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Actual ET modelling based on the Budyko framework and the sustainability of vegetation water use in the loess plateau

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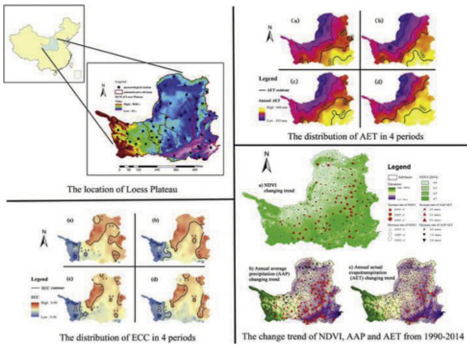
HIGHLIGHTS

- Water balance between precipitation and vegetation water use was studied to show the sustainability of ecology remediation.
- The Budyko Framework was used to simulate the regional actual evapotranspiration in loess plateau.
- Both the AAP and the AET were showing an increase trend, but the increase rate of the AAP was greater than the AET.
- It seems more sustainable generally for vegetation water use in most areas of loess plateau with the vegetation recovery.

GRAPHICAL ABSTRACT



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ABSTRACT

Jointly influenced by the natural factors and the artificial protection measures, the ecological environment of Loess Plateau has been significantly improved in recent years, but which has already brought about some water-related problems. To maintain the balance between precipitation and water consumption is an important foundation for sustainable development of the ecology remediation. This study used Budyko Framework to simulate the actual water consumption of 161 sub-basins from 1990 to 2014. Based on the simulation results, the research also analyzed the evolution characteristics of water balance in Loess Plateau from 1990 to 2014. Results show that, with the increase of vegetation coverage, the regional precipitation and actual evapotranspiration were both showing a significant increasing trend, and the increasing rate of precipitation was 1.91 mm/a on average, which was greater than the increasing rate of actual evapotranspiration of 1.34 mm/a. To further demonstrate the water balance regime in Loess Plateau, the evapotranspiration coefficient (ECC) was used to quantitatively indicate the ratio of the vegetation water consumption and the total precipitation. The average values of ECC were 0.868, 0.863, 0.851 and 0.837 respectively in four sub-periods of 1990–1999, 2000–2004, 2005–2009 and 2010–2014. The above analyses indicate that with the vegetation recovery and ecological restoration, the percentage of evapotranspiration in the total precipitation is keeping decreasing and in turn the percentage of water yield in the total precipitation is keeping increasing. Consequently, it seems more sustainable for vegetation water use in most areas of Loess Plateau currently.

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1. Introduction

Owing to its tendency to erode and collapse as well as to the impact of climate change (e.g., intensive rainstorms and extreme drought) and human activities (e.g., overgrazing and coal-mining), the Loess Plateau in China has become one of the most serious soil erosion and eco-environmentally vulnerable regions in the world (Zhu et al., 1983; Liang et al., 2013). To control severe soil erosion problems and to improve the ecological environment in the Loess Plateau, several soil and water conservation measures including afforestation, pasture reestablishment, terraces, and check-dams have been implemented since the 1950s (Wang et al., 2015a, 2015b). Among these measures, the Grain-for-Green project is a large and important reforestation campaign, which was started at the end of the 1990s under the support of the Chinese government. According to remote-sensed images, the average vegetation coverage in the Loess Plateau has significantly increased to as much as 59.6% in 2013, which is almost twice the vegetation coverage in the late 1990s (Chen et al., 2015). At the same time, along with an increase in vegetation coverage and restoration of the ecological environment, the amount of river sediment in the entire area has also significantly decreased, which was reduced by 26% in the period between 2000 and 2010 compared to that in the period between 1990 and 1999 (Wang et al., 2015a, 2015b). Despite this success, an argument emerged in recent years questioning the sustainability of the vegetation recovery because of limited water resources in the Loess Plateau. As is known to all, extensive vegetation recovery will result in excessive water consumption and a loss of soil water, thus causing a negative impact on the ecological sustainability in the Loess Plateau.

The Loess Plateau is located in a water-deficient inland region, where precipitation is the main source of water. At the same time, the depth of the vadose zone layer in the Loess Plateau is always large, with an average depth between 50 and 200 m. Therefore, precipitation alone is often insufficient in replenishing groundwater; likewise, groundwater is also unlikely to return to the soil layer to support vegetation growth (Zhang et al., 2014). Consequently, from the perspective of water balance, evapotranspiration and runoff are the two main causes of water loss in the Loess Plateau.

Obviously, an increase in vegetation coverage may cause more water consumption through evapotranspiration, which will probably alter the balance between water input and water output in the Loess Plateau, which in turn, brings about a series of negative impacts on the ecosystem and the environment. To maintain a sustainable development of the ecological system in the Loess Plateau, it is of great importance that the balance between precipitation and actual evapotranspiration (AET) is maintained. However, with the expansion of the “green area” in the Loess Plateau, the regional AET is showing a significant change with a high degree of uncertainty. Therefore, the main purpose of this study is to analyze the temporal and spatial evolution of the regional AET, which is also a key indicator for the sustainability of vegetation restoration in the Loess Plateau.

The Budyko model is showing great applicability in estimating regional AET and stream flow owing to its simplicity and flexibility (Budyko, 1969). Budyko (1958) first postulated that long-term average annual evapotranspiration at the basin scale is determined by precipitation (water factor) and available solar radiation (energy factor). Based on this assumption, Budyko (1974) derived a simple water balance model known as Budyko's Hypothesis that showed good agreement with long-term water balance data obtained from a number of catchments. The work of Budyko has led to more theoretical studies in trying to understand how climatic and catchment characteristics affect the equilibrium or long-term average water balance (Milly, 1994; Zhang et al., 2001; Potter et al., 2005).

Budyko's Hypothesis proposed an important relationship between annual average precipitation, actual evapotranspiration, and potential evapotranspiration. However, this relationship was only a conceptual expression when the Budyko framework was first proposed; therefore, it could not be directly used to analyze the water balance for a basin or catchment with high heterogeneity in underlying surface conditions and climatic variables. To overcome the shortcomings mentioned above, many studies were conducted to improve the Budyko framework to adapt the theory to accommodate complicated underlying surface conditions and changing environments (Cui and Sun, 1979; Wu, 1983; Yang, 1987; Zhang et al., 2004). Among these studies, Fu (1981) proposed an analytical expression (named Fu's Equation) to depict the relationship proposed in Budyko's Hypothesis, and this approach has received significant attention and was implemented extensively in China. Sun et al. (2007) applied Fu's Equation to analyze the elements of water balance in 108 basins in arid and semi-arid regions in China and has fully validated the applicability and feasibility of the equation within the Budyko framework.

As mentioned earlier, this study aims to analyze the evolution in the characteristics of water balance between precipitation and vegetation water consumption using the Budyko framework and to evaluate the sustainability of vegetation water use based on the condition of water resources in the Loess Plateau. The contents of this study can be summarized as follows: 1) The Budyko framework based on the water-heat coupling theory will be introduced in this study, and the annual AET in 161 sub-basins of the Loess Plateau from 1990 to 2014 will be estimated and validated; 2) The spatial and temporal distribution of precipitation, the PET, and the AET in the period between 1990 and 2014 will be analyzed, and 3) the evapotranspiration coefficient (ECC) will be introduced to quantify the sustainability of vegetation water use in the Loess Plateau. We will then calculate the annual ECC in the 161 sub-basins from 1990 to 2014 separately to reveal the regional water pressure induced by the combined influence of natural restoration and artificial protection measures in the Loess Plateau.

2. Materials and methods

2.1. Study area

The Loess Plateau is a large ecological and agricultural zone in China, located at the upper and middle reaches of the Yellow River (Fig. 1). The Loess Plateau covers an area of 628,000 km^2, with a latitude between 33°43'and 41°16′N and a longitude between 100°54′ and 114°33′E, which is surrounded by the Taihang Mountain to the east, the Riyue-Helan Mountain to the west, the Qinling Mountain to the south, and the Yinshan Mountain to the north. Therefore, it is a special plateau surrounded by mountains on all sides (as shown in Fig. 1).

From the perspective of administrative regions, the Loess Plateau is covered by a number of provinces such as Shanxi, Shaanxi, Gansu, Qinghai, the Ningxia Autonomous Region, and the Inner Mongolia Autonomous Region. The majority of the Loess Plateau experiences a sub-humid and semi-arid climate, with the average annual temperature ranging from 4.3 °C to 14.3 °C (Yu et al., 2015). Precipitation is mainly concentrated in the summer, ranging from 200 mm in the northwest to 750 mm in the southeast, 80% of which is distributed between June and September. Solar energy is abundant in the Loess Plateau, with 2200–2800 sunshine hours and $(5.0–6.3) \times 10^9$ J/m^2 of total solar radiation annually. The annual potential evapotranspiration is estimated to be much higher than the precipitation, ranging from 865 mm to 1274 mm.

The Loess Plateau has been one of the most important agricultural regions in China for thousands of years (Fu, 1989). Nevertheless, drought hazards have occurred frequently in the past few decades and have caused great agricultural and socio-economic losses (Boardman et al., 2003). The Loess Plateau is also an ecologically vulnerable area suffering from severe water shortages, serious soil erosion, and land degradation. Since the 1990s, the Chinese government has initiated a series of environmental restoration and protection programs. In this process, water is an important factor for vegetation recovery, agricultural sustainability, water conservation, and soil conservation.

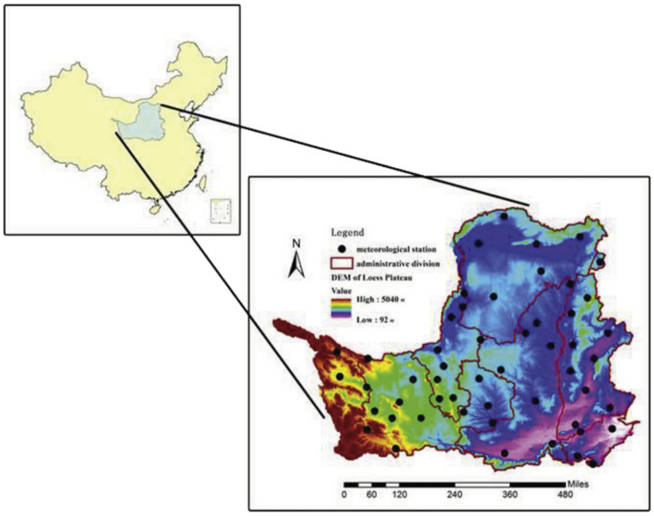

Fig. 1. Location of the Loess Plateau and the distribution of Meteorological stations.

As a result of the implementation of the Grain for Green Project, the vegetation coverage in the Loess Plateau changed dramatically. To study the temporal evolution of the actual evapotranspiration and precipitation, this research divided the entire study period (1990–2014) into four typical stages relative to the implementation of the Grain for Green Project, which are respectively, the period before implementation (1990–1999), the initial stage just after implementation (2000–2004), the middle stage (2005–2009), and the final stage (2010–2014). To study the spatial distribution of the AET and precipitation throughout the entire period, the Loess Plateau was divided into 161 sub-basins based on the Digital Elevation Model (DEM) analysis through the GIS platform (Fig. 2). Moreover, to verify the reliability of the estimated results by the Budyko framework, we also collected the runoff data in six watersheds within the Loess Plateau and retrieved the observed AET data in the six watersheds based on water balance analysis.

2.2. Data source and collection

This study will use and evaluate two types of data. The first type of data involves the required parameters used to estimate AET using the Budyko framework, which includes the data from weather stations (e.g., daily precipitation, daily maximum temperature, daily minimum temperature, daily relative humidity, daily sunshine hours or radiation intensity, daily atmospheric pressure, and wind speed), the soil type and properties, the high-resolution digital elevation data, and the vegetation types and coverage data. The date from the weather stations were downloaded through the China Meteorological Sharing Network from 52 stations evenly distributed in the Loess Plateau. The high-resolution digital elevation data was acquired from the Land Processes Distributed Active Archive Center of USA (http://www.gdem.aster.ersdac.or.jp/index.jsp), and the vegetation types and coverage data were obtained from the Data Center for Resources and Environmental Sciences in the Chinese Academy of Sciences (http://www.resdc.cn). The second type of data involves the observed runoff data collected respectively from six typical watersheds, which were used to retrieve the AET based on the water balance analysis. We compared the simulated regional AET with the observed AET to validate the reliability of the research results. In this study, runoff data in the six typical watersheds were obtained from six hydrological stations located at Yanchuan, Suide, Zhangjiashan, Qin'an, Hejin, and Liujiahe (the locations are shown in Fig. 2), which are available at the National Data Sharing Infrastructure of Earth System Science (http://www.geodata.cn/).

2.3. The regional AET estimation using Budyko framework

Based on the hydrological water–heat coupling theory, the annual regional actual evapotranspiration is mainly influenced by two factors; one of the factors is the availability of water on the land surface, and the other is the availability of energy on the land surface. The climatologist, Budyko, assumed that the long-term average ratio of the annual actual evapotranspiration and the annual mean precipitation (AET/AAP) were primarily controlled by the water–energy balance in a natural basin (Mohd Hasan et al., 2016), and it

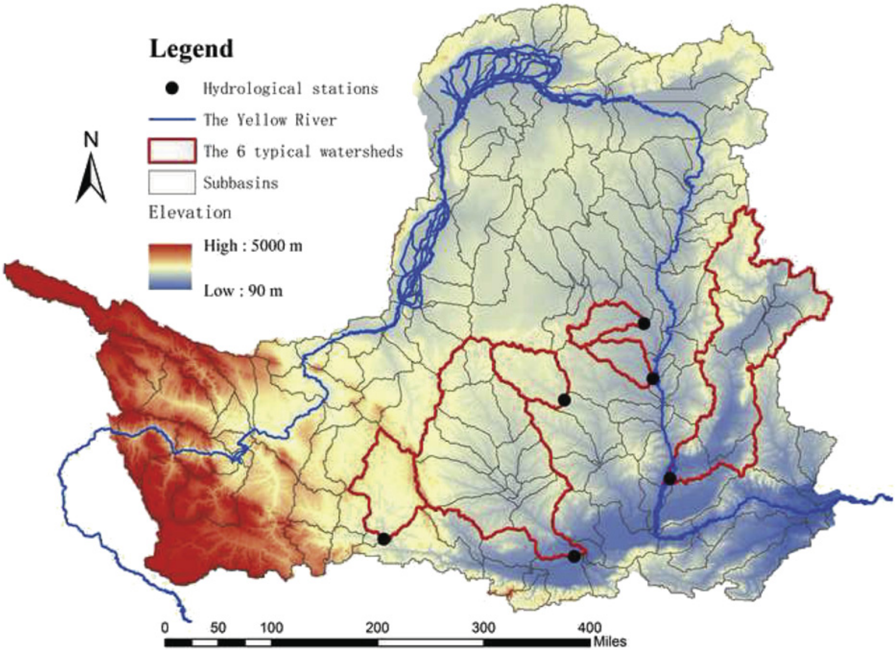

Fig. 2. Distribution of the 161 sub-basins and six typical watersheds in the Loess Plateau.

is a function (f) of the aridity index ϕ ($\phi = \frac{ET_0}{AAP}$). This function is shown in Eq. (1):

$$\frac{AET}{AAP} = f\left(\frac{ET_0}{AAP}\right) = f(\phi) \tag{1}$$

where, AET is the annual regional actual evapotranspiration, in mm; AAP is the annual precipitation, in mm; ET_0 is the annual potential evapotranspiration, in mm; and ϕ is the aridity index. For a watershed under humid conditions ($\phi<1$), the available energy limits the evapotranspiration, whereas under arid conditions ($\phi>1$), the available water is the limiting factor for evapotranspiration.

Generally, the AAP is directly obtained from meteorological stations, and ET_0 is always calculated using the Penman–Monteith (P–M) method based on the observed meteorological data and parameters. The P–M method is one of the most widely accepted methods used to calculate potential evapotranspiration, which is also a physically-based method that is recommended by many international organizations (such as the International Commission on Irrigations and Drainage, the Food and Agriculture Organization of the United Nations, and the American Society of Civil Engineers). Therefore, the P–M method is adopted in this study, and the equation is as follows:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\cdot\frac{900}{273+T}\cdot u_2.(e_a - e_d)}{\Delta + \gamma(1 + 0.34\cdot u_2)} \tag{2}$$

where, ET_0 is the potential evapotranspiration, in mm·day^{-1}; Δ is the slope of the saturation vapor pressure curve, in kPa·°C^{-1}; T is the mean daily air temperature, in °C; e_a is the saturation vapor pressure, in kPa; R_n is the net radiation at the surface, in MJ/($m^2\cdot d$); e_d is the actual atmospheric water vapor pressure, in kPa; G is the all wave ground heat flux, in MJ/($m^2\cdot d$); γ is the psychometric constant, in kPa·°C^{-1}; and u_2 is the daily average wind speed at 2 m height, in m·s^{-1}.

Budyko proposed an important relationship between the AAP, the AET, and ET_0 as shown in Eq. (1); however, the function (f) is only a conceptual expression, which cannot be directly used to calculate the actual evapotranspiration and the runoff. Fu (1981) proposed an analytical expression (referred to as Fu's Equation) to depict the function (f), which has proven to be feasible in China in many prior studies. The Fu's Equation is shown as:

$$\frac{AET}{AAP} = 1 + \frac{ET_0}{AAP} - \left[1 + \left(\frac{ET_0}{AAP}\right)^{\omega}\right]^{\frac{1}{\omega}} \tag{3}$$

where ω is an integration constant, which ranges from 1 to infinity. All other variables have already been described in Eq. (1).

ω is an important parameter in Fu's Equation, which is mainly influenced by the underlying surface conditions in the study area, such as topography, infiltration capacity of the soil layer, and vegetation types. Sun et al. (2007) proposed a semi-empirical formula to estimate ω to solve Fu's Equation, which is as follows:

$$\omega = 2.947 - 0.155\left(\frac{k_s}{i_r}\right) + 5.882\left(\frac{S_{max}}{ET_0} - 2.096\tan\beta\right) \tag{4}$$

where, $\frac{k_s}{i_r}$ is defined as the relative soil infiltration capacity; k_s is the soil saturated conductivity, in mm/h; i_r is the annual precipitation intensity, which is calculated as: $i_r = \frac{AAP}{n\cdot 24}$, n is the total number of rainy days in the year; $\frac{S_{max}}{ET_0}$ is defined as the relative water-holding capacity of the underlying surface in which, $S_{max} = (\theta_f - \theta_w)\cdot d_{root}$, θ_f is the filed capacity of the soil layer, and θ_w is the wilting point of the soil layer; d_{root} is the effective root depth, in mm, which is determined according to the varieties of vegetation.

2.4. Method to validate the estimated regional AET

The Loess Plateau is located inland and is extremely distant from any ocean. As a result, external water resources are very limited. Therefore, precipitation is the most important source of water supply in the Loess Plateau. Meanwhile, the unsaturated zone is very deep in the Loess Plateau, which ranges from 50 m to 200 m throughout the entire area. Therefore, groundwater resources are also difficult to utilize (Zhang et al., 2014). To conclude, precipitation is the main source of water input while evapotranspiration and water runoff are the main sources of water loss in the Loess Plateau. Consequently, the water balance in the Loess Plateau can be described with the following equation:

$$P - R - AET = \Delta G + \Delta S \tag{5}$$

where P represents average precipitation for a given time interval (a year), in mm; R is the equivalent runoff depth for a given time interval (a year), in mm; AET is the actual evapotranspiration for a given time interval (a year), in mm; ΔS is the change in the amount of soil water stored in the soil layer for a given time interval (a year), in mm, and ΔG is the equivalent depth of groundwater replenishment, in mm. As mentioned above, because the unsaturated zone is very deep in the Loess Plateau, the water flux between the groundwater system and the unsaturated zone is too small to be neglected. Moreover, for a complete hydrological year, there is almost no change in the amount of soil water stored in the soil layer. Consequently, to analyze the annual or inter-annual water balance in the Loess Plateau, the following expression is used:

$$AET = P - R \tag{6}$$

As mentioned earlier, in this study, we collected the runoff data respectively from six hydrological stations and the precipitation data from the China Meteorological Sharing Network was used. Based on Eq. (6), the annual AET in the six typical watersheds was calculated, which can then be used to validate the estimated regional AET using the Budyko framework in the corresponding watersheds.

3. Results and analysis

3.1. Validation of the estimated AET

Based on the runoff data collected from the six hydrological stations (Yanchuan, Suide, Zhangjiashan, Qin'an, Hejin, and Liujiahe) from 1990 to 2014, the annual AET in the corresponding watersheds can be calculated using Eq. (6). In the validation process, we compared the observed AET results with the estimated AET results determined using the Budyko framework in the six typical watersheds. The comparison charts were drawn separately for the six typical watersheds, as shown in Fig. 3.

As shown in Fig. 3, there are six sub-graphs showing the validation results for the six typical watersheds. In each sub-graph, the X-axis represents the observed annual AET based on the water balance analysis, and the Y-axis represents the estimated annual AET based on the Budyko framework. The validation period is from 1990 to 2014. The points in each sub-graph represent the annual AET in these 25 years. The validation results show that the estimated values agree well with the observed values because the points are more or less distributed along the 1:1 lines. To further illustrate the validation results, the correlation coefficient (R) and the confidence level (Sig) were introduced to quantitatively depict the consistency between the estimated and the observed results. As shown in Fig. 3, the R values are above 0.90 for the six typical watersheds and the Sig values for all the typical watersheds are below 0.05, showing that all the correlations in the six typical stations are statistical significant at a 95% confidence level. Based on the above analysis, the reliability of the estimated regional AET using the Budyko framework is convincing and acceptable. Therefore, the

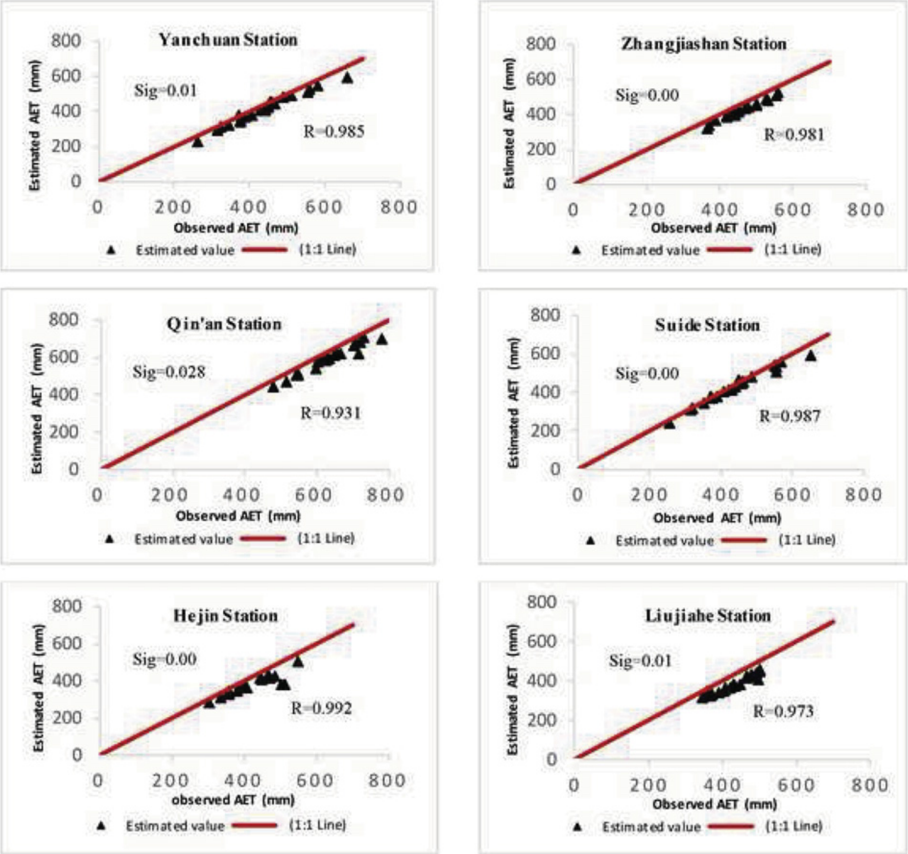

Fig. 3. Comparison between the observed annual AET and the estimated value of the annual AET in the six typical watersheds. If the R value is above 0.8, it indicates a strong correlation between the observed value and the estimated value. The Sig value indicates the statistical significance level of the correlation between the observed value and the estimated value. If Sig value is below 0.05, it means the correlation is significant at 95% confidence level.

estimated results are feasible and can be used for water balance analysis in the entire Loess Plateau.

3.2. The spatial-temporal variation of precipitation, the regional PET, and AET from 1990 to 2014

3.2.1. The temporal variation of precipitation, regional PET, and AET

Fig. 4 shows the changing trend of precipitation, regional PET, and AET over time.

Fig. 4 shows that the annual precipitation from 1990 to 2014 reveals a significant rising trend, increasing at a rate of 1.9 mm/a. Specifically, the average value of annual precipitation from 1990 to 1999 was 436 mm, decreasing at a rate of 2.46 mm/a; in contrast, the average value of annual precipitation from 2000 to 2014 was 462 mm, increasing at a rate of 3.26 mm/a. Identical to the changing trend in precipitation, the annual AET in the entire Loess Plateau also shows a significant rising trend, increasing at a rate of 1.3 mm/a. The average value of the annual AET from 1990 to 1999 was 361 mm, decreasing

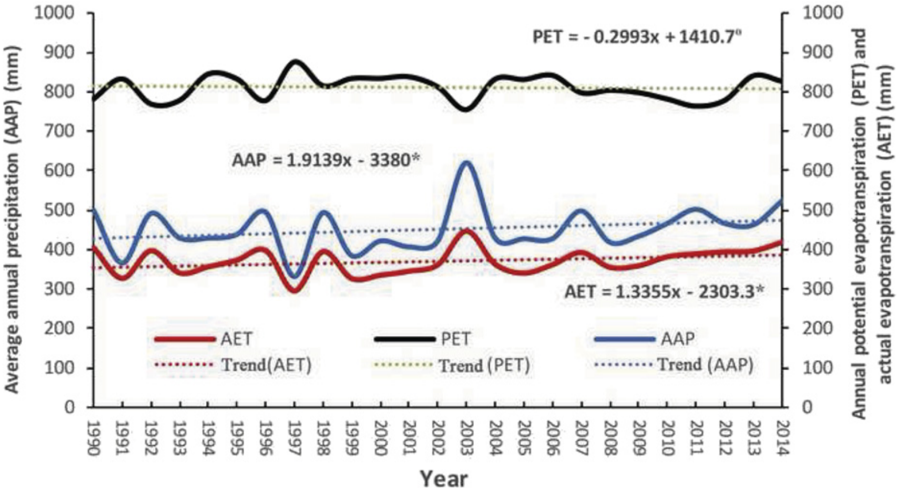

Fig. 4. The changing trend of the AAP, the regional *PET*, and *AET* over time ("*" means the changing trend is statistically significant at 95% confidence level, and "o" means the changing trend is not statistically significant.)

at a rate of 3.34 mm/a; the average value of the annual AET from 2000 to 2014 was 376 mm, increasing at a rate of 3.25 mm/a. In conclusion, based on the observed data, it is proven that both annual precipitation and annual AET have significantly increased after the Grain for Green Project was implemented. Comparatively, as shown in Fig. 4, the annual PET from 1990 to 2014 shows a decreasing trend, but the trend is not statistically significant. According to statistics, the average value of the annual PET from 1990 to 2014 was 811 mm, decreasing at a rate of 0.3 mm/a. Therefore, it was concluded that the growth of regional AET cannot be attributed to the PET i.e., the factor of energy supply, but to the factor of water supply and underlying soil conditions.

3.2.2. The spatial variability of precipitation, the regional PET, and AET

To quantitatively characterize the spatial variation of precipitation and regional PET and AET in the study period, this study used the Inverse Distance Weighting (IDW) method for interpolation. Actually, there are several interpolation methods, such as the Inverse Distance Weighting method, the Thiessen polygon method, and the Kriging method (Babak and Deutsch, 2009). The Inverse Distance Interpolation is a robust and widely used estimation technique. In this study, we firstly interpolated the values to map the spatial distribution of the annual precipitation and annual regional evapotranspiration based on the above three methods; a comparison was made between the accuracy of the results calculated using different spatial interpolation techniques. The results indicated that the accuracy of the different methods was satisfactory. This conclusion is similar to that of the studies by a previous researcher (Yu et al., 2015). Therefore, the Inverse Distance Weighting method was adopted in this study.

Fig. 5 shows the distribution map of the average annual precipitation of all four stages throughout the study period in the Loess Plateau.

Generally speaking, the annual precipitation decreased from the southeast to the northwest region in the Loess Plateau. Observing the precipitation change throughout the four stages, it can be concluded that the entire Loess Plateau is getting wetter after the Grain for Green Project was implemented. As shown in Fig. 5(a), during the first stage (1990–1999), the average annual precipitation in the Loess Plateau was 436 mm, but the low-precipitation area (precipitation below 400 mm) was as large as 3×10^5 km^2, accounting for almost 48% of the total area of the Loess Plateau. After the implementation of the Grain for Green Project, the average annual precipitation slightly increased, which was recorded at 441 mm during the second stage (as shown in Fig. 5b) and 460 mm during the third stage (shown in Fig. 5c). As shown in Fig. 5(d), during the fourth stage (2010–2014), the average annual precipitation in the Loess Plateau was as much as 484.5 mm, and the low-precipitation area (precipitation below 400 mm) was reduced to 1.9×10^5 km^2, accounting for only 30% of the total area of the Loess Plateau.

Fig. 6 shows the distribution map for the annual PET in all four stages in the entire study period in the Loess Plateau.

As shown in Fig. 6, the annual PET before 1999 was 814 mm, and it was 798 mm after 2010. Although there was a slight decreasing trend in case of the PET, the trend is not statistically significant based on the significance test. From the spatial distribution perspective, the high-value ($PET > 800$) zones were mainly located in the northwestern, middle, and southeastern parts of the Loess Plateau, whose areas have not changed noticeably before and after the implementation of the Grain for Green Project. As a consequence, there is no obvious change in the annual PET of the entire Loess Plateau. Fig. 7 shows the average annual AET of all four stages in the Loess Plateau.

Similar to the annual precipitation, in all four stages, the annual AET showed an increasing trend. As shown in Fig. 7(a), during the first stage (1990–1999), the average annual AET in the Loess Plateau is 351.5 mm, and the high-AET area (AET above 400 mm) was is large as 2.4×10^5 km^2, accounting for 38% of the total area of the Loess Plateau. After the Grain for Green Project was implemented, the average annual AET slightly increased, and the high-AET area significantly increased as well. As shown in Fig. 7(d), during the fourth stage (2010–2014), the average annual AET in the Loess Plateau is 396.1 mm, and the high-AET area is much as 4.6×10^5 km^2, accounting for 73.2% of the total area of the Loess Plateau.

3.3. The spatial-temporal distribution pattern of the NDVI, the AAP, and AET

The factors of NDVI, AAP, and AET are closely interrelated. To reveal and analyze this phenomenon, we separately mapped the temporal-spatial distribution of the NDVI, AAP, and AET in the Loess Plateau in the period between 1999 and 2014, as shown in Fig. 8.

The temporal-spatial distribution pattern of NDVI, as shown in Fig. 8(a), indicates that the vegetation coverage kept increasing almost throughout the entire Loess Plateau, except for a few sub-basins

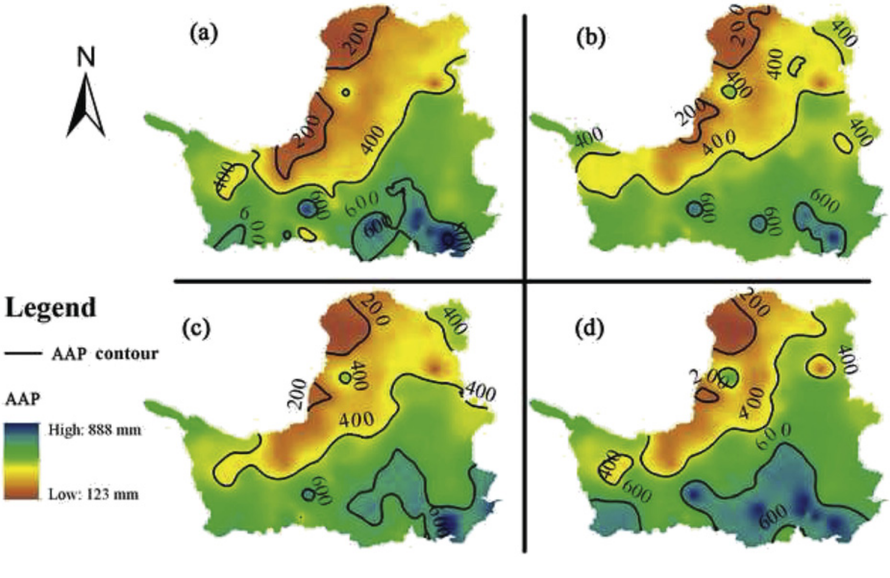

Fig. 5. The spatial distribution of the AAP in all four stages. (a) the spatial distribution of the average annual precipitation before the Grain for Green Project (1990–1999), (b) the spatial distribution of the average annual precipitation in the initial stage after the Grain for Green Project launched (2000–2004), (c) the spatial distribution of the average annual precipitation in the middle stage after the Grain for Green Project launched (2005–2009) and (d) the spatial distribution of the average annual precipitation in the late stage after the Grain for Green Project was launched (2010–2014).

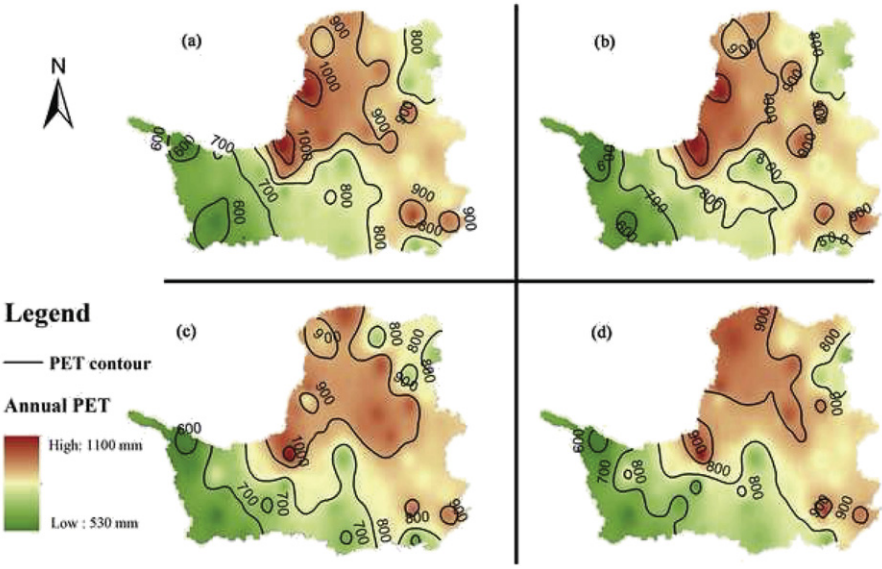

Fig. 6. The spatial distribution of average annual PET in all four stages. (a) the spatial distribution of the average annual potential evapotranspiration before the Grain for Green Project (1990–1999), (b) the spatial distribution of the average annual potential evapotranspiration in the initial stage after the Grain for Green Project launched (2000–2004), (c) the spatial distribution of the average annual potential evaporation in the middle stage after the Grain for Green Project launched (2005–2009) and (d) the spatial distribution of the average annual potential evapotranspiration in the late stage after the Grain for Green Project launched (2010–2014).

(there are only four sub-basins in total). The average value of NDVI was initially 0.37 in 1990, and it increased to 0.58 in 2014 for the entire Loess Plateau. From the spatial pattern, the eastern, middle, and southern parts of the Loess Plateau showed a greater increase in vegetation coverage, where the average NDVI was as much as 0.4. However, the northwestern corner, the southeastern corner, and the westernmost parts of the Loess Plateau had a relatively smaller increase in vegetation coverage.

Comparatively, the AAP and the AET both had similar spatial distribution patterns with respect to the vegetation coverage in the Loess Plateau. As shown in Fig. 8(b), the annual average precipitation shows a significantly increasing trend in the middle, southern, and eastern parts of the Loess Plateau, where the annual average precipitation was below 450 mm in the 1990s; it increased to above 480 mm after 2010. Nonetheless, the annual average precipitation in the northwestern part of the Loess Plateau showed a slightly decreasing trend, which could have been influenced by both atmospheric circulation and local climate (Jaagus et al., 2009). As was illustrated earlier in this paper, the AET is closely related to precipitation because the water supply factor is the determinant for regional actual evapotranspiration in the Loess Plateau. Therefore, the spatial pattern of the AET is highly similar to that of the AAP. As shown in Fig. 8(c), in the eastern and southern

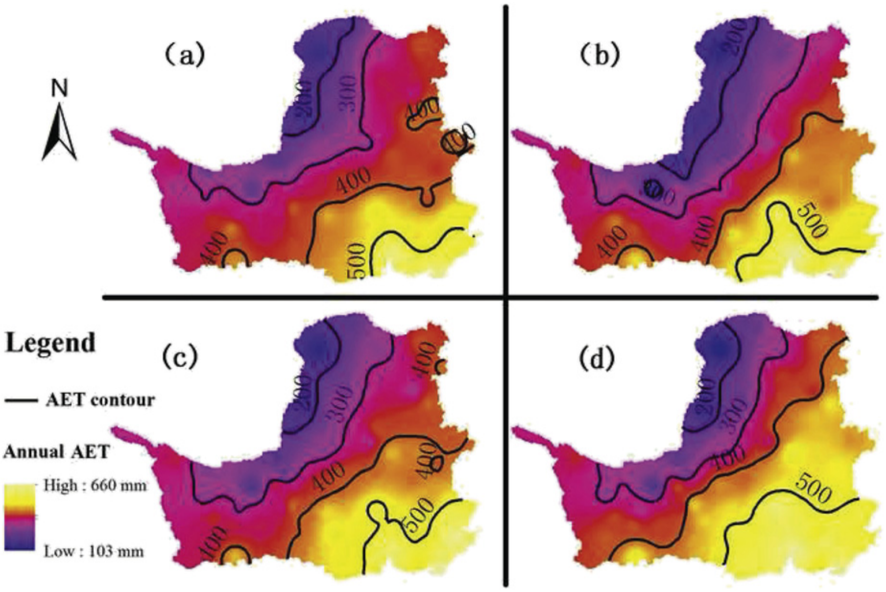

Fig. 7. The spatial distribution of the average annual AET in all four stages. (a) the spatial distribution of the average annual *AET* before the Grain for Green Project (1990–1999), (b) the spatial distribution of the average annual *AET* in the initial stage after the Grain for Green Project launched (2000–2004), (c) the spatial distribution of the average annual *AET* in the middle stage after the Grain for Green Project launched (2005–2009) and (d) the spatial distribution of the average annual *AET* in the late stage after the Grain for Green Project launched (2010–2014).

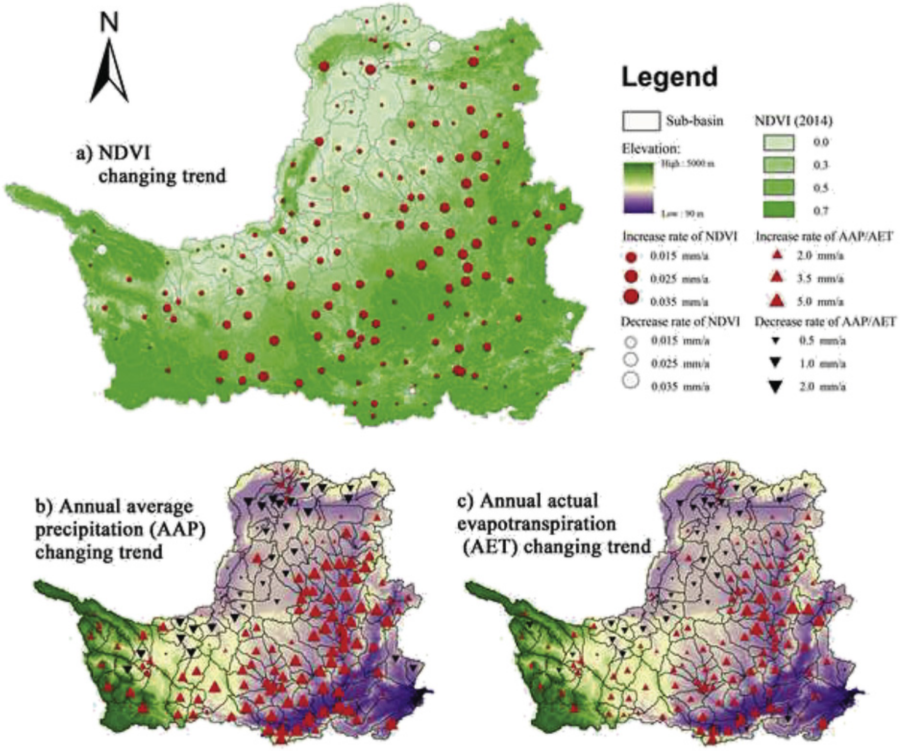

Fig. 8. The spatial-temporal distribution of NDVI, AAP, and AET from 1990 to 2014.

parts of the Loess Plateau, the AET shows an obviously increasing trend, where the annual value of the AET was around 400 mm before 1999, and it improved to above 450 mm after 2010. Similarly, the annual value of the AET in the northwestern region of the Loess Plateau shows a slightly declining trend.

Based on the above analysis, it can be concluded that there is a complex response relationship and mutual feedback among NDVI, precipitation, and regional AET. The increase in regional precipitation most likely led to the increase in the regional AET. However, the rate of increase of AET is statistically less than the rate of increase of precipitation. Consequently, with vegetation recovery jointly influenced by natural restoration and artificial protection measures, the Loess Plateau is getting wetter, and the water scarcity issue can be alleviated to some extent.

4. Discussions

4.1. The reliability of our research results

Jointly influenced by climate change and strong human activities, climatic variables have high uncertainty in the Loess Plateau. In this study, we used the observed meteorological data from 52 stations evenly distributed in the Loess Plateau; additionally, we used high-resolution digital elevation and vegetation type and coverage data to analyze the spatial and temporal variation of precipitation, the PET, and the AET respectively in the 161 sub-basins of the Loess Plateau. The research results show that annual precipitation and AET have been proven to have significantly increased from 1990 to 2014, specifically showing a sharp increase after the Grain for Green Project was implemented (after the year of 1999) based on the observed data. In contrast, the annual PET from 1990 to 2014 showed a slightly decreasing trend, but this is not statistically significant.

The above findings on the change in the characteristics of precipitation and AET are consistent with previous studies with respect to climatic variables in the Loess Plateau. For example, Yan (2015) studied the changing trend of temperature and precipitation based on the observed meteorological data from 1961 to 2014 in the entire Loess Plateau. The results illustrated that precipitation showed a general downward trend in the entire period from 1961 to 2014. However, the results also showed a significant upward trend specifically after 1990. Li et al. (2012a) studied the effect of changes in extreme precipitation and temperature events on the Loess Plateau and concluded that more frequent and intense precipitation would occur during the 21st century; the total annual precipitation would be slightly rising. Wang et al. (2011) constructed multi-annual water balances to estimate the grand average of annual AET and runoff for forestlands and non-forestlands of 57 basins; they found that the annual AET increased as a result of vegetation restoration in the Loess Plateau.

Nonetheless, the findings on the changing characteristics of the PET are not well matched with a previous study of Li et al. (2012b). Li et al. calculated the reference evapotranspiration from 1961 to 2009 and also forecasted the reference evapotranspiration using the HadCM3 (Hadley Centre Coupled Model, version 3) outputs under two emission scenarios (A2 and B2) using a statistical downscaling method. The study concluded that the reference evapotranspiration had increased significantly owing to a downward trend in relative humidity and an upward trend in temperature in the Loess Plateau from 1961 to 2009 and continued to increase in the 21st century. However, the study conducted by Zhang et al. (2015) is basically consistent with the conclusion of our research. They investigated the temporal and spatial distribution of the reference evapotranspiration using observed historical data from the Yellow River Basin of China from 1961 to 2012 and found that the annual mean reference evapotranspiration had a declining trend at a rate of 12.9 mm/10a. Based on the above analysis, the inconsistent research conclusions on the PET in previous studies are mainly due to the high uncertainties of climatic variables and different data sources. In our study, we used the observed meteorological data collected from the China Meteorological Sharing Network, where the reliability of data was fully validated before the data was published online. Consequently, we admit that the results in this study are convincing and acceptable.

4.2. The sustainability of vegetation water use based on evapotranspiration coefficient (ECC) evaluation

Maintaining sustainable vegetation growth in the Loess Plateau is one of the most pressing concerns of the government as well as environmentalists. The water supply factor is the most important limiting factor in the Loess Plateau for vegetation recovery. Therefore, the water balance indicator of the ECC was introduced to demonstrate the sustainability of vegetation water use in the Loess Plateau. The ECC is the ratio of the AET to precipitation, which is also an important indicator to quantify water loss owing to vegetation consumptive water use. In addition, the runoff coefficient (RCC) is another important indicator to quantify the potential runoff generated on the underlying surface. As mentioned previously, precipitation is the main source of water input while evapotranspiration and runoff are the main sources of water output in the Loess Plateau. Consequently, the ECC and the RCC are the two main quantitative indices to characterize water balance in the Loess Plateau; theoretically, the sum of the ECC and the RCC is a constant, equal to one. That is to say, if the ECC increases, the RCC will decrease accordingly and vice versa.

To further demonstrate the spatial distribution of the ECC and the RCC across the Loess Plateau, the spatial pattern maps of the ECC were drawn as shown in Fig. 9.

Fig. 9 shows spatial distribution of the ECC across the Loess Plateau in all four stages. Generally speaking, the ECC shows a significantly decreasing trend from 1990 to 2014. As shown in Fig. 9(a), the total area with an ECC above 0.9 from 1990 to 1999 is 2.33×10^5 km^2, accounting for 36.7% of the total area of the Loess Plateau. However, in the period from 2010 to 2014 (as shown in Fig. 9d), the total area with an ECC above 0.9 reduced to 1.15×10^5 km^2, accounting for only 17.8% of the total area of the Loess Plateau. Actually, the average ECC in the entire Loess Plateau kept declining particularly after the Grain for Green Project was implemented. According to our calculated results, the average ECC was 0.868, 0.863, 0.851, and 0.837 respectively in the four stages. Therefore, the RCC correspondingly showed an increasing trend from 1990 to 2014, which means that the runoff water yield in the Loess Plateau surprisingly increased with vegetation restoration.

Many studies (Wang et al., 2011; Chen et al., 2015; Wang et al., 2015a, 2015b) in recent years found that large-scale forestation and vegetation recovery will likely reduce water yield and consequently threaten regional water supply and sustainable development. Thus, a trade-off between forestation for erosion control and the maintenance of suitable water yield for water supply must be carefully balanced. According to statistics (Li et al., 2014), the upper and middle reaches of the Yellow River, which are mainly located in the Loess Plateau, had an annual runoff of 4.55×10^{10} m^3 in the period between 1960 and 1969, when the annual precipitation was 432 mm; the annual runoff was reduced to 2.43×10^{10} m^3 in the period between 1990 and 1995, when the annual average precipitation was 389 mm. Further, the annual runoff was reduced to 2.09×10^{10} m^3 in the period between 2000 and 2010, when the average annual precipitation was 391 mm. Based on the above analyses, the RCC values in the three periods were 15.5%, 9.2%, and 7.8%, respectively. The figures demonstrate that large-scale forestation and vegetation recovery may cause a reduction of water yield in the Loess Plateau.

However, our findings in this research prove that large-scale forestation and vegetation recovery are not likely to be the main reasons for the reduction of water yield in the Loess Plateau. Alternatively, with economic and social development, more and more water is intercepted by reservoirs or check-dams and diverted to urban and industrial water users, probably resulting in a runoff decline in the trunk stream of the Yellow River.

5. Conclusions

This research analyzed the temporal and spatial evolution of the regional annual precipitation, the annual PET, and the annual AET from 1990 to 2014 and calculated the water balance indicator (ECC) to illustrate the sustainability of vegetation water use in the Loess Plateau as well. The main conclusions from this study can be summarized as follows:

1) The Budyko theory was introduced in this study to simulate the regional AET from 1990 to 2014 for 161 spatially distributed sub-basins in the Loess Plateau. Our results show that the simulated AET is well matched with the observed AET. The values of the correlation coefficient (R) for the six typical validation stations are all above 0.9, and the Sig values for the six typical stations are all below 0.05. Therefore, the

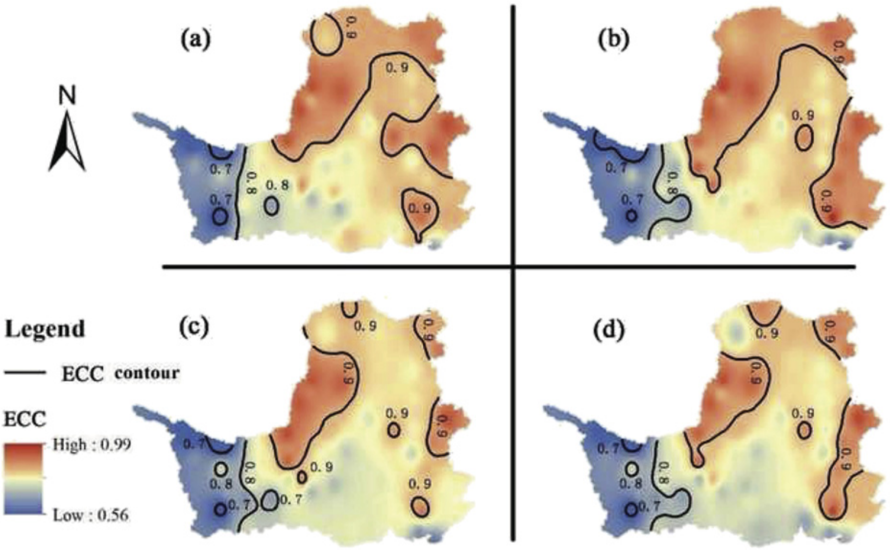

Fig. 9. The spatial distribution of the ECC in all four stages. (a) the spatial distribution of the coefficient before the Grain for Green Project (1990–1999), (b) the spatial distribution of the coefficient in the initial stage after the Grain for Green Project launched (2000–2004), (c) the spatial distribution of the coefficient in the middle stage after the Grain for Green Project launched (2005–2009) and (d) the spatial distribution of the coefficient in the late stage after the Grain for Green Project launched (2010–2014).

Budyko framework used in this study was proven to be accurate and feasible.

2) The spatial-temporal patterns of precipitation, the PET, and the AET from 1990 to 2014 of the Loess Plateau were analyzed in this study. Based on the results, the average values of precipitation and the AET in the entire Loess Plateau showed a significantly increasing trend. However, the average values of the PET had no noticeable change throughout the study period. The relationship between the NDVI and EEC proved that regional AET significantly increased with the increase in vegetation coverage in the Loess Plateau. The relationship between the NDVI and ECC proved that both precipitation and the AET synchronously increased; however, the rate of increase of precipitation was obviously greater than that of the AET. Based on the above findings, it can be concluded that the runoff yield in the Loess Plateau will increase with vegetation recovery, and blue water resources are likely to become more abundant in the future.

3) To evaluate the sustainability of vegetation water use with vegetation recovery in the Loess Plateau, the ECC was introduced to quantitatively indicate the ratio of water consumption due to vegetation to the total precipitation in the period from 1990 to 2014. The results show that the ECC exhibited a significantly decreasing trend in the Loess Plateau. The average values of the ECC were 0.868, 0.863, 0.851, and 0.837 in the four periods from 1990 to 1999, 2000 to 2004, 2005 to 2009, and 2010 to 2014, respectively. Hence, we can also conclude that the sustainability of vegetation water consumption slightly increased with vegetation recovery in the Loess Plateau.

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