Key Points:
- Surface water yield generally does not decrease in the Loess Plateau after revegetation
- Faster increases in regional precipitation outweighs enhanced evapotranspiration
- Revegetation accelerates the local moisture recycling and contributes to the rainfall increases

Supporting Information:
Supporting Information may be found in the online version of this article.

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Citation:
Zhang, B., Tian, L., Yang, Y., & He, X. (2022). Revegetation Does Not Decrease Water Yield in the Loess Plateau of China. *Geophysical Research Letters*, 49, e2022GL098025. https://doi.org/10.1029/2022GL098025

Received 1 FEB 2022
Accepted 10 APR 2022

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Abstract Vegetation restoration over degraded drylands has considerable climate, carbon and ecosystem benefits, yet its water impacts remain contentious. Previous studies suggest that extra vegetation in drylands could lead to decreased soil moisture and runoff caused by enhanced evapotranspiration. However, these studies ignore important vegetation-climate feedbacks that can partially offset such negative consequences. Here, we examine how revegetation affects water budgets in China’s Loess Plateau, where the world’s largest revegetation occurs. Despite increased evapotranspiration, long-term observations exhibit robust increasing trends (2.76 mm yr⁻²) of surface water yield over a large swath (82.3%) of the Plateau since revegetation starts. This is mainly caused by increased regional precipitation that outweighs increases in evapotranspiration. Numerical experiments further reveal that the increased precipitation is largely driven by revegetation-induced enhancement in land-atmosphere interactions that greatly accelerate local moisture recycling. Our findings highlight the importance of considering vegetation-climate feedbacks in assessing hydrological responses to large-scale vegetation changes.

Plain Language Summary Vegetation restoration is one of the most effective ecological engineering measures for ecosystem remediation and climate mitigation, and has been widely implemented across the globe over the past few decades. Previous studies suggest that revegetation could threaten long-term water sustainability of the Loess Plateau in China, a typical dryland region that has witnessed widespread vegetation restoration over the past two decades, as extra vegetation consumes more water through evapotranspiration, leading to decreased soil moisture and runoff. Here we challenge this conclusion by showing that a large swath of the Loess Plateau has experienced robust upward trends of surface water yield since the start of large-scale vegetation restoration. This is primarily caused by increased regional precipitation that outpaces the increased evapotranspiration induced by revegetation. Further, we demonstrate that the increase in precipitation is largely driven by enhanced land-atmosphere interactions that accelerate local moisture recycling following revegetation. Our results suggest that previous offline assessments, which ignore important vegetation-climate feedbacks, may overstate the threats of revegetation on dryland water resources. These findings provide an important scientific basis for guiding current and future revegetation activities toward sustainable ecosystem development and water resources management.

1. Introduction
As one of the most effective measures for ecosystem remediation and climate mitigation, large scale vegetation restoration has been implemented worldwide over the past few decades (C. Chen et al., 2019; B. Zhang et al., 2021) which profoundly impacts water budgets (Y. Li et al., 2018; Luo et al., 2020; Spracklen et al., 2012), carbon cycle (Jackson et al., 2005) and ecosystem services (Y. Chen et al., 2015; Feng et al., 2016). On one hand, newly planted vegetation stores extra carbon (Cheng et al., 2017), reduces soil erosion (Ran et al., 2013; S. Wang et al., 2016), and provides biofuel for bioenergy production (Feng et al., 2016). On the other hand, extra vegetation requires more water to grow, adding potential burdens on local water sustainability (H. Chen et al., 2008; Y. Chen et al., 2015). As drylands have limited water resources, whether vegetation restoration can sustain in the long term is of particular interest to local ecosystems (Feng et al., 2016; Jia et al., 2017; Y. Wang et al., 2011).
One such example is the “Grain for Green Project” (GfGP) implemented in China’s Loess Plateau, the largest active vegetation restoration program in the world (W. Liang et al., 2015; McVicar et al., 2010). With more than 8.7 billion US$ investment, about 16,000 km² of rain-fed croplands have been converted to perennial non-native vegetation since 1999, leading to an increased vegetation coverage by ~25% between 1999 and 2013 (Feng et al., 2016; M. Zhang and Wei, 2021; S. Zhang et al., 2018). The increased vegetation cover, combined with other engineering measures (i.e., check dam, terrace, level furrow, and fish-scale pits), has effectively reduced soil erosion on the Loess Plateau. As a result, sediment discharged into the Yellow River has declined from $14.7 \times 10^8$ t yr$^{-1}$ in the 1950s to $1.1 \times 10^8$ t yr$^{-1}$ in 2015 (S. Wang et al., 2016). However, such sediment benefits are accompanied by soil desiccation and plant mortalities, raising serious concerns regarding whether revegetation is detrimental to water sustainability in the long term. Previous studies suggest that revegetation activities could jeopardize local water resources as extra vegetation increases water consumption through enhanced transpiration (Jia et al., 2017; Y. Wang et al., 2011; S. Zhang et al., 2018). However, these assessments neglect important land-atmosphere coupling in this region, a key physical process that can significantly modulate the regional water cycle, especially related to precipitation ($P$). In general, changes in $P$ can be explained by two mechanisms: changes in (a) advection of moisture (i.e., moisture supply of atmospheric circulations) and (b) local moisture recycling (i.e., moisture supply from local $E$) (Trenberth, 1999). The first mechanism is associated with climate change (F. Chen et al., 2021) and climate variability (Eltahir & Bras, 1994), while the second mechanism is more related to changes in local moisture and energy partitioning induced by surface properties changes (Burde & Zangvil, 2001; Lean & Warrilow, 1989; Rios-Entenza et al., 2014), for example, changes in vegetation cover in this case.

Here we combine long-term hydrometeorological observations, diagnostics modeling, and numerical experiments with explicit representation of land-atmospheric interactions to anatomize how vegetation restoration affects the surface water yield (defined as precipitation minus evapotranspiration) in the Loess Plateau. In contrast to previous studies (Feng et al., 2016; Jia et al., 2017; Y. Wang et al., 2011), we do not find consistent declining trends in observed streamflow ($Q$) records throughout the Plateau. In fact, most catchments in the Plateau exhibit no trends or even upward trends of $Q$ since the implementation of GfGP. This is primarily caused by increased $P$ that outpaces increases in evapotranspiration after the implementation of vegetation restoration. We further demonstrate that increases in $P$ are largely driven by enhanced land-atmosphere interactions that accelerate local moisture recycling. Our results suggest that previous offline assessments have overestimated the negative effects of revegetation on water yield in the Loess Plateau. Unbiased evaluation of large-scale revegetation programs on water sustainability needs to carefully consider vegetation-climate feedbacks.

2. Materials and Methods

2.1. Study Area

The Loess Plateau is located in northern China and is characterized by a highly erodible thick Loess soil (92.2 m on average, Y. Zhu et al., 2018). It is traversed by the upper and middle reaches of the Yellow River and covers a total area of ~640,000 km² (Figure 1). To prevent soil and water losses and improve local ecological conditions, the Chinese government has implemented GfGP since 1999. The specific measures of the GfGP for vegetation restoration mainly include: (a) returning sloped farmland and converting barren to forest, grassland, and shrub, and (b) planting trees in grassland or shrub (B. Zhang et al., 2021). Figure S1 in Supporting Information S1 summarizes the sensitivities in simulated accumulative $P$ for different schemes of artificial revegetation over the Loess Plateau based on Weather Research and Forecast (WRF) simulations for a selected year (i.e., 2010). The magnitude of accumulative $P$ is quite sensitive to diverse artificial revegetation measures over this region (Figure S1 in Supporting Information S1). The entire Loess Plateau and its 11 main revegetation catchments are selected to investigate the impact of revegetation on surface water yield (Table S1 in Supporting Information S1).

2.2. Data

Monthly $Q$ observations from 1982 to 2015 in the Loess Plateau and 11 main revegetation catchments are obtained from the Ministry of Water Resources of the People's Republic of China (Y. Yang et al., 2021). The long-term hydro-meteorological characteristics of these catchments are provided in Table S1 in Supporting Information S1. In addition, we use monthly $P$ during 1982–2015 with 0.1° spatial resolution from the China Meteorological
Forcing Dataset (CMFD) (Y. Chen et al., 2011). This data set was developed by the Institute of Tibetan Plateau Research under Chinese Academy of Sciences, and represents an optimal combination of in-situ observation, satellite retrials and meteorological reanalysis. Figure S2 in Supporting Information S1 shows that the CMFD P and in-situ observed P are highly consistent at the 76 meteorological stations in the region (mean R² of 0.98 across all stations), demonstrating the validity and accuracy of the CMFD gridded P over the Loess Plateau. Observed P at 76 meteorological stations is obtained from the Meteorological data center of the China Meteorological Administration.

Monthly evapotranspiration (E) is estimated based on multiple datasets, including the Global Land Evaporation—The Amsterdam Method E product (Martens et al., 2017) (GLEAM; 0.25° × 0.25°), the Priestley-Taylor Jet Propulsion Laboratory model forced with remotely-sensed vegetation dynamics and ground-based auxiliary meteorological variables (0.1° spatial resolution; Fisher et al., 2008; Shao et al., 2019; Shao et al., 2021), and the modified WRF model with vegetation dynamics (WRF-DYN) simulation (10 km spatial resolution). The ensemble mean of E datasets is used here given the large uncertainties of E from individual models (Han et al., 2020; Lian et al., 2018). Validation against observed E at 13 eddy-covariance sites and three lysimeter sites demonstrates the high accuracy of the ensemble mean of E (Figure S3 in Supporting Information S1). The specific
date sources of flux tower-based $E$ and lysimeter-based $E$ observations are provided in Table S2 in Supporting Information S1. Both $P$ and $E$ are further aggregated for individual catchments for catchment-level analyses.

The Global Land Surface Satellites (GLASS) vegetation fraction, Leaf Area Index (LAI), and albedo are used to represent vegetation cover conditions and are obtained from the National Remote Sensing Center of China (S. Liang et al., 2013; Xiao et al., 2013). The GLASS products have a temporal resolution of 8 days and a spatial resolution of 0.05°, providing one of the longest LAI and albedo time series (i.e., from January 1982 to present (N. F. Liu et al., 2013; Z. Zhu et al., 2013)). The GLASS vegetation fraction, LAI, and albedo are also further aggregated to monthly scale and resampled to 0.1° × 0.1° spatial resolution. We use satellite-observed global land cover products obtained from the European Space Agency Climate Change Initiative (ESA CCI) (Plummer et al., 2017) to describe land cover changes, which are available from the Copernicus Climate Change Service Climate Data Store. This global land cover data set classifies the land surface into 22 categories with 300 m spatial resolution and annual interval from 1992 to the present.

To calculate the advection moisture flux over the entire mainland China, we use the European Centre for Medium-Range Weather Forecasts atmospheric reanalysis (ERA-Interim, 0.25° × 0.25° grid) for wind, humidity, and surface pressure (Dee et al., 2011). The ERA-Interim reanalysis data includes 6-hourly specific humidity, zonal, and meridional wind speeds at the lowest 23 pressure levels (200–1000 hPa), and surface pressure from 1980 to 2015. The ERA-Interim data also provides initial and lateral boundary conditions for the WRF model. A brief description of all datasets used in this work is summarized in Table S3 in Supporting Information S1.

### 2.3. Numerical Simulations Using the WRF Model

In this study, we use version 3.8.1 of the WRF to investigate the response of regional climate to revegetation. WRF is an advanced and flexible atmospheric simulation system that has been used extensively in both climate and hydrological research (Heikkilä et al., 2011). For the WRF spatial setting, we adapt a single-domain (centered at 37°N, 108°E) with a horizontal resolution of 10 km. The number of vertical levels is 30, and the top-level is 50 hPa. This domain consists of 160x160 grids with the Lambert conformal conic projection.

Accurate simulation of $P$ is a prerequisite for evaluating vegetation impacts on regional water cycle over the Loess Plateau. Microphysics, planetary boundary layer, and cumulus schemes are three key WRF physical schemes that are directly linked to $P$ processes (L. Li et al., 2014). We thus identify the optimal parameterization schemes through a large ensemble (≈616) of sensitivity tests, with a combination of 11 microphysics, 8 planetary boundary layer, and 7 cumulus schemes, to obtain an optimal combination of parameterizations for reproducing $P$ over the Loess Plateau. In these experiments, the WRF model is initialized on 1 June 2007, and run through 31 July 2007. The first month of simulations is discarded as spin-up. These two months are selected because the spatiotemporal patterns of $P$ in 2007 are close to those of the climatology (1982–2015) over the Loess Plateau. Normalized Taylor diagrams (Taylor, 2001) are applied to evaluate the performance of different parameterization schemes in our sensitivity experiments (Figure S4 in Supporting Information S1). In addition, the pattern correlation coefficient (PCC) (Walsh & McGregor, 1997) is applied to assess the performance of WRF to reproduce the spatial pattern of $P$ (Figure S4 in Supporting Information S1). PCC is the correlation of a sequence of grids $x_i$ between the observed $P$ and corresponding values $y_i$ from the simulated $P$. The optimal combination of physical parameterization schemes used in this study includes the CAM5.1 microphysics (Neale et al., 2010), the Dudhia shortwave radiation scheme (Dudhia, 1989), Rapid Radiative Transfer Model (RRTM) longwave radiation scheme (Mlawer et al., 1997), MYNN2.5 planetary boundary (Nakanishi & Niino, 2006), Revised MM5 Monin-Obukhov surface layer scheme (Jiménez et al., 2012), the Noah land surface model (Ek et al., 2003), and Kain-Fritsch cumulus schemes (Kain, 2004).

With this optimal scheme combination, long-term simulations (1999–2015) over the Loess Plateau are performed. The simulation begins at 1200 UTC 1 September 1999, and ends at 1200 UTC 31 December 2015, with the first four months from 1 September 1999 to 31 December 1999 considered as spin-up time and therefore are excluded from the analysis. To examine the impact of revegetation on the surface water yield, we carry out two simulation experiments to investigate the response of $P$ to artificial vegetation planting over the Loess Plateau: (a) control experiment (WRF-CTL), and sensitivity experiment (WRF-DYN) (Table S4 in Supporting Information S1). Differences in the input data between these two sets of experiments are land cover types, vegetation fraction,
LAI, and albedo, while all other settings are kept to the same. Except for the aforementioned vegetation dynamic parameters, other parameters are based on the default values.

We use WRF parameterizations based on the vegetation condition in 1999 to conduct the control experiment (WRF-CTL), which does not consider the effects of GfGP. Different from WRF-CTL, WRF-DYN incorporates dynamic information from 1999 to 2015 to mimic the implementation of GfGP. In the WRF-DYN case, we change land cover types within the Loess Plateau based on the ESA CCI land cover product, which has been widely used for climate-vegetation feedbacks given its long-term data records and consistency. The vegetation fraction, LAI, and albedo data are derived from the GLASS products. Compared with the MODIS products, the GLASS vegetation fraction, LAI, and albedo product have higher temporal resolution and can well capture the surface vegetation conditions (N. F. Liu et al., 2013). Differences in the simulated P between two experiments are used to examine the responses of P to vegetation restoration.

Figure S4a in Supporting Information S1 shows the sensitivity analysis of the cloud microphysics scheme. The spatial correlation coefficients (PCC) of each experiment are concentrated at around 0.65, and the root mean square error (RMSE) varies from 1.05 to 1.32 mm month\(^{-1}\). Among them, CAM 5.1 (Neale et al., 2010) performed the best (PCC = 0.66, RMSE = 1.14 mm month\(^{-1}\)). Generally speaking, the choice of cloud microphysical scheme has no obvious impact on P simulation in the study area. Based on the sensitivity test of the cloud microphysical parameterization scheme, the sensitivity test of the atmospheric boundary layer scheme is carried out (Figure S4b in Supporting Information S1). Simulated P in the study area is more sensitive to the atmospheric boundary layer scheme, and the PCC distribution range is 0.59–0.71. Among them, MYNN 2.5 (Nakanishi & Niino, 2006) achieves the highest PCC (0.71). Therefore, we choose MYNN 2.5 scheme as the planetary boundary layer scheme in WRF. Based on the first two sensitivity experiments, the final test to select the scheme for cumulus convection parameterization is carried out, based on 8 cumulus convection schemes. As shown in Figure S4c in Supporting Information S1, simulated P is most sensitive to the cumulus convective parameterization schemes (PCC and RMSE are in the ranges 0.56–0.72 and 0.88–1.18 mm month\(^{-1}\), respectively). The Kain-Fritsch42 scheme performed best, with a higher PCC (0.71), and the degree of spatial variability was closer to the CMFD. Therefore, based on the three sets of sensitivity tests, this study compared and selected the optimal WRF parameterization scheme combination that most accurately reproduced the P in the Loess Plateau. This combination comprised the RRTM longwave radiation scheme, Dudhia shortwave radiation scheme, CAM5.1 cloud microphysics scheme, MYNN2.5 atmospheric boundary layer scheme, Kain-Fritsch cumulus convection scheme, and Noah land surface process scheme.

Although running WRF with the optimal parameterization scheme can substantially improve the accuracy of P simulation over the Loess Plateau, the simulation results still have some errors. One source of P error arises because the experiments described above all use the WRF default static land surface data, which cannot effectively reflect the drastic land surface changes on the Loess Plateau after large-scale vegetation restoration. Therefore, this study also considers the optimal combination of parameterization schemes when using the 2007 land-cover data to drive the model, and explores the impact of vegetation dynamics on the P simulation (the same parameterization scheme is reevaluated when dynamic vegetation is included). As shown in Figure S4c in Supporting Information S1, after considering the true surface changes, the WRF P simulation was further improved (PCC = 0.74).

In summary, considering vegetation dynamics can accurately reproduce the P distribution on the Loess Plateau.

### 2.4. Surface Water Budgets

We use linear regression to estimate the annual trend of surface water yield (P–E) during 1982–2015. Combined with measured Q, we quantify the trend of catchment water storage changes \(\Delta W(=P–E–Q)\) over the Loess Plateau and 11 main revegetation catchments.

### 2.5. Field Observations

To further examine the impact of revegetation on soil water content, a 3-year in-situ experiment is conducted in a small catchment (i.e., Yuanzegou catchment; 37°14′N, 110°20′E, 2014–2016) on the Loess Plateau (Figure S5 in Supporting Information S1). This catchment is one of the typical heavily gullied catchments over the Loess Plateau with an area of 0.58 km\(^2\). To control the severe soil and water losses, the gullies are restored into forest, shrub, and grassland. The sampling sites are scattered over sites with different revegetation types (i.e.,
grassland, forest, and shrub) and bare soil, with each land use type having at least five sampling points (Figure S6 in Supporting Information S1). Soil water content from all these sampling sites is collected using an EC-5 soil moisture sensor at five different depths (S. Wang et al., 2016; 20, 60, 100, and 160 cm). The measured soil water content at different layers is then converted into soil water depth in mm within the 0–200 cm soil column.

3. Results

3.1. Observed Changes in Vegetation and Streamflow Over the Loess Plateau

Satellite-based observations have witnessed widespread vegetation greening on the Loess Plateau over the past 34 years (1982–2015), as indicated by a statistically significant increasing trend of annual LAI (0.0063 m$^2$ m$^{-2}$ yr$^{-1}$, $p < 0.05$) (Figure 1). This long-term greening trend is mainly driven by a sharp increase in LAI after the implementation of the GfGP in 1999. During 1982–1999, regional averaged LAI increases at a rate of 0.0038 m$^2$ m$^{-2}$ yr$^{-1}$. This trend is almost doubled (0.0068 m$^2$ m$^{-2}$ yr$^{-1}$) in the second half (1999–2015) of the study period after the GfGP was enacted. The greening trend is particularly high over the 11 main revegetation catchments with an average increasing rate of 0.0106 m$^2$ m$^{-2}$ yr$^{-1}$ (ranging from 0.0013 to 0.0277 m$^2$ m$^{-2}$ yr$^{-1}$). Moreover, about 80% of the Loess Plateau has experienced increased LAI over 1999–2015 (statistically significant in ∼36% of the Plateau), especially in the central and eastern parts of the Plateau (Figure 1).

Observed long-term $Q$ shows an interesting change over the past 34 years. Despite the fact that annual $Q$ in all 11 catchments has declined with an average rate of $-0.77$ mm yr$^{-2}$ (ranging from $-1.67$ mm yr$^{-2}$ to $-0.15$ mm yr$^{-2}$) during 1982–2015, this declining trend in $Q$ has dramatically slowed down since the initiation of large-scale revegetation practices (i.e., 1999–2015). Specifically, trends of annual $Q$ during 1982–1999 vary from $-6.40$ to $0.20$ mm yr$^{-2}$ across the 11 catchments, with an average trend of $-1.34$ mm yr$^{-2}$. In contrast, after the implementation of GfGP in 1999, 8 out of the 11 catchments shows an increasing trend ($p$-value < 0.05) in annual $Q$, with an average trend over all 11 catchments reversing to a positive rate of 0.50 mm yr$^{-2}$ (ranging from $-1.03$ mm yr$^{-2}$ to 2.70 mm yr$^{-2}$) for the following 17 years (1999–2015) (Figure 1). For the remaining three catchments still showing declined $Q$ after 1999, their decreasing trends are much smaller than those before the implementation of GfGP (Figures 1 and S7 in Supporting Information S1).

3.2. Anatomy of Water Budget Changes Over the Loess Plateau After the GfGP

To understand why recent $Q$ increases, we examine changes in water budgets in the Loess Plateau since the implementation of GfGP (1999–2015, Figure 2). Consistent with previous findings (Feng et al., 2016; Shao et al., 2019), $E$ shows an increasing trend at the plateau scale (at a rate of 3.66 mm yr$^{-2}$) and in all 11 catchments (at an average rate of 5.59 mm yr$^{-2}$, ranging from 1.54 to 10.67 mm yr$^{-2}$) after the implementation of GfGP in 1999. This indicates that vegetation restoration does lead to higher overall water consumption in the region. Meanwhile, observed $P$ over the entire Plateau (at a rate of 6.42 mm yr$^{-2}$) and 11 catchments (at an average rate of 7.57 mm yr$^{-2}$, ranging from 3.70 to 14.68 mm yr$^{-2}$) also show upward trends, but with larger magnitudes than those of $E$. The stronger increase of $P$ than $E$ over the Loess Plateau directly leads to an increased surface water yield ($P$–$E$, at a rate of 2.76 mm yr$^{-2}$). Out of the 11 catchments, $P$ increases faster than $E$ (so increased water yield) over 8 of them (except for Weihe, Tuwei, and JialuRiver catchments) (Figure 2). At the pixel level, positive trends in $P$–$E$ are detected over 82.3% of the entire Loess Plateau, suggesting an overall increased surface water yield in the region (Figure S8 in Supporting Information S1). As a result of catchment water balance, changes in catchment $\Delta W$ also show an increasing trend in most of the 11 catchments during 1999–2015, with an averaging trend of 1.50 mm yr$^{-2}$ (ranging from $-2.93$ to 8.68 mm yr$^{-2}$) (Figure 2).

3.3. Impacts of Vegetation Restoration on Climate and Hydrology in the Loess Plateau

Our above analysis suggests that observed increases in water yield during 1999–2015 in the Loess Plateau are mainly caused by faster increases in $P$ that outpace the rate of $E$ increases. To quantify the impacts of vegetation changes on local $P$, we conduct two sets of coupled land-atmosphere simulations based on the WRF Model with and without considering vegetation dynamics (denoted as WRF-DYN and WRF-CRL, respectively, see Methods for details). Our modeling results indicate that incorporating vegetation dynamics in WRF (WRF-DYN) is key to improve the $P$ simulations (Figures 3a and 3b). Compared to the control experiment (WRF-CTL, no vegetation
dynamics), which substantially underestimates the observed climatology of annual $P$ (448.6 mm yr$^{-1}$) and its long-term (1999–2015) trend (6.42 mm yr$^{-2}$, $p < 0.05$), WRF-DYN well reproduces the magnitude (443.7 mm yr$^{-1}$) and trend (5.10 mm yr$^{-2}$, $p < 0.05$) of annual $P$ after considering vegetation dynamics (Figures 3a and 3b). We estimate that increases in LAI during 1999–2015 in the Loess Plateau have led to enhanced surface evapotranspiration by 17.2% (2.66 mm yr$^{-2}$, Figures 3f and 4), which subsequently increases water vapor content by 5.4% (2.69 kg kg$^{-1}$ m s$^{-1}$) within the atmospheric boundary layer (Figure 4). In addition, increased LAI reduces surface albedo (Figures 3c and 3d), allowing the land to absorb more solar radiation. The increased available energy results in a higher surface temperature and sensible heat flux from the land to the atmosphere, despite a concurrent cooling effect introduced by enhanced evapotranspiration. On average, estimated surface temperature, near-surface air temperature (at 2 m height), and sensible heat flux increase by 0.45°C, 0.35°C, and 3.79 W m$^{-2}$, respectively. Together they lead to increased convective available potential energy convective (CAPE) by 17.2% and increased vertical velocity by 18.9% (Figures 3h and 3i). Higher CAPE and vertical velocity indicate larger convective instability of the atmospheric boundary layer. This, together with increased atmospheric moisture content, jointly promote increases in $P$. Our modeling results show that vegetation restoration on the Loess Plateau has led to an increased annual $P$ by 15.0% (or 1.8 mm yr$^{-2}$), which contributes $\sim$35% to the total simulated $P$ increase (5.1 mm yr$^{-2}$) in the region (Figure 4).

In addition to the overall $P$ increase, extreme $P$ events (defined as rainfall intensity larger than 12 mm day$^{-1}$) decline at a rate of $-0.27\%$ yr$^{-1}$ during 1999–2015 when vegetation dynamics are considered, compared to the scenario without vegetation change (Figure 4). The declined extreme $P$ with increased total $P$ amount potentially enhances soil infiltration and consequently leads to increased water storage in the region. Although local

Figure 2. Observed trends of water budget over the Loess Plateau after the Grain for Green Project (GfGP). Changes in the trend of precipitation ($P$), evapotranspiration ($E$), water yield ($P-E$), and soil water storage ($\Delta W$) over the Loess Plateau (maps in central panels) and in the 11 catchments (surrounding bar plots) after the implementation of GfGP (1999–2015). The cross in the map and asterisks in the bar plots indicate that trends are statistically at the 95% confidence level.
Figure 3. Precipitation changes induced by the Grain for Green Project and the underlying physical mechanisms. Observed and Weather Research and Forecast (WRF) simulated precipitation with static (control experiment) and dynamic vegetation scenarios over the Loess Plateau at (a) interannual and (b) monthly time scales. (c) Temporal evolution of annual mean Leaf Area Index and Albedo over the Loess Plateau. Comparison of simulated energy fluxes ((d): net radiation; (e) sensible heat flux; (f) latent heat flux) between two WRF scenarios. Impact of revegetation on atmospheric dynamics: (g) land surface temperature, (h) convective available potential energy, (i) vertical velocity, and (j) integrated moisture flux from 700 to 300 hPa pressure levels. The box plot in panels (d−h) represents the distribution of all pixels.
Figure 4.
$E$ increases after GfGP, the increase of $P$ is at a much faster rate than that of $E$ (Figure 4). This, combined with decreased extreme $P$, leads to an enhanced surface water yield ($P$–$E$) by 2.44 mm yr$^{-2}$, which closely matches the observed water yield increase in the region (i.e., 2.76 mm yr$^{-2}$).

4. Discussion

Previous studies suggest that vegetation restoration on China’s Loess Plateau has led to a considerable reduction in $Q$ at the basin scale (Feng et al., 2016; S. Wang et al., 2016) and serious soil desiccation at the site level (H. Chen et al., 2008; Jia et al., 2017; Y. Wang et al., 2011; W. Yang, 2001), threatening the region’s water resources. Here, we examine changes in surface water budgets across the entire Loess Plateau and in 11 main revegetation catchments. Consistent with previous findings (H. Chen et al., 2008; Feng et al., 2016; Jia et al., 2017; Y. Wang et al., 2011; S. Wang et al., 2016; W. Yang, 2001), we find that there is a significant reduction in annual $Q$ over the entire study period (1982–2015) in all 11 revegetation catchments. However, after the implementation of GfGP in 1999, $Q$ records do not support the declined water resources conclusion claimed by previous studies. Instead, observed $Q$ increases in most of the catchments and surface water yield also exhibit an upward trend across the majority of the Plateau (Figures 1, 2, and, S7 in Supporting Information S1). These results strongly suggest that historical revegetation does not reduce regional water availability in the Loess Plateau.

The increased surface water yield is caused by increased $P$ that outweighs increases in $E$ (Figure 2). Our WRF-based simulations show that the enhancement in local moisture recycling caused by revegetation-induced redistribution of water and energy fluxes is the key driver for $P$ increases in the Loess Plateau during the revegetation period (1999–2015) (Figures 3 and 4). The increased $P$ caused by revegetation, in turn, benefits surface water yield and enhances the long-term sustainability of the GfGP. Unfortunately, this important feedback process has been ignored in previous analyses assessing revegetation-induced changes in hydrology in this region (H. Chen et al., 2008; Feng et al., 2016; Jia et al., 2017; Y. Wang et al., 2011; S. Wang et al., 2016). The land-atmosphere system is a fully coupled system; taking observed climate variables as independent external forcings while only accounting for revegetation-induced $E$ increases would amplify the negative role of revegetation on surface water availability. For example, if the contribution of revegetation to local $P$ increases (6.42 mm yr$^{-2} \times 34.9\% = 2.24$ mm yr$^{-2}$) were neglected and given the same strength of $E$ increases (3.66 mm yr$^{-2}$), surface water yield would present a much smaller increasing trend (i.e., 0.52 mm yr$^{-2}$) than the observed one (2.76 mm yr$^{-2}$). These results highlight the importance of considering the feedback of vegetation changes to $P$ in regional climate modeling and hydrological assessment studies. Nevertheless, a large proportion of the increased surface water yield is partitioned to the increase of $\Delta W$ and less to $Q$ that can be directly accessed for human use. This is likely due to the thick soil layer (typically ranging from 30 to 80 m (Y. Wang et al., 2011)) that stores most of the infiltrated water in the region.

Finally, it should be noted that despite the overall increases in regional surface water yield, decreases in surface water yield can occur at local scales. Our results show that decreased water yields are found in 17.7% of the Loess Plateau, which is primarily distributed in arid regions (mean annual $P$ less than 400 mm) with forests being the main revegetation type. Field experiments show that soil water content under forests is significantly lower than that under grasslands and shrublands, and the decline of soil water content in tree-planted areas are significantly greater than that in grass or shrub areas (Gao et al., 2014) (Figures S5 and S6 in Supporting Information S1). This suggests that planting trees may have larger negative impacts on surface water availability than planting grasses and/or shrubs, which is likely due to a higher foliage cover and a more developed rooting system of trees that generally result in higher water consumption than grasses and shrubs (Figure S9 in Supporting Information S1). Nevertheless, revegetated forests only occupy less than 18.0% of the total area and revegetated grasslands and shrublands account for more than 40.0% of the entire region (Figure S10 in Supporting Information S1). Recent
studies (e.g., Tuinenburg et al., 2022) find that large-scale reforestation may enhance global precipitation levels due to enhanced moisture supply that can alter atmospheric circulation. Our study provides new regional evidence that atmospheric circulation contributes nearly two-thirds of the P increase over the Loess Plateau. While reforestation could contribute to P increase through local land-atmosphere feedbacks, the resulting water yield also depends on changes in large-scale atmospheric circulation patterns (Tuinenburg et al., 2022). Without changes in atmospheric circulation, P increase might not outpace E increase and the overall water budget following revegetation would be different. In addition to P uncertainties, additional uncertainties may come from E, given the large structural and parameterization uncertainties in existing E products (Cheng et al., 2021; X. Liu et al., 2020; Trugman et al., 2018), which will further complicate the water budget analysis. A more comprehensive uncertainty quantification warrants further research, which should consider all ensembles of E, not just the ensemble mean. Our findings can guide ongoing and future revegetation activities (e.g., selecting optimal vegetation species at optimal locations) in other arid and semi-arid regions, beyond the Loess Plateau, towards sustainable water and ecosystem management.

Data Availability Statement
Monthly Q observations from 1982 to 2015 in 11 main catchments on the Loess Plateau are obtained from the Ministry of Water Resources of the People’s Republic of China (http://www.mwr.gov.cn/sj/tjgh/zyygh/). Monthly gridded P during 1982–2015 with 0.1° spatial resolution is obtained from the China Meteorological Forcing Data set (http://www.tpcdc.ac.cn/zh-hans/data/7a35329c-c53f-4267-a007-e0037d913a21f). In situ measurements of P at 76 meteorological stations are provided by the Meteorological data center of the China Meteorological Administration (http://www.nmic.cn/data/cdcedetail/dataCode/SURF_CLI_CHN_MUL_MMON_19812010.html). The Global Land Surface Satellites Leaf Area Index, surface albedo, and vegetation coverage products can be accessed from http://www.glass.umd.edu/Download.html. The GLEAM E product can be downloaded from the GLEAM home/landing page (https://www.gleam.eu/), the users need to fill their email in the GLEAM home/landing page, and then will receive a password to the SFTP within a few minutes to download GLEAM E product. Satellite-observed global land cover products are available from the Copernicus Climate Change Service Climate Data Store (https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-land-cover?tab=overview). The European Centre for Medium-Range Weather Forecasts atmospheric reanalysis (ERA-Interim) can be downloaded from: https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim.

Acknowledgments
B. Zhang is supported by the National Natural Science Foundation of China (NSFC) (42041004, 42022001, and 41877150) and the National Key R&D Program of China (2020YFA0608403). L. Tian would like to acknowledge support from the National NSFC (42001029). X. Yang acknowledges support from the Singapore Ministry of Education. Tian would like to acknowledge financial support from the Singapore Ministry of Education Academic Research Fund Tier-1 Project (R-302-000-265-133). We thank the high-performance computing service platform in Lanzhou University (https://hpc.lzu.edu.cn/) for providing technical and hardware support. The computational work for this article was partially performed on resources of the National Supercomputing Centre, Singapore. We thank Chansheng He, Rui Shao, Biao Long, Xuejin Wang, and Tongxuan Su from Lanzhou University for collecting data.

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