in northern China, large-scale GGP initiatives began on the Loess Plateau in 1999. While vegetation growth effects have been remarkable [10] and research on policy impacts on farmer characteristics [11] and economic benefits [12] is extensive, discussion of regional environmental effects—particularly interactions between restored vegetation and the atmosphere—remains limited. Previous studies have used mesoscale meteorological models coupled with land surface vegetation schemes [13], RegCM models [14], and mesoscale climate models [15] to simulate impacts of vegetation changes on local climate. However, most research relies on modeling approaches, with few using observational data to demonstrate vegetation restoration feedbacks on climate at local or regional scales. For the Loess Plateau, whether GGP implementation may cause regional temperature changes based on observational data remains unclear. This study utilizes remote sensing-derived vegetation cover data, meteorological station data from 54 sites within the Loess Plateau GGP area, and ERA-Interim surface heat flux data, applying spatial analysis cross-validation and surface heat balance analysis to explore potential relationships among these three factors at the station scale.

1. Study Area and Data

The Loess Plateau is located in the middle and upper reaches of the Yellow River, encompassing the vast area west of the Taihang Mountains, east of the Riyue Mountains in Qinghai, north of the Qinling Mountains, and south of the Yinshan Mountains [17], covering approximately 62.4×10^4 km². The region features deep soils primarily composed of cinnamon soil, black loam, and yellow loessial soil, with excessively large capillary pores and poor water retention [18]. Most areas receive average annual precipitation of 400 mm, with high spatial variability and pronounced seasonal distribution concentrated in storm events. The region experiences a typical continental monsoon climate. These unique topographic and soil characteristics, combined with frequent rainstorms, cause severe water erosion, making it an ecologically fragile zone and key soil conservation area in China.

This study primarily uses observed temperature data from ground meteorological stations, satellite-derived vegetation data, and ERA-Interim reanalysis surface heat flux data. Ground observational data were obtained from the China Meteorological Data Sharing Network. We selected 54 meteorological stations in the Loess Plateau and surrounding areas based on three principles: (1) continuous temperature data with no missing months during the growing season; (2) stations located within GGP coverage areas; and (3) grassland or forest as

the dominant land cover type after the GGP implementation, with green space proportion $>33.33\%$ (calculated from 1:100,000 land use data [19] in the ArcGIS platform). The selected station distribution is shown in [Figure 1: see original paper].

NDVI data were derived from SPOT VEGETATION sensors. For 1998–2008, we used VGT-S10 10-day maximum value composite data (1 km spatial resolution) from the Heihe Plan Data Management Center (<http://westdc.westgis.ac.cn>). For 2008–2010, data were obtained from the Belgian VITO Institute's image processing and archiving center (<http://www.vito-eodata.be>). ERA-Interim re-analysis data have a horizontal resolution of $0.125^\circ \times 0.125^\circ$ and vertical resolution as referenced in relevant literature [20]. Monthly mean surface heat fluxes from ERA-Interim for 1998–2000 and 2008–2010 were used to analyze surface heat balance conditions.

2. Data Processing

Temperature data comprised monthly mean temperature (T_{mean}), monthly maximum temperature (T_{max}), and monthly minimum temperature (T_{min}) for the vegetation growing season. NDVI data used monthly maximum composites from VGT-S10 datasets for the growing season (hereinafter NDVI_g). ERA-Interim surface heat fluxes included latent heat flux (LH), sensible heat flux (SH), and atmospheric downward longwave radiation (LD). Growing season mean heat flux values were calculated, and Kriging interpolation was applied to estimate values for the 54 stations. All station temperature values, NDVI_g, and heat fluxes used averages of surrounding pixels. We analyzed temporal variation characteristics by calculating means, standard deviations, and coefficients of variation (CV) for NDVI_g and temperature variables during the two periods (1998–2000 and 2008–2010).

3. Methods

3.1 Spatial Pattern Analysis

To analyze the spatial patterns of vegetation and temperature changes during the growing season across the Loess Plateau, we used ArcGIS 10.0 spatial analysis tools to compute mean values and coefficients of variation for NDVI_g and temperature variables during the two periods.

3.2 Spatial Cross-Validation of Vegetation and Temperature Changes

To quantify the impact of Loess Plateau vegetation changes on temperature, we selected two typical periods for difference analysis: the initial GGP stage (1998–2000, S1) and ten years after implementation (2008–2010, S2). We calculated the change in mean annual NDVI_g, temperature variables, and heat fluxes between the two periods (ΔNDVI_g , ΔT_{mean} , ΔT_{max} , ΔT_{min} , ΔLH , ΔSH , ΔLD). Using ArcGIS 10.0 overlay analysis, we examined relationships between vegetation

cover and temperature/surface heat fluxes to explore underlying mechanisms.

4. Results

4.1 Spatiotemporal Vegetation Changes

During the GGP implementation period, NDVIg increased significantly from S1 to S2, with the mean value rising from 0.38 to 0.45—a substantial increase of 18.42%. The maximum NDVIg also increased by 13.16%. Spatial distribution differences between the two periods were pronounced. Vegetation restoration areas increased markedly, with high-cover regions (NDVIg 0.6) expanding from 25.10% to 35.42% of the total area. The central and southeastern Loess Plateau showed the most significant greening, with increases covering 92.37% of the region. However, some degradation occurred, primarily north of Lanzhou, possibly due to combined natural conditions and human activities. This area lies in a semi-arid to arid zone with water shortages and challenging ecological restoration [21], where potential overgrazing may drive vegetation degradation in windy, sandy grasslands [22]. The maximum NDVIg decrease reached -0.28.

4.2 Site-Scale Vegetation Cover and Temperature Changes

At the site scale, NDVIg statistics showed increases across all metrics from S1 to S2, while temperature variable maxima and means decreased, indicating a consistent cooling trend. Conversely, temperature minima increased, suggesting Loess Plateau temperature conditions remain influenced by large-scale global warming, though local forcing effects are more pronounced. Further paired-sample t-tests at the 0.01 significance level revealed significant differences in NDVIg and Tmean between periods, while Tmax and Tmin differences were not significant.

The spatial distribution of NDVIg and temperature changes exhibited roughly opposite patterns. Vegetation cover increases were most pronounced at sites in central-southern Loess Plateau near the main Yellow River channel, with the largest increase at Lishi Station ($\Delta\text{NDVIg} = 0.19$). The smallest changes occurred at northwestern stations, with the maximum NDVIg value appearing at Jining Station in the northeastern Loess Plateau (0.04). Temperature decreases were widespread in areas with vegetation increase. For Tmean, cooling was most evident in central-southern sites near the Yellow River main channel, with the greatest decrease at Yangquan Station (-1.95°C). Warming occurred at a few southwestern sites, with the highest increase at Foping Station (0.79°C). For Tmax, the spatial distribution pattern differed, with warming concentrated in southwestern areas and cooling in central regions. The highest warming occurred at Foping Station (1.25°C), while the maximum cooling was at Maguan Station (-1.54°C). For Tmin, warming sites remained concentrated in the southwest, with the highest increase at Foping Station (0.82°C). Spatial variability of daily minimum temperature at vegetation-covered stations was higher than that of daily mean and maximum temperatures.

Cross-validation analysis of vegetation cover and temperature changes during the study period revealed a significant positive spatial correlation between vegetation increase and temperature decrease. The effect of vegetation on temperature was greater during daytime than nighttime. Across most of the Loess Plateau, the number of sites in the quadrant showing vegetation increase with temperature decrease was highest, comprising 64.81% and 72.22% of sites for T_{mean} and T_{max} , respectively. Sites showing vegetation increase with temperature increase were extremely rare, representing only 5.56%, 3.70%, and 5.56% for T_{mean} , T_{max} , and T_{min} , respectively. This daytime dominance likely occurs because most energy exchange activities between vegetation and atmosphere happen during illuminated daylight hours.

4.3 Surface Heat Balance Analysis

These results suggest vegetation cover increase may impact local thermal conditions on the Loess Plateau, producing cooling effects. Vegetation can influence the atmosphere by altering underlying surface albedo, roughness, and evapotranspiration, thereby affecting ground circulation and energy balance and causing local temperature changes [2-3]. To further verify these findings, we employed heat balance analysis to explore the basic processes and potential physical mechanisms of vegetation cover impacts on temperature.

We selected physical quantities affecting surface energy balance relationships [23], including changes in sensible heat flux (ΔSH), latent heat flux (ΔLH), and atmospheric downward longwave radiation (ΔLD). We also classified growing season vegetation cover changes into high-greening sites ($\Delta NDVI_g > 0.1$), medium-greening sites ($0.05 < \Delta NDVI_g \leq 0.1$), and low-greening sites ($0 < \Delta NDVI_g \leq 0.05$), quantitatively 统计 ing corresponding temperature and heat flux changes.

Temperature changes showed gradient distribution across greening levels, consistent with $\Delta NDVI_g$ changes. As greening degree increased, cooling magnitude for each temperature variable also increased. Except for a few warming instances at medium and low greening sites, temperature decreases intensified with greater greening. High-greening sites showed greater temperature reduction than medium-greening sites.

Heat flux changes aligned with $\Delta NDVI_g$ changes. With vegetation cover increase, latent heat flux increased significantly due to enhanced regional soil moisture, increased roughness, and greater leaf area index and evapotranspiration. Sensible heat flux decreased. Specifically, 74.07% of sites showed simultaneous vegetation cover and latent heat flux increases (0.46–44.77 W/m²), while 64.81% showed vegetation increase with sensible heat flux decrease (–0.22 to –30.53 W/m²). Downward longwave radiation changes can be explained through surface albedo—vegetation albedo is much lower than desert [24]. Increased vegetation cover on the Loess Plateau altered surface albedo, affecting short-wave solar radiation absorption and longwave radiation emission. Many studies

demonstrate that vegetation increase can reduce surface albedo, increasing absorbed solar radiation and creating positive albedo feedback, though this may be partially offset by cooling from higher evapotranspiration [26]. Increased evapotranspiration enhances atmospheric water vapor, boosting cloud cover and causing significant downward longwave radiation reduction. Sites with decreased longwave radiation accounted for 79.63% of the Loess Plateau, with reduction magnitudes of -0.02 to -13.91 W/m^2 .

From a heat balance perspective, vegetation increase enhances soil moisture and surface impedance, increases vegetation transpiration, and strengthens turbulent vertical diffusion due to increased roughness, leading to latent heat flux increase and sensible heat flux decrease. Although sensible heat flux reduction was smaller than latent heat increase, the effective heat flux (net radiation minus ground heat flux) increased by 0.24 – 14.24 W/m^2 . Because net absorbed radiation increased alongside albedo reduction, and effective heat flux values increased, lower surface temperatures were required to achieve new balance between absorbed shortwave radiation and emitted longwave radiation. This cooling result aligns with numerical simulation studies of vegetation impacts on climate over the Loess Plateau [15, 27], but differs from positive feedback analyses in Arctic vegetation growth [28] and land cover change sensitivity studies in China [29]. At the regional scale, the Loess Plateau's cold winters and extensive grassland cover make vegetation evapotranspiration crucial—it can weaken warming caused by albedo reduction under increased vegetation cover. Vegetation must transpire more water to achieve new energy balance, creating sustained cooling feedback during the growing season.

5. Conclusions

Based on meteorological observations, satellite remote sensing, and ERA-Interim reanalysis surface heat flux data, this study cross-validated vegetation growth status and spatiotemporal temperature variable changes before and after ecological engineering implementation on the Loess Plateau (S1: 1998–2000; S2: 2008–2010) to explore vegetation restoration feedbacks on temperature. Using surface heat balance analysis, we examined basic processes and potential physical mechanisms of vegetation impacts on temperature, revealing vegetation-atmosphere interactions. Key findings include:

1. Loess Plateau vegetation restoration was evident, with significant growing season NDVI increases. Correspondingly, the three temperature variables (T_{mean} , T_{max} , T_{min}) decreased during the growing season in S2. Vegetation cover increase was spatially positively correlated with temperature variable decreases.
2. Vegetation cover increase was spatially positively correlated with latent heat flux increase and with decreases in sensible heat flux and downward longwave radiation. Vegetation restoration caused near-surface cooling through enhanced evapotranspiration, potentially mitigating climate

warming impacts on the Loess Plateau ecosystem.

Study limitations include data uncertainties and model deficiencies that hinder quantitative conclusions about temperature feedback magnitude from increased vegetation activity. Future research should improve observational spatiotemporal precision and introduce additional parameters in model simulations, such as leaf area index and surface albedo, to make land surface process parameterizations more realistic. These improvements will enhance understanding of vegetation' s role in the climate system.

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