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# **RESEARCH ARTICLE**

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#### **Key Points:**

- Annual ET significantly increased, caused by increased transpiration and interception, which was partly offset by decreased soil evaporation
- Although the average ET of forest was larger, the change in total ET of the region was dominated by that in grassland and cropland
- Vegetation greening and the intensifying ET were primarily associated with the rapid urbanization and agricultural intensification

#### **Supporting Information:**

Supporting Information S1

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# Rapid Urbanization and Agricultural Intensification Increase Regional Evaporative Water Consumption of the Loess Plateau

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Abstract Changing evapotranspiration (ET) will impact freshwater availability, knowledge of which is a critical prerequisite for policy development related to water resources management in an evolving climate, especially for water-limited regions. However, the socio-economic effects are not considered due to the lack of detailed information about this. Here we used a well-validated remote sensing model and multiple socio-economic factors to investigate the driving factors of ET changes over the Loess Plateau during 1982–2012. Results showed that the modeled annual ET significantly increased by  $\sim 2 \text{ mm yr}^{-2}$ during this period (p < 0.001), caused by increased transpiration (2.16 mm yr<sup>-2</sup>) and interception  $(0.27 \text{ mm yr}^{-2})$ , which was partly offset by decreased soil evaporation  $(-0.47 \text{ mm yr}^{-2})$ . Meanwhile, although the average ET of the forest was larger ( $480.4 \pm 14.8 \text{ mm yr}^{-1}$ ), it was found that the change in total ET of the region was dominated by that in grassland and cropland (1.1 km<sup>3</sup> yr<sup>-2</sup>, 90% altogether). Factorial simulations indicated that the intensifying ET over 79.4% and 9.1% of the study area can be explained by vegetation greening and climate change, respectively. Further analysis suggested that the vegetation greening and the increased ET were primarily associated with the rapid urbanization and agricultural intensification. Our findings highlight the potential unfavorable effects of socio-economic activities on water resources management on this coupled natural-human system that is already facing water scarcity issues.

# 1. Introduction

Water is especially valuable for food production and ecosystem functioning (Immerzeel et al., 2020; Oki & Kanae, 2006). Global trends of population growth, rising living standards, and rapidly increasing urbanization are increasing the demand for water resources (Florke et al., 2013; Steffen et al., 2015; Wada et al., 2014). Added to this is the growing threat of climate change which will have enormous effects on water availability, and thus challenge global sustainable development (Qin et al., 2020). It has been reported that water scarcity affects more than 40% of the global population and is projected to rise. Over 1.7 billion people are currently living in river basins where water use exceeds recharge (https://www.un.org/sustainabledevelopment/ water-and-sanitation/). The contradiction between the supply and demand of water resources is particularly strong in arid and semi-arid regions where these competing uses can be found upstream, downstream, and sometimes across borders (Kahil et al., 2019; Li et al., 2018; Veldkamp et al., 2017; Yin et al., 2017; Zhou et al., 2019). As the major component of water balance, evapotranspiration (ET) returns about 60% of annual precipitation to the atmosphere through biotic transpiration and abiotic evaporation from rainfall interception and bare soil (Oki & Kanae, 2006; Zeng et al., 2018). This percentage can reach 90% in some water-limited regions (Bastiaanssen et al., 2007; Xu et al., 2020), thereby having a major influence on the availability of water resources (Dijke et al., 2019; Jung et al., 2010). Therefore, understanding of the spatial and temporal variation in ET and its driving factors is critical for water resources management (Evaristo & McDonnell, 2019; Piao et al., 2010; Yang et al., 2012; Zhang et al., 2017).

The Loess Plateau is a water-limited region and is well known for its high soil erosion rates. In order to address pressing environmental problems and to improve ecosystem services, a series of large-scale



conservation programs have been implemented by the Chinese government since the beginning of this century (Bryan et al., 2018; Liu et al., 2008). According to satellite observation, vegetation coverage on the Loess Plateau has almost doubled between 1999 and 2013 (Chen et al., 2015), especially in low-coverage areas (Fu et al., 2016). However, many studies based on observation (filed experiment and satellite observation) and models have pointed that such large-scale vegetation restoration has a strong effect on the hydrological cycle (Feng et al., 2017; Huang et al., 2020; McVicar et al., 2007; Zhang et al., 2020) and aggravate water shortages in this coupled natural-human system that is already facing water scarcity issues (Liang et al., 2015; Wang et al., 2016). Nevertheless, much work has focused on soil moisture, groundwater recharge, and water yield but pay less attention to the dynamics of ET which is the most active process in the regional hydrological cycle. Until recently, some researchers have explored the variation of ET in response to climate change and human activities (Gao et al., 2020; Jin et al., 2017; Lv et al., 2019; Shao et al., 2019; Wang et al., 2020). However, most of these research efforts were limited to specific regions or within shorter periods. More importantly, they overlooked the effects of multiple socio-economic factors, which may exert directly and indirectly effects on vegetation dynamics and subsequent ET (Chen et al., 2019). This knowledge gap counts as one of many barriers to developing policy and achieving UN Sustainable Development Goals (SDGs, 6.6) targets on water resources (https://sustainabledevelopment. un.org/partnerships/goal6/). Therefore, a detailed study of the effects of these factors on changes in ET is still needed.

There are various methods for ET estimation. In situ measurements, such as sap flow measurement, eddy covariance technique, and Bowen ratio systems, are generally regarded as the most reliable methods (Baldocchi et al., 2001; Jiao et al., 2019; Wagle et al., 2015; Zhang et al., 2008). However, these methods or observation networks cover only a small portion of the terrestrial ecosystem of land surface and are limited to measurement of a small scale (point, field, and landscape scale). Sole reliance on individual sites may lead to biased estimates at regional scales, as many sites cannot represent a larger area (Rahman et al., 2001; Wang & Dickinson, 2012; Wylie et al., 2003). Alternatively, considerable efforts have been made to develop process-driven land surface models and or hydrological models such as Community Land Model Carbon-Nitrogen version 4.0 (CLMCN4) (Flanagan & Syed, 2011), Organizing Carbon and Hydrology In Dynamic Ecosystems (ORCHIDEE) (Krinner et al., 2005), Soil and Water Assessment Tool (SWAT) (Baker & Miller, 2013), and Variable Infiltration Capacity model (VIC) (Xie et al., 2015) to understand terrestrial water cycle mechanism at different spatial scales. However, besides suffered from multitudinous parameters, these models are generally based on simplifying scientific hypotheses about how ecosystems are structured and how vegetation responds to changes in the environment (Anav et al., 2015; Beer et al., 2010). Therefore, different sets of equations, parameter values, and forcing variables result in different estimates of ET.

Fortunately, satellite remote sensing, which can capture land surface information from larger geographic extents, provides an effective tool and method for deriving the ground parameters for ET simulation at a large scale (Zhang et al., 2016). By integrating satellite measurements of optical parameters that are directly related to vegetation activity (e.g., leaf area index and incoming photosynthetically active radiation) with ground-based climate data, numerous models have been proposed for estimating ET at the regional or global scale over the past decades, such as machine learning (ML) models (Fang et al., 2020; Jung et al., 2009), the surface energy balances (SEB) models (Bastiaanssen et al., 1998; Kustas & Norman, 1999; Sun et al., 2009), and the Penman-Monteith (PM) models (Mu et al., 2011; Zhang et al., 2016, 2019). These models generally performed well in comparison with flux tower observations at different ecosystems worldwide. However, the performance of ML-based models is highly dependent on the observed sample and suffers from the assumptions in a space for time substitution which makes some uncertainties in ET trends or variability (Jung et al., 2011; Zeng et al., 2014). The accuracy of the SEB models largely relies on the quality and reliability of thermal remote sensing inputs which are limited to clear-sky conditions (Zhang, Kimball, & Running, 2016). In this study, a PM-based model, which is driven by satellite observation vegetation index and surface meteorological input (Jin et al., 2017; Mo et al., 2015), was applied to estimate ET on the Loess Plateau from 1982 to 2012. Then, we explored the temporal and spatial changes in ET and identified its climate and anthropic controlling factors.



# 2. Methods and Materials

#### 2.1. Model Algorithm

A remote sensing model based on the vegetation index and meteorological factors was used to estimate ET of the Loess Plateau. The ET includes three components, namely, vegetation transpiration ( $E_t$ ), evaporation from the soil surface ( $E_s$ ), and interception ( $E_t$ ):

$$ET = E_t + E_s + E_i \tag{1}$$

The calculation of  $E_t$  is based on the water cover fraction of canopy ( $f_{wet}$ ) and the potential transpiration ( $E_{tp}$ ), which is influenced by temperature and water stress, expressed as follows:

$$E_t = (1 - f_{wet}) E_{tp} f_t f_w \tag{2}$$

$$f_{wet} = RH^4 \tag{3}$$

where  $f_t$  and  $f_w$  are the stress functions of air temperature and atmospheric water vapor pressure deficit, respectively, and RH is relative humidity (%).

Potential transpiration rate is calculated with the PM equation as follows:

$$E_{tp} = \frac{1}{\lambda} (\Delta R_{nc} + f_c \rho C_p D / r_a) / (\Delta + \gamma \eta)$$
(4)

where  $\lambda$  is the latent heat of vaporization of water (J kg<sup>-1</sup>);  $\Delta$  is the slope of saturation vapor pressure curve (kPa °C<sup>-1</sup>);  $R_{nc}$  is the net radiation absorbed by the canopy (MJ m<sup>-2</sup> d<sup>-1</sup>);  $f_c$  is the fractional cover of vegetation;  $\rho$  is the air density (kg m<sup>-3</sup>);  $C_p$  is the specific heat capacity of air (MJ kg<sup>-1</sup> °C<sup>-1</sup>); D is the saturated water vapor pressure deficit of air (kPa);  $r_a$  is the aerodynamic resistance between the canopy and the reference height (s m<sup>-1</sup>);  $\gamma$  is the psychrometric constant (kPa °C<sup>-1</sup>); and  $\eta$  is the ratio of the minimum stomatal resistance of a natural plant functional type to that of the reference crop and the minimum stomatal resistances are adopted as Keenan et al. (2014) and Bastiaanssen et al. (2012).

The estimation of fractional vegetation cover  $(f_c)$  is based on the measures of the transmittance of light through the canopy considering the vegetation elements as opaque (Xiao et al., 2016):

$$f_c = 1 - P_{tr}(0) \tag{5}$$

$$P_{tr}(\varphi) = e^{-\sqrt{a} \times k_c(\varphi) \times \Omega \times LAI}$$
(6)

$$k_c(\varphi) = \sqrt{x^2 + \tan^2(\varphi)/x + 1.774 \times (x + 1.182)^{-0.733}}$$
(7)

where  $P_{tr}(\varphi)$  is the fraction of the light transmitted through the canopy (%),  $\varphi$  is the solar zenith angle (degree), *a* is the absorptivity of leaves for radiation,  $\Omega$  is the clumping index taking into account the non-random spatial distribution of phyto-elements within the canopy radiation, LAI is the leaf area index of the canopy,  $k_c(\varphi)$  is the canopy extinction coefficient, and *x* is the ratio of average projected areas of canopy elements on horizontal and vertical surfaces.

The expressions of constraints from air temperature ( $f_t$ ) and water vapor pressure deficit ( $f_w$ ) are as follows (Mu et al., 2007; Zhang et al., 2010):

$$f_t = \exp\left(-\left[\left(T_a - T_{opt}\right)/T_{opt}\right]^2\right)$$
(8)

$$f_w = (D - D_o) / (D_c - D_o)$$
(9)

where  $T_a$  is the air temperature (°C);  $T_{opt}$  is the optimal temperature for canopy transpiration (20 °C); and  $D_o$  and  $D_c$  are the water vapor pressure deficits when stomata starts to shrinking and closes completely (kPa), respectively.



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The actual soil evaporation ( $E_s$ ) is calculated using potential soil evaporation ( $E_{sp}$ ) and soil moisture constraint function (Fisher et al., 2008). This function is based on the complementary hypothesis of Bouchet (1963), which defines land-atmosphere interactions from air vapor pressure deficit and relative humidity.

$$E_s = \min(E_s, E_{ex}) \tag{10}$$

$$E_s = (f_{wet} + f_{SM} \times (1 - f_{wet})) \times E_{sp}$$
<sup>(11)</sup>

$$f_{SM} = RH^{D/\beta} \tag{12}$$

$$E_{sp} = \frac{1}{\lambda} \left[ \Delta (R_{ns} - G) + (1 - f_c) \rho C_p D / r_{as} \right] / (\Delta + \gamma)$$
(13)

where  $f_{SM}$  is the soil moisture constraint which is an index of soil water deficit;  $\beta$  define the relative sensitivity of  $f_{SM}$  to air vapor pressure deficit;  $R_{ns}$  is the net radiation absorbed by soil surface (MJ m<sup>-2</sup> day<sup>-1</sup>);  $r_{as}$  is aerodynamic resistance between reference height and soil surface; and *G* is the soil heat flux (MJ m<sup>-2</sup> day<sup>-1</sup>).  $E_{ex}$  (mm day<sup>-1</sup>) decreases with the depletion of surface soil moisture, expressed as follows (Syvitski et al., 2005):

$$E_{ex} = S(t^{0.5} - (t-1)^{0.5})$$
(14)

where *S* is the soil-controlled exfiltration volume, determined by the soil texture and structure, which is usually falling by  $3-5 \text{ mm day}^{-1.5}$ , taken here as 4 mm day<sup>-1.5</sup>; *t* is the days, which elapsed since the day following rainfall.

The evaporation of precipitation intercepted by the canopy  $(E_i)$  is calculated following the Priestley and Taylor (1972):

$$E_i = f_{wet} \times R_{nc} \times a_{PT} \times \Delta / (\Delta + \gamma)$$
(15)

where  $a_{PT}$  is the Priestley-Taylor model coefficient for a wet surface condition (1.26).

The net radiation fluxes absorbed are divided with a weight of  $f_c$  for the canopy and the soil surface underneath respectively, namely,

$$R_{nc} = f_c R_n \tag{16}$$

$$R_{ns} = R_n - R_{nc} \tag{17}$$

where  $R_n$  is net radiation (MJ m<sup>-2</sup> day<sup>-1</sup>);  $R_{ns}$  is the net radiation absorbed by the soil surface (MJ m<sup>-2</sup> d<sup>-1</sup>); and  $R_{nc}$  is the net radiation absorbed by the canopy (MJ m<sup>-2</sup> day<sup>-1</sup>).

We calculated  $R_n$  using the formula according to Allan et al. (1998):

$$R_n = R_S - R_L \tag{18}$$

$$R_S = (1 - \alpha) R_{solar} \tag{19}$$

$$R_{solar} = \left(a_s + b_s \frac{n}{N}\right) R_o \tag{20}$$

$$R_L = \left(0.1 + 0.9\frac{n}{N}\right) (0.34 - 0.14\sqrt{e_a})\sigma(T_a + 273)^4 \tag{21}$$

where  $R_s$  and  $R_L$  are the incoming net shortwave radiation and the outgoing net long-wave radiation (MJ m<sup>-2</sup> day<sup>-1</sup>), respectively.  $R_{solar}$  is solar or shortwave radiation (MJ m<sup>-2</sup> day<sup>-1</sup>), and it was estimated from sunshine duration using the Angstrom-Prescott formula (Prescott, 1940) with the regression coefficients  $a_s$  and  $b_s$ . We used the averaged values of coefficients  $a_s$  and  $b_s$  at 9 National Meteorological Observatory stations within the Loess Plateau reported by Wang et al. (2012);  $\alpha$  is the land surface albedo; n and N are the actual and potential sunshine durations (h day<sup>-1</sup>), respectively;  $R_o$  is the incoming solar



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Figure 1. The Loess Plateau and the land cover distribution (2010).

radiation at the top of the atmosphere (MJ m<sup>-2</sup> day<sup>-1</sup>);  $e_a$  is the air vapor pressure (kPa); and  $\sigma$  is the Stefan-Boltzmann constant. We calculated the albedo from a combination of the black-sky albedo and white-sky albedo. The details of the albedo estimation are described in the Supporting Information S1.

#### 2.2. Simulation Strategy

In this study, we performed five experiments simulations to evaluate the contribution of each driving factor to changes in annual ET over the Loess Plateau during 1982–2012. (S1) varying vegetation (LAI, albedo, and land cover), (S2) varying mean air temperature, (S3) varying sunshine duration, (S4) varying relative humidity, and (S5) varying wind speed. The control simulation is the simulation forced by the mean values of driving factors during the period 1982–1985. The ET result from the control simulation indicates the value given the normal vegetation and climate conditions (1982–1985).

# 2.3. Study Area

The Loess Plateau (roughly within  $34^{\circ}-41^{\circ}N$ ,  $98^{\circ}-114^{\circ}E$ ), with an area of ~632,520 km<sup>2</sup>, is located in the middle reaches of the Yellow River basin in northwestern China, accounting for 6.3% of the entire land area of China (Figure 1). This region is consist of the entirety or parts of seven provinces: Ningxia (NX), Qinghai (QH), Gansu (GS), Shaanxi (SaX), Henan (HN), Inner Mongolia (IM), and Shanxi (SX). The long-term annual average precipitation is approximately 430 mm, with 60%–70% of the annual precipitation occurring between June and September in the form of high-intensity rainstorms, which often cause extreme soil erosion and drought frequently occurs. The annual average temperature is 9.0°C with a minimum mean temperature of  $-4.6^{\circ}C$  in winter and a maximum annual temperature reaching 20.9°C in summer (Yan et al., 2013). The major land cover types are grassland and cropland. The plateau acts an important role in food and energy production for China (Fu et al., 2016). Because of the rapid population growth and economic development, total water consumption was tripled during the past three decades



(Liang et al., 2019), which intensified the water resources competition of this coupled nature-human system and may undermine the regional socio-economic and ecological sustainability.

#### 2.4. Data

#### 2.4.1. Meteorological Data

Meteorological forcing data, mainly including precipitation, air temperature, sunshine duration, relative humidity, and wind speed, were obtained from the China Meteorological Data Sharing Service System at 65 stations located in and around the Loess Plateau (Figure 1). The point measurements of the stations were spatially interpolated by methods of gradient inverse distance square (GIDS) at a spatial resolution of 1 km. The GIDS has been proved more precise compared with the ordinary kriging and inverse distance squared interpolation method (Mo et al., 2015), for it provides accurate estimates of spatial climatic variables by considering the effects of terrain, latitude, and longitude through multivariate regressive analysis (Nalder & Wein, 1998).

#### 2.4.2. Vegetation Index Data

The Global Land Surface Satellite (GLASS) LAI data with a spatial resolution of 0.05° and a temporal resolution of 8 days from 1982 to 2012 were used for running the model. This product was retrieved from time-series Moderate Resolution Imaging Spectrometer (MODIS) and Advanced Very High Resolution Radiometer (AVHRR) surface reflectance data. Extensive validation for all biome types indicates that the GLASS LAI product can provide temporally continuous LAI profiles with more improved quality and accuracy compared to the current MODIS and CYCLOPES products (Mu et al., 2011). Therefore, the GLASS LAI product has been used widely for detecting the trend in vegetation (Zhu et al., 2016).

#### 2.4.3. Surface Solar Radiation Data

We used a daily surface solar radiation data set from the research element, Data Assimilation and Modeling Center (DAM) for Tibetan Multi-spheres to validate the solar radiation. This data set was produced by merging two data sets, the hybrid model estimate at 716 China Meteorological Administration stations and the artificial neural network (ANN)-based model estimate at 96 radiation stations. The latter, which has higher accuracy, was used to correct the hybrid model estimate dynamically at a monthly scale (Tang et al., 2013). In general, the DAM data set can be used for hydrological modeling, land surface modeling, engineering applications, and some radiation-related scientific studies. Finally, 69 stations located in the Loess Plateau from 1982 to 2010 were selected. A comparison with DAM data set indicates a good performance of the daily solar radiation simulations (Figure S1a), with a coefficient of determination ( $R^2$ ) of 0.98 and the root mean square error (RMSE) of 1.11 MJ m<sup>-2</sup> day<sup>-1</sup>.

#### 2.4.4. Land Surface Albedo Data

Land surface albedo is an important parameter to describe the radiant forcing in the climate system because it determines how much solar radiation will be absorbed at the land surface (Dickinson, 1995). A long-time series of global albedo products is needed to understand the mechanism of climate change (Liu et al., 2013). Therefore, we calculated the actual albedo (blue-sky albedo) from a combination of the black-sky shortwave albedo (BSA) and white-sky shortwave albedo (WSA) (see Supporting Information S1). Finally, the 8-day calculated albedo (GLASS albedo) were interpolated to daily values with the Lagrange polynomial method.

To verify the accuracy of the GLASS albedo, we used the 8-day composite MODIS Surface Reflectance Product (MOD09A1). MOD09A1 includes estimates of surface spectral reflectance for the seven spectral bands at 500-m spatial resolution, and atmospheric corrections for gases, thin cirrus clouds, and aerosols are implemented during the production of MOD09A1 (Vermote & Vermeulen, 1999). The production process of MOD09A1 first eliminates pixels with a low observational coverage and then selects an observation with the minimum blue band value during the 8-day period (Xiao et al., 2006). A linear combination of 7 MODIS spectral band was carried out to calculate albedo. The coefficients, shown in Table S1, were obtained from Liang et al. (1999), which have been shown to estimate shortwave albedo accurately. Results showed GLASS albedo compared well with MODIS albedo at the grid and regional scale:  $R^2$  of 0.79 and 0.52, respectively (Figures S1b and S1c).

#### 2.4.5. Land Cover Data

Land cover maps in 1980, 1995, 2000, 2005, and 2010 with the resolution of 1 km were used for ET estimation. The maps were generated from the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences (Liu et al., 2005). The China National Environmental Monitoring Center used historical US Landsat Thematic Mapper/Enhanced Thematic Mapper (TM/ETM) images and the missing





Figure 2. Monthly time-series comparisons between modeled ET and observed ET. (a) Haibei, (b) Shouyang, (c) Changwu, and (d) Shapotou.

scenes were supplemented by adopting the data before or after these years. The land cover map includes 10 main classes, needle-leaf forest, evergreen broadleaf forest, deciduous needle-leaf forest, deciduous broadleaf forest, mixed forest, shrubland, grassland, cropland, water, and others. However, due to the small area of forest (7.6%–7.8%) on the Loess Plateau, all the forest types were merged and used for the analysis. The land cover data were without the consideration of temporal changes for a certain period when land cover data were available. These data represent the land cover in five periods: (1) 1982–1989 (1980), (2) 1990–1999 (1995), (3) 2000–2004 (2000), (4) 2005–2009 (2005), and (5) 2010–2012 (2010).

# 2.4.6. ET Validation Data

In order to validate the modeled ET, several types of assessments were conducted. We first collected ET observed data from two flux tower sites (Haibei and Shouyang) (Liu et al., 2011) and two on-site observation (Changwu and Shapotou) within the Loess Plateau (Figure S2). The annual streamflow data at 25 hydrological stations from 1982 to 2012 used for water balance validation came from the National Earth System Science Data Center (Table S2), assuming that the annual change of water storage was negligible in the long term. Meanwhile, our study collected ET components data based on filed experiments from 14 studies (Table S3).

#### 2.4.7. Socio-Economic and Other Data

The gross domestic product (GDP), industrial added value, number of the agriculture, forest, husbandry and fishery (AFHF) employees, urbanization rate, chemical fertilizer, total power of agricultural machinery, and





**Figure 3.** Comparison of the estimated ET (1982–2012) to catchment water balance ET in 25 catchments within the Loess Plateau. (a) Five-year mean ET (mm yr<sup>-1</sup>); (b) annual ET trend (mm yr<sup>-2</sup>). The numbers in Figure 3b represent the catchment ID, as given in Table S2.



Figure 4. Validation of the ET components. (a) ET, (b-d) percentage of transpiration  $(E_t)$ , soil evaporation  $(E_s)$ , and interception evaporation  $(E_i)$  to evaportanspiration (ET), respectively.





**Figure 5.** Spatial distribution of mean annual ET and its components over 1982–2012. (a) Mean annual ET, (b) the percentage of  $E_t$  to ET (%), (c) the percentage of  $E_s$  to ET (%), and (d) the percentage of  $E_i$  to ET (%).

grain production at the county level during 1980–2012 were obtained from the statistical yearbook of each province and each city and the National Earth System Science Data Center. The missing data were filled with the nearest value. Given that most of the missing data are concentrated in the period 1980s, average or cumulative values for 1980–1984 and 1985–1989 were used for analysis. The investment and area of interventions of the six conservation programs were collected from Bryan et al. (2018). The irrigation water withdrawal for each province (except for Shanxi), Shanxi, and Hetao irrigation area were obtained from the Yellow River Water Resources Bulletin (http://www.yrcc.gov.cn/other/hhgb/), Shanxi Water Resources Bulletin (http://slt.shanxi.gov.cn/zncs/szyc/szygb/), and the Hetao Irrigation District Administration, respectively. The distribution of large irrigation district rasterized originally from a polygon map (Wang et al., 2010) and resampled to 1 km<sup>2</sup> spatial resolution.

# 3. Results

# 3.1. Model Validation

To test the robustness of the model, we first compared the monthly modeled ET against the flux tower ET and on-site observed ET (Figure 2). Result showed that the time-series variation in ET of these sites was





**Figure 6.** Box plot of annual ET for different land cover types. (a) Average ET (mm yr<sup>-1</sup>) and (b) total ET (average ET multiplied land cover area) (km<sup>3</sup> yr<sup>-1</sup>). Each box represents the interquartile range of the data (25%-75% quantile) and the whiskers are the maximum and minimum data (i.e., highest and lowest horizontal lines), respectively. The numbers in the bracket are the contribution of different land cover to regional total ET.

well captured by the model, with RMSE ranging from 12.5 mm month<sup>-1</sup> for Haibei to 20.4 mm month<sup>-1</sup> for Changwu and the corresponding  $R^2$  ranging from 0.6 to 0.93.

Meanwhile, the comparisons between simulated and observed each 5-year mean water balance ET (precipitation-streamflow) for the 25 catchments during 1982–2012 indicated that the model performed well over the long term, as judged by model statistics ( $R^2 = 0.83$ , RMSE = 60.5 mm yr<sup>-1</sup>) (Figure 3a). However, the modeled ET was slightly underestimated for most of the catchments. This is reasonable because the water balance-based ET is likely to be overestimated due to water withdrawal from the river (Figure S3). In addition, the estimated ET trend also compared reasonably well to the water balance ET trend ( $R^2 = 0.78$ , Figure 3b).

The ET components were also checked against field experiments covering the whole Loess Plateau (Figure S2). The comparison again suggested the good performance of the model, with  $R^2$  of the  $E_t/ET$ ,  $E_s/ET$ , and  $E_i/ET$  being 0.77, 0.76, and 0.69, respectively (Figure 4). Overall, the validation showed that the model was robust and it can be used to analyze the changes in ET over the Loess Plateau.

#### 3.2. Magnitude of ET

The spatial patterns of modeled mean annual ET and the percentage of ET components were shown in Figure 5. Generally, the annual ET over the study region exhibited large spatial heterogeneity and showed gradients increasing from the northwestern parts to the southeastern parts, which was consistent with previous studies (Jin et al., 2017; Shao et al., 2019). Annual ET was generally higher than 400 mm yr<sup>-1</sup> in the mountainous and southeastern plateau where forest and irrigated cropland were distributed (Figure 5a). Meanwhile, relative higher precipitation amount or warm temperature also support vegetation growth in these regions. By contrast, annual ET was usually less than 200 mm yr<sup>-1</sup> in the northwestern parts where the land cover was dominated by desert and the climate was extreme drier with mean annual precipitation less than 200 mm yr<sup>-1</sup>. In these areas, most of ET came from  $E_s$ , with the estimated  $E_s/ET$  percentage being above 90% (Figure 5c). In addition, it was obvious that annual ET in irrigation areas was relatively higher, suggesting a good performance of our model in shaping the spatial pattern of ET. Regarding the relative contribution of the different ET components, it was shown that in southeastern parts and irrigation regions,  $E_t$  and  $E_i$  were larger, whereas in other regions,  $E_s$  was a substantial contributor (Figures 5b–5d). Furthermore,  $E_i/ET$  in mountainous was as high as above 0.20, which was in line with observations from Jiao et al. (2018).

Averaged spatially over the whole plateau, the average annual ET from 1982 to 2012 was  $359.6 \pm 26.6 \text{ mm yr}^{-1}$  or 219.6  $\pm$  15.2 km<sup>3</sup> yr<sup>-1</sup>. E<sub>t</sub> accounted for ~40% of ET (144.2  $\pm$  22.6 mm yr<sup>-1</sup>), E<sub>s</sub> for ~44% (159.1  $\pm$  11 mm yr<sup>-1</sup>), and E<sub>i</sub> for ~16% (56.2  $\pm$  8.8 mm yr<sup>-1</sup>), which suggested that evaporation consumed more water than transpiration. The E<sub>t</sub>/ET was considerably lower than the global estimates that integrated

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**Figure 7.** Spatial patterns of annual trends of (a) ET, (b)  $E_t$ , (c)  $E_s$ , and (d)  $E_i$  from 1982 to 2012. Insets in each panel show pixels with significantly (p < 0.05) negative (red) or positive (blue) trends.

CMIP 5 models with filed observations ( $62 \pm 6\%$ ) (Lian et al., 2018). For different land cover types, as expected, forest showed the highest average annual ET of  $480.4 \pm 14.8 \text{ mm yr}^{-1}$  (Figure 6a). Shrub had the second-largest ET ( $431.5 \pm 14.9 \text{ mm yr}^{-1}$ ), which was approximately equal to that of irrigated cropland ( $424.5 \pm 37.7 \text{ mm yr}^{-1}$ ), followed by the rainfed cropland ( $382.8 \pm 34.1 \text{ mm yr}^{-1}$ ) and grassland ( $307.3 \pm 22.4 \text{ mm yr}^{-1}$ ). However, in terms of the total volumes of water evaporated, grassland and cropland (including rainfed crop and irrigated crop) contributed ~77% of the mean annual total ET (Figure 6b), which can be primarily ascribed to the large area (~78% of the study area).

# 3.3. Changes in ET

The upward trends occurred widely across the study area with 88.6% experiencing significantly positive trends of ET (Figure 7a). The highest increasing rates of ET were mainly distributed in the middle and southern parts of the plateau and reached up to 10 mm yr<sup>-2</sup>. By contrast, ET at only 11.4% of the plateau experienced a negative trend, which was scattered in the mountainous around the plateau. Strong positive ET trends were mainly as a result of increased  $E_t$  (Figure 7b). On the contrary, except for the northern parts,







Figure 8. Interannual changes of annual ET and its components during 1982-2012.

 $E_s$  over most of the region presented a decreasing trend (Figure 7c). Compared with  $E_t$  and  $E_s$ , the trend of  $E_i$  exhibited obviously mixed trend, with 38.8% of the area having significantly positive trends and 6.5% negative trends (p < 0.05), respectively (Figure 7d).

The average annual ET over the Loess Plateau presented a significantly increasing trend from 1982 to 2012 (p < 0.001), with a rate of ~2 mm yr<sup>-1</sup>, which means more than 60 mm increase in the annual ET during the past 31 years (Figure 8). This was caused by significant positive trends in E<sub>t</sub> (2.16 mm yr<sup>-2</sup>, p < 0.001) and slight positive trends in E<sub>i</sub> (0.27 mm yr<sup>-2</sup>, p = 0.12), which was partly offset by a significant but much lower negative trend in E<sub>s</sub> (-0.47 mm yr<sup>-2</sup>, p = 0.03). Meanwhile, the E<sub>t</sub>/ET percentage ratio during the recent decade (2000–2012) was obviously higher than the first 20 years (0.44 vs. 0.37).

The overall increasing trends in ET were also consistent among land cover types, with the increasing trends being all significant at the level of 0.05 (Figure 9). Rainfed cropland and irrigated cropland showed the largest increase in average ET at a rate of ~3 mm yr<sup>-2</sup>, followed by grassland (1.7 mm yr<sup>-2</sup>), forest (1.0 mm yr<sup>-2</sup>), and shrub (0.7 mm yr<sup>-2</sup>). However, when the area of different land cover types was considered, it was found that grassland and cropland (including rainfed and irrigated cropland) together accounted for ~90% of the estimated total ET increase (1.12 km<sup>3</sup> yr<sup>-2</sup>) over the study area (Figure 9f). By contrast, forest and shrub had a total of 0.69 km<sup>3</sup> (i.e., 0.022 km<sup>3</sup> yr<sup>-1</sup> × 31 years = 0.69 km<sup>3</sup>) and 0.77 km<sup>3</sup> (0.025 km<sup>3</sup> yr<sup>-1</sup>) increase of ET, respectively, which together contributes only 4% of the regional total ET increase over 31 years (1982–2012). Furthermore, it was found that the changes in total ET were mainly dominated by that in the constant vegetation (areas that experienced no change in the five land cover maps), regardless of the land cover types. Land cover change-induced ET has only accounted for 8.5% (change / [change + constant], expressed as a percentage) of the increase in regional total ET (Figure 9f).

#### 3.4. Attribution of ET Changes

In order to understand the control of ET changes on the Loess Plateau, we first analyzed the trends in satellite vegetation greenness index (LAI) and meteorological variables including precipitation and potential evapotranspiration (PET, the combined indicator of air temperature, sunshine duration, relative humidity, and wind speed) by using linear regression. The changes in the GLASS LAI showed significantly positive values over a large proportion (91.1%) of the plateau from 1982 to 2012 (Figure S4a), consistent with a recent report





**Figure 9.** Changes in annual ET for different land cover types during 1982–2012. (a–e) Interannual changes of average ET (mm yr<sup>-2</sup>) and (f) trend in total ET (km<sup>3</sup> yr<sup>-2</sup>). The \*\*\*, \*\*, and \*\* indicate the significance at the 99%, 95%, and 90% confidence interval, respectively. Constant means the trend in total ET where areas that experienced no change in the five land cover maps, otherwise they were defined as change.

from global terrestrial vegetation trends (Zhu et al., 2016). The regions with the largest greening trends (typically above 0.02 m<sup>2</sup> m<sup>-2</sup> yr<sup>-1</sup>, 28.3%) occurred in mid-southern and eastern Loess Plateau. By contrast, only 1.7% of pixels primarily concentrated in the Mu Us Desert area have experienced significantly decreasing trends in LAI. Overall, the whole region showed a significant upward LAI trend (0.01 m<sup>2</sup> m<sup>-2</sup> yr<sup>-1</sup>, p < 0.001), with a faster rate in the recent 10 years (Figure 10a). Annual precipitation presented a contrasting trend with positive values in northern and western parts but negative values in the remaining areas, producing a slightly decreasing trend of -0.36 mm per year over the entire region (Figures S3b and 10b). Contrast to precipitation, the annual PET increased over large areas in the study area (94%, Figure S3c), with a spatially averaged rate of 1.32 mm yr<sup>-2</sup> (p = 0.07) (Figure 10c). The average ET was correlated significantly with variations in GLASS LAI (r = 0.89, p < 0.001) but was not significant for annual precipitation (r = 0.37, p = 0.12) and PET (r = -0.12, p = 0.53) (Figure 10d). These variables explained as high as ~90% of the variation in annual ET.

The controlled factorial experiments under different scenarios (see section 2) suggested that vegetation greening (increased LAI) explained the largest contribution to the annual positive ET trend (1.95 mm yr<sup>-2</sup>), followed by temperature (0.15 mm yr<sup>-2</sup>). By contrast, relative humidity (-0.29 mm yr<sup>-2</sup>), sunshine duration (-0.18 mm yr<sup>-2</sup>), and wind speed (-0.06 mm yr<sup>-2</sup>) imposed a negative effect on ET (Figure 11a). Overall, climate change had a dominant role in the increasing ET trend over 9.1% of the study area





Figure 10. Interannual changes of (a) LAI, (b) precipitation (P), and (c) potential evapotranspiration (PET) from 1982 to 2012. (d) Relationship between ET and LAI, P, and PET. The \*\*\* indicates the significance at the 99% confidence interval.

(Figures 11b and 11d). Positive effects of climate change in the Ziwu Mountains and western Guanzhong irrigation area were attributed to rising temperature and sunshine duration (Figures S5a, S5b, S6a, and S6b). In comparison, the decline of relative humidity and wind speed may lead to the decreasing ET trend in some places in the Mu Us Desert and mountains surrounding the study region (Figures S5c, S5d, S6c, and S6d). However, all these positive or negative effects were exceeded by the impact of vegetation greening, which was further confirmed by the consistent spatial patterns of ET trends between ET-ALL (all forcing) and ET-V (only vegetation varying) (Figures 11b–11d). Meanwhile, we found that the effect of vegetation on changes in ET during 2001–2012 was much higher than that during 1982–2000 (Figure 11a).

Precipitation is the most important climatic factor limiting vegetation growth on the Loess Plateau, which presented a nonsignificant trend. However, LAI has increased significantly in this region (Figures 10 and S4a). Thus, anthropic activities may be the dominant drivers of vegetation dynamics, and we further focused on the changes in multiple socio-economic factors. Statistical data showed that the urbanization rate of the plateau increased from 35.2% in 1990 to 46.1% in 2012 (Figure 12a). By contrast, the number of AFHF employees firstly presented a gradual increase from the 1980s to 1999 (increased by 9%) and then obviously decreased from 2000 to 2012 (decreased by 13%) (Figure 12b), suggesting that fewer people were engaged in agriculture production during the recent 10 years. Meanwhile, the annual chemical fertilizer use and the total power of agricultural machinery increased from 2.3 million to 5.1 million tonnes and from 24 million kilowatts to 85.8 million kilowatts, a 1.2-fold and 2.6-fold increase, respectively (Figures 12c and 12d).

These factors were commonly seen as the main driving factors of the expansive greening on the Loess Plateau. Change in urbanization rate was significantly positive related with changes in leaf areas of forest, shrub, and grassland, with r = 0.54, r = 0.66, and r = 0.91, respectively (Figures 13a–13c), despite no clear correlation was found against the changes in forest and shrub leaf area in some provinces. Meanwhile, the leaf area of grassland was found to be negative correlated with the number of AFHF employees, with r = -0.85 and p < 0.001 (Figure 13d). In terms of cropland greening, chemical fertilizer and the total





**Figure 11.** Attribution of ET changes. (a) Modeled ET trends driven by vegetation dynamics (V), air temperature (T), sunshine duration (S), wind speed (W), and relative humidity (H) affecting ET over the Loess Plateau, (b) dominant driving factors of ET, defined as the driving factor that contributes the most to the increase (or decrease) in ET in each grid cell. Spatial patterns of linear trends in annual ET for (c) varying vegetation (LAI, land cover, and albedo varying), and (d) varying climate (T, S, H, and W varying). The \*\*\*, \*\*, and \* indicate the significance at the 99%, 95%, and 90% confidence interval, respectively. Inset in figure (a) shows yearly contributions of the vegetation and climate change to ET changes. Insets in figure (c) and (d) show pixels with significantly (p < 0.05) negative (red) or positive (blue) trends.

power of agricultural machinery were positively correlated with changes in irrigated and rainfed cropland leaf area (Figures 13e–13h). Moreover, it was found that the total grains production has increased by ~100% from 2.3 million tonnes in the 1980s to 4.5 million tonnes in 2012, although some decrease during 1999–2002 which was ascribed to the decline in the arable area (Figure S7).

This was further corroborated at the county level (Figure 14). Specifically, there was a positive correlation relationship between urbanization rate and leaf area of forest, shrub, and grassland in 48%, 43%, and 68% of the counties, respectively (Figures 14a–14c). By contrast, a negative correlation between AFHF employees and leaf area of grassland was found in 34% of counties (Figure 14d). The 51% and 64% of the counties for changes in cropland leaf area were significantly influenced by chemical fertilizer and the total power of agricultural machinery, respectively (Figures 14e and 14f).

Governmental policies and subsidies also stimulated vegetation greening. We selected the six major conservation programs of the Loess Plateau, which involved agricultural production and cultivated land protection,





**Figure 12.** Interannual changes of (a) urbanization rate, (b) number of the agriculture, forest, husbandry and fishery (AFHF) employees, (c) chemical fertilizer usage, and (d) total power of agricultural machinery from the 1980s to 2012. Different color represents each province. Variables before 1990 in figures (b–c) are the average annual values of the period 1980–1984 and 1985–1989.

forest ecosystem protection, and grassland restoration. Statistical data showed that ~196 billion Yuan was invested by the end of 2012 and most of these investments came from the period after 2000 (~97%, 189.7 billion Yuan). With the region's economic development (8.6-fold) (Figure 15c) and industrialization (12-fold) (Figure 15d), total annual investment increased steadily, from 4.5 billion in 2000 to 28 billion in 2012 (inset in Figure 15a). Correspondingly, the total area of these programs was 68.9 Mha during the study period (Figure 15b), with varying obviously between activities and over time (inset in Figure 15b).

# 4. Discussion

ET is a major component of the global water cycle and provides a critical nexus between terrestrial water, carbon, and surface energy exchanges (Jung et al., 2010). Changes in ET due to climate or land-use change have a major effect on water balance. Therefore, a comprehensive understanding of what control ET is an essential look forward (Dijke et al., 2019). Our results showed that the modeled ET exhibited a significantly increasing trend across the Loess Plateau over the past three decades (Figures 7 and 8), which was consistent with previous studies that recent global hydrological cycle has been enhanced (Huntington, 2006;





**Figure 13.** Driving forces of vegetation changes. Relationship between leaf area of forest (a), shrub (b), and grassland (c and d) versus urbanization rate and AFHF employees. Relationship between leaf area of rainfed cropland (e and g) and irrigated cropland (f and h) versus chemical fertilizer and machine power. The insets show the corresponding correlation coefficient of each province. The \*\*\*, \*\*, and \* indicate the significance at the 99%, 95%, and 90% confidence interval, respectively.

Zhang et al., 2015). But the trend in ET of the study area was much larger than the ensemble of all the observation-based reconstructions of global terrestrial ET over a similar period (Zeng, Piao, et al., 2018) (19.6 mm versus  $7.65 \pm 1.26$  mm yr<sup>-1</sup> per decade). More than 80% of this intensification of ET was caused by the increasing trend in LAI (Figure 11) and land-use change-induced total ET has only contributed 8.5% to the regional intensification of ET (Figure 9f), suggesting the significant impacts of vegetation greening on the water cycle. Indeed, a recent global terrestrial ET study found that Earth's greening has caused an increase of  $12.0 \pm 2.4$  mm yr<sup>-1</sup> in terrestrial ET, about  $55 \pm 25\%$  of the observed total increase in terrestrial ET over 1982–2011 (Zeng et al., 2018), which was also supported by some other researchers (Zhang et al., 2015; Zhang, Peña-Arancibia, et al., 2016). Strong evidences have pointed out that afforestation will reduce the water yield (Evaristo & McDonnell, 2019; Farley et al., 2005). Indeed, compared with grassland and cropland, with deeper rooting depth and larger LAI, forest can access more moisture from the ground and increases the re-evaporation of rainfall intercepted by leaves (Yang et al., 2016), thus the higher average ET (Figure 6a). However, due to the smaller area of forest (~7.7% of the study area), the magnitude and the change in total ET were dominated by that in grassland and cropland ecosystems (Figures 6b and 9f).

Vegetation greenness has been increasing globally since at least 1981 when satellite technology enabled large-scale vegetation monitoring (Piao et al., 2020). Factorial simulations with multiple vegetation models suggested that the rising atmospheric carbon dioxide concentration was the dominant driver of greening on





**Figure 14.** Correlation coefficient (*r*) between leaf area of (a) forest, (b) shrub, and (c) grassland versus urbanization rate. (d) Correlation coefficient between the leaf area of grassland and AFHF employees. Correlation coefficient between the leaf area of cropland versus (e) chemical fertilizer and (f) machinery power. White areas indicate the statistically insignificant county (p > 0.05).

the global scale, with other factors (such as climate change and land cover change) being notable at the regional scale (Zhu et al., 2016). In most middle and high-latitude areas over the Northern Hemisphere, it was generally assumed that temperature warming might be favorable for vegetation growth due to the direct warming effect on Rubisco enzymatic activity and indirect lengthening of the active growing season (Liu et al., 2018; Myneni et al., 1997; Nemani et al., 2003; Yang et al., 2015). This was also confirmed on the Loess Plateau. In response to global warming, the phenology timing in the Loess Plateau was 6.6 days earlier in spring and the date of the end of the growing season was delayed 9.6 days, respectively, over the past three decades (Sun et al., 2015), which may further regulate the annual ET amount (Ryu et al., 2008). Precipitation is a key limiting factor in the arid and semi-arid regions, which presented a nonsignificant trend in our study area (Figures 10b and S4b). Therefore, human activities were the key driver of the vegetation greening (54%-82%) of the Loess Plateau (Li et al., 2017). Since the 1990s, the population of this region has continued to increase and living standards have also improved, which has stimulated the demand for food consumption. To pursue high food production, profit-maximizing producers may substantially increase the factors of production. The direct consequence is that the total grain production of the plateau has doubled over the past three decades with stable or slightly decreased arable area land (Figure S7). The agricultural intensification with chemical fertilizer and total power of agricultural machinery might contribute to cropland vegetation greening (Figures 13e-13h, 14e, and 14f). Our result was consistent with Chen et al. (2019) and Wang et al. (2020) who concluded that the cropland greening in China and the Loess Plateau was mainly caused by human land-use management practices such as multiple cropping and heavy fertilizer usage. Urbanization and urban expansion, on the one hand, generally occurred at the expense of grassland or cropland, which directly related to the decrease in vegetation covers and ET of the land surface, thereby reducing atmospheric humidity and elevating vapor pressure deficit in urban core areas (Hao et al., 2018; Lin et al., 2020; Luo & Lau, 2019). However, the growth of urban areas





**Figure 15.** (a) Cumulative investment and (b) area for the six conservation programs (insets are annual value) from the 1980s to 2012. (c) Gross domestic product (GDP) and (d) industrial added value for each province from 1990 to 2012. Variables before 1990 in figures (a) and (b) are the cumulative values of the period 1980–1984 and 1985–1989.

only accounted for a small fraction of land changes in the Loess Plateau. On the other hand, rapid urbanization and decreased AFHF employees mean that more and more rural populations migrated to cities and fewer people were engaged in agricultural activities which may decrease human disturbance (such as animal husbandry and forage collection), thereby reducing the stress of the countryside areas within the Loess Plateau and promoting the vegetation growth (Figures 13a–13d and 14a–14d). Meanwhile, stimulated by a series of ecological conservation programs (Figure 15), Grain for Green program, in particular, farmers have switched livelihood activities dominated by subsistence farming into off-farm activities such as migrant labor and rural business or high market-oriented horticulture/orchard farming (Dang et al., 2020) and few people were intent on destroying vegetation that has been restored (Yin et al., 2014). Furthermore, economic development and industrialization may also play important role in enhancing farm household income and reducing the pressure on the land-system to provide livelihoods (Figures 15c and 15d). Nevertheless, it should be noted that the effects of these multiple socio-economic and policy factors operating concurrently on vegetation greening, and thus, ET are often integrated and blended (Bryan et al., 2018). These various mechanisms and processes driving ET changes were summarized in Figure 16.

Assuming that precipitation does not change in response to vegetation greening, increased ET will reduce soil moisture and runoff (Piao et al., 2020), with important implications for the region's economy and environment, especially for arid and semi-arid regions. Globally, the greening of the Earth has significantly decreased soil water content by  $1.41 \pm 0.42$  mm over the last 30 years (p < 0.01), dominated by the greening of water-limited regions (Zeng, Peng, & Piao, 2018). The evidence of our study showed that the increased ET,





Figure 16. Causal network. Variables connected by arrows denoting causal influence, with each relationship being positive (an increase in variable A leads to an increase in variable B or vice versa) or negative (an increase in variable A leads to a decrease in variable B or vice versa).

either because of the direct effect of temperature on evaporative demand or the indirect effect of land use practice and urbanization on vegetation greening, has exceeded the changes in corresponding precipitation (Figures 8 and 10b), coupled with the decreased of soil moisture ( $-0.02 \text{ m}^3 \text{ m}^{-3} \text{ decade}^{-1}$ , p < 0.001) and water yield ( $-0.29 \text{ km}^3 \text{ yr}^{-2}$ , p < 0.001) (Figure S8). These results indicated that the increase in evaporative water consumption caused by vegetation greening on the Loess Plateau is becoming increasingly serious. It should be noted that a recent study has found that the global greening-induced ET ( $12.0 \pm 2.4 \text{ mm yr}^{-1}$ ) increases the amount of atmospheric precipitable water, causing a precipitation increase of  $12.1 \pm 2.7 \text{ mm yr}^{-1}$  over the past 30 years (Zeng, Peng, & Piao, 2018). But in water-limited regions such as the Loess Plateau, the greening was modeled to significantly decrease soil moisture through the atmospheric water cycle.

As we have known, irrigation is the largest use of water worldwide, accounting for more than 84% of global consumption (Brauman et al., 2016). The total global water withdrawal has increased significantly during the past three decades, of which 68% driven by the increase in irrigation (Huang et al., 2018). Some studies have stated that irrigation increased global ET by 1.2%-2% (Müller Schmied et al., 2014; Rost et al., 2008). However, this was not the case in our study. In order to tackle water scarcity, the Chinese central government has arranged about five billion loans per year since 1996 to support the development of agricultural infrastructures. The main water-saving technologies include pipe systems, lined canals, sprinkler systems, and drip irrigation systems. These technological adoptions have greatly reduced the water use intensity of irrigation (Zhou et al., 2020). According to the Water Resources Bulletins, the irrigation was found to be decreased on the Loess Plateau, despite increased in Gansu and Shanxi provinces (Figure S9), suggesting that water-saving achievements were remarkable. Nevertheless, the total agricultural land water consumption (ET) has been increasing (Figure 9f), which may be due to the high agricultural yields (Figure S7). Meanwhile, to pursue high income, farmers in some parts of the southern plateau were more inclined to plant economic fruits (such as apple and apricot) on tablelands (Li et al., 2017), which also resulted in increased ET. These results highlight the potential negative effects of socio-economic activities on water resources management on this coupled natural-human system that is already facing water scarcity issues. For the long-term sustainability of water resources, vegetation restoration and agricultural land management should fully consider local water resources, as the current vegetation cover has already approached sustainable water resource limits (Feng et al., 2016; Liang et al., 2019). Future climate scenarios showed that the increasing rate of precipitation was similar to that of ET (Shao et al., 2019), which can maintain a



sustainable ecohydrological environment, but some studies showed the opposite cases (S. Zhang, Y. Yang, et al., 2018; S. Zhang, D. Yang, et al., 2018). Therefore, long-term continuous monitoring is needed.

In terms of the potential sources of uncertainties in the analysis, it should be noted that, although the land cover types varied during the study period, this study assumed that the cropland within the irrigation districts were all irrigated, otherwise it will be nourished by rainfall. Although the magnitude and trend of irrigated cropland ET can be clearly identified compared with that of the rainfed cropland, there are some patches of nonirrigated lands within irrigated pixels, which may result in some uncertainties. In addition, vegetation and climate have complex, interactive effects on terrestrial ET. Therefore, it was impossible to completely separate the effects of vegetation and climate change on ET, due to vegetation in response to land ecosystems and climate change (Zeng et al., 2017). On the one hand, climate change (e.g., warming) could promote vegetation productivity through an extension in the growing season duration and enhance nitrogen mineralization rate (Liang et al., 2017; Richardson et al., 2010) and thus exert an indirect effect on ET by influencing vegetation. On the other hand, vegetation greening can cool and warm local surface temperature (Li et al., 2015) and increase precipitation (Li, Piao, et al., 2018) through vegetation biophysical feedbacks. This highlights the necessity of better understanding the interactions among these driving factors and the underlying mechanisms responsible for biophysical and hydrological cycles.

# 5. Conclusions

In this study, we used a remote sensing model and multiple socio-economic factors to analyze the causes of ET changes on the Loess Plateau. The validation showed consistency between the simulations and observations from the flux-tower, on-site experiment, and water-balance. We then analyzed the spatial and temporal patterns of ET over the Loess Plateau from 1982 to 2012. Results showed that annual mean ET was  $359.6 \pm 26.6 \text{ mm yr}^{-1}$  or  $219.6 \pm 15.2 \text{ km}^3 \text{ yr}^{-1}$  during the study period, which presented gradients increasing from the northwestern parts to the southeastern parts. E<sub>t</sub> accounted for ~40% of ET (144.2  $\pm$  22.6 mm yr<sup>-1</sup>),  $E_s$  for ~44% (159.1 ± 11 mm yr<sup>-1</sup>), and  $E_i$  for ~16% (56.2 ± 8.8 mm yr<sup>-1</sup>). Over the past 31 years, the modeled annual ET significantly increased by ~2 mm yr<sup>-2</sup>, which was caused by increased  $E_t$  (2.16 mm yr<sup>-2</sup>, p < 0.001) and E<sub>i</sub> (0.27 mm yr<sup>-2</sup>, p = 0.12), but was partly counteracted by a significant but much lower decreased  $E_s$  (-0.47 mm yr<sup>-2</sup>, p = 0.03). For different land cover types, although forest can transpire and intercept more water due to a deeper rooting depth and larger leaves, the magnitude and the change in total ET were dominated by that in grassland and cropland (38% and 39%, 38% and 52%, respectively). Finally, we conducted the controlled factorial experiments to investigate the contribution of individual influencing factors to the spatial and temporal characteristics of ET. It was found that vegetation greening explained the largest contribution to the increasing ET trend (1.95 mm yr<sup>-2</sup>). Combined climate change effects lead to a negative impact on the ET (-0.21 mm yr<sup>-2</sup>), most notably in the northeastern parts. Overall, vegetation greening explained most of the ET increasing trends in the Loess Plateau (88.6%), while climate change resulted in intensifying ET over 9.1% of the region. Our study further indicated that the rapid development of urbanization and agricultural intensification leads to widespread vegetation greening and the consequent increased ET. For the long-term sustainability of water resources, the potential negative effects of socio-economic activities should be considered on the Loess Plateau that is already facing water scarcity issues.

# **Conflict of Interest**

The authors declare that they have no conflict of interest.

# Data Availability Statement

Meteorological data are available at http://data.cma.cn/data/detail/dataCode/A.0029.0001.html. GLASS LAI product and shortwave albedo are available at http://www.geodata.cn/data/index.html?word=LAI% 20%20avhrr0.05 and http://www.geodata.cn/data/index.html?word=abd%20avhrr0.05, respectively. Land cover maps are obtained from Liu et al. (2005). Flux tower observed ET are available upon request from Liu et al. (2011). Two on-site observed ET are provided by the National Earth System Science Data Center (available at http://www.cnern.org.cn/data/meta?id=41487 and http://www.cnern.org.cn/data/meta?id=40593). The observed streamflow data are obtained from the National Earth System Science Data Center



(http://www.geodata.cn/data/datadetails.html?dataguid=76188621745435&docId=10375). Socio-economic data are obtained from the statistical yearbook of each province, each city (available upon request from the corresponding author), and the National Earth System Science Data Center (http://loess.geodata.cn/data/datadetails.html?dataguid=234503177125355&docId=609, http://loess.geodata.cn/data/datadetails.html?dataguid=128950061187032&docId=693, http://loess.geodata.cn/data/datadetails.html?dataguid=254292 464098081&docId=688, http://loess.geodata.cn/data/datadetails.html?dataguid=113554975257899&docid=687, http://loess.geodata.cn/data/datadetails.html?dataguid=113554975257899&docid=687, http://loess.geodata.cn/data/datadetails.html?dataguid=25594046530378&docid=690, http://loess.geodata.cn/data/datadetails.html?dataguid=230103208918169&docid=689). It should be noted that all the above data are not posted publicly and one can request permission through registration and submitting the purpose and the financial support. The irrigation water withdrawal data are obtained from the Yellow River Water Resources Bulletin (http://slt.shanxi.gov.cn/zncs/szyc/szygb/), and the Hetao Irrigation District Administration. All data for this paper are properly cited and referred to in the reference list.

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