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Response of evapotranspiration to changes in land use and land cover and climate in China during 2001–2013

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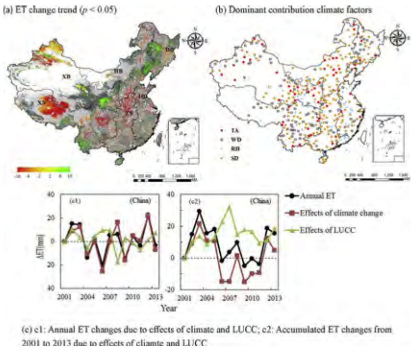
HIGHLIGHTS

- Individual effects of climate change and LUCC on ET in China were quantified.
- Effect of climate change on ET was much more significant than effect of LUCC.
- Deforestation had a greater influence on ET relative to afforestation.
- Sunshine duration was the dominant climatic factor for ET changes in China.

GRAPHICAL ABSTRACT



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ABSTRACT

Land surface evapotranspiration (ET) is a central component of the Earth's global energy balance and water cycle. Understanding ET is important in quantifying the impacts of human influences on the hydrological cycle and thus helps improving water use efficiency and strengthening water use planning and watershed management. China has experienced tremendous land use and land cover changes (LUCC) as a result of urbanization and ecological restoration under a broad background of climate change. This study used MODIS data products to analyze how LUCC and climate change affected ET in China in the period 2001–2013. We examined the separate contribution to the estimated ET changes by combining LUCC and climate data. Results showed that the average annual ET in China decreased at a rate of −0.6 mm/yr from 2001 to 2013. Areas in which ET decreased significantly were mainly distributed in the northwest China, the central of southwest China, and most regions of south central and east China. The trends of four climatic factors including air temperature, wind speed, sunshine duration, and relative humidity were determined, while the contributions of these four factors to ET were quantified by combining the ET and climate datasets. Among the four climatic factors, sunshine duration and wind speed had the greatest influence on ET. LUCC data from 2001 to 2013 showed that forests, grasslands and croplands in China mutually replaced each other. The reduction of forests had much greater effects on ET than change by other land cover types. Finally, through quantitative separation of the distinct effects of climate change and LUCC on ET, we conclude that climate change was the more significant than LULC change in influencing ET in China during the period 2001–2013. Effective water resource management and vegetation-based ecological restoration efforts in China must consider the effects of climate change on ET and water availability.

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1. Introduction

Water is an important resource for maintaining the sustainable development of agriculture and other related socio-economic activity. Over the past few years, water scarcity has become a very serious global problem, and water resource allocation is becoming an important issue as a result of population rise and climate change (Sun et al., 2008). There is an urgent need to fully understand environmental effects on water resources for science-based management and rational allocation of water resources.

Evapotranspiration (ET) is an important component of both the hydrological cycle and surface energy balance. In recent years two factors have had increasing effects on ET: land use and land cover change (LUCC) due to human activity, and climate change (Vörösmarty et al., 2000). We must quantify the distinct effects of LUCC and climate change on ET in order to gain an understanding of regional hydrological cycles and energy balances. This understanding will make us better able to maintain ecosystem functions and services, and to ensure efficient water resources managements (Allen et al., 2011a, 2011b).

The global terrestrial ET data product MOD16 was developed based on land surface characteristics from remote sensing and the Penman–Monteith equation (Monteith, 1965). The MOD16 dataset was evaluated by global flux measurement data, and the estimated accuracy of the data reached 86% (Mu et al., 2011). The dataset has been widely used to study temporal and spatial characteristics of ET on a regional scale own certain advantages (Autovino et al., 2016). In China, some researchers (Jia et al., 2012; Zhang et al., 2016a) found that MOD16 is reasonably practicable and trustworthy on the regional scale although MOD16 in some pixels are overestimated or underestimated.

In the context of climate change, the trend of change in ET and its relationship with climate factors have been widely considered (Roderick and Farquhar, 2004; Tang et al., 2011; Irmak et al., 2012; Croitoru et al., 2013). In one study, Peterson et al. (1995) found that although temperature continuously increased, surface evaporation continuously decreased. Roderick and Farquhar (2002) called this contradiction the *evaporation paradox*. In recent years, many scholars around the world have studied the effects of climate change on the temporal and spatial characteristics of ET (Brutsaert Amp and Parlange, 1998; Golubev et al., 2001; Xu et al., 2006a). For example, some studies concluded that ET has decreased in most countries, and that the decrease might be caused by a reduction in solar radiation and a decrease in wind speed (Gao et al., 2006; Zhang et al., 2007; Zheng et al., 2009). ET increases in some individual areas (Yu et al., 2002; Burn and Hesch, 2007; Dinpashoh et al., 2011) were mainly related to increases in wind speed and decreases in relative humidity.

In addition to climate, ET is highly affected by land cover properties such as leaf area index (Sun et al., 2011a, 2011b). Some researchers believed that LUCC had greater impact on the hydrological cycle than climate change (e.g., Xu et al., 2016) and may cancel or mask the effects of climate change (Hao et al., 2011). LUCC affects ET on the regional scale mainly through vegetation changes (e.g., deforestation and afforestation, or grassland reclamation), agricultural development activities (e.g., farmland reclamation, crop cultivation, and agricultural management), and urbanization (Bronstert et al., 2002). ET change rates differ among land cover types that have different underlying surfaces (Olchev et al., 2008; Douglas et al., 2009; Dias et al., 2015).

In previous studies, several researchers have comprehensively quantified the combined effects of climate change and LUCC on ET in China (Li et al., 2009; Kim et al., 2013; Zhao et al., 2016); however, the individual effects of climate change and LUCC on ET change have not been fully explored. Since 2000, China has seen a large change in land cover as a result of rapid urbanization and implementations of a few large scale ecological restoration projects, including *Grain for Green* program, the *Natural Forest Conservation Program*, and *Three-North Shelterbelt Program* (Feng et al., 2005; Qiu et al., 2011; Xiao et al., 2015; Zhang et al., 2015). These massive LUCCs together with climate change have clearly influenced ET in China. There have debate in China on the causes of large-scale changes in water balances. Currently, it is unclear how LUCC and climate change have respectively contributed to change in water resources in different geographic regions (Feng et al., 2016). Whether the LUCCs had determined ET trends or whether the great effect of LUCCs on ET can be ignored in comparison with the effect of climate change on ET becomes an endless debate. Thus, quantification of the individual effect of climate change and LUCC on changes in ET, and determination of the dominant factor have practical significance for the national-scale ecological campaigns amid a changing climate (Ma et al., 2008; Bao et al., 2012; Hao et al., 2015; Xie et al., 2015).

Therefore, the objectives of this study were to: 1) characterize the spatial and temporal variability of ET in China from 2001 to 2013, 2) quantifying individual contributions of climate change and LUCC. Our guiding hypothesis for this study is that climate change may cancel or aggravate the effects of LUCC on regional ET. Research results may offer important knowledge for land and water managers to take proper watershed actions to mitigate the likely effects of climate on watershed water balances.

2. Materials and methods

2.1. Data

The moderate resolution imaging spectroradiometer (MODIS) is a key sensor aboard both the Terra and Aqua satellites which are part of NASA's (the United States National Aeronautics and Space Administration) Earth Observation System. MODIS data products are well validated and used widely across the world (Friedl et al., 2010; Mu et al., 2011; Hu et al., 2015; Zeng et al., 2015). In this study, we used the yearly 500 m MCD12Q1 land cover data based on the International Geosphere-Biosphere Programme classification (IGBP; Loveland and Belward, 1997) (http://ladsweb.nascom.nasa.gov), and yearly 1 km MOD16A3 ET data from the Numerical Terra dynamic Simulation Group at the University of Montana (http://ntsg.umt.edu). All 1 km ET data were interpolated to 500 m using the nearest neighbor resampling method. We reclassified land cover types into five categories: forests, croplands, grasslands, wetlands, and bare lands. The forests category includes evergreen needleleaf forests, deciduous needleleaf forests, evergreen broadleaf forests, deciduous broadleaf forests, mixed forests, and shrublands.

The meteorological datasets used were acquired from the National Meteorological Information Center of the China Meteorological Administration (http://cdc.cma.gov.cn). The datasets include average temperatures (TA) (°C), sunshine duration (SD) (h), wind speeds (WD) at 10 m height (m/s) and relative humidity (RH) (%). Data from 596 meteorological stations were used in the study period. Stations with lost data or data anomalies were eliminated. Fig. 1 shows the regional distribution of the 596 stations according to a Chinese climatic and geographic regionalization (Jin et al., 2016; Zheng et al., 2013). Spatial distributions of each climatic variable at the 500 m resolution were interpolated from all stations and used to match the spatial distribution of ET using the Kriging method, further for calculating contributions of each climatic variable on the regional scale. Finally, the spatial dataset including land cover, ET, and meteorological data was converted into the albers equal area conical projection at the 500 m resolution.

2.2. Methods

2.2.1. Trend analysis

This study assessed the trends of annual ET for the period 2001–2013 with the following linear equation:

$$y = ax + b, (x = n, n + 1, \ldots, N) \tag{1}$$

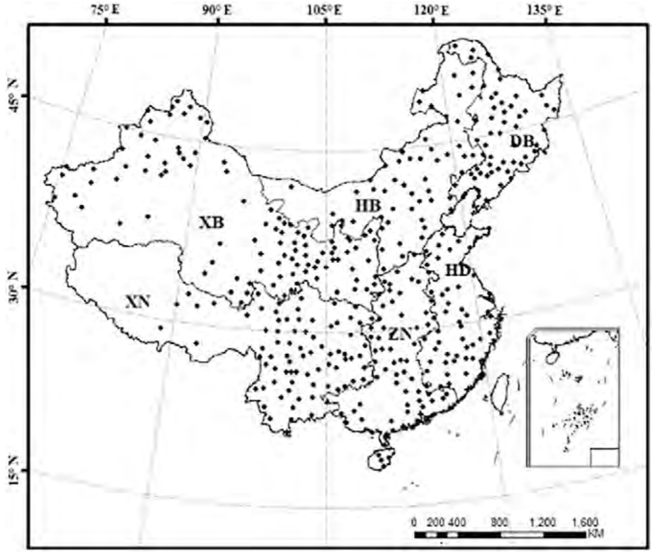

Fig. 1. The spatial distribution of meteorological sites with six region divisions (Dong Bei (DB) is northeast in China, Hua Bei (HB) is the north China, Xi Bei (XB) is northwest in China, Hua Dong (HD) is the eastern China, Zhong Nan (ZN) is middle-of-south in China, Xi Nan (XN) is southwest in China).

where y is the trend of annual ET; x is the year; a and b are the slope and intercept respectively; n represents the starting year of the time series; and $N–n + 1$ is the sample size.

A positive value of a shows an increasing trend, whereas a negative value of a shows a decreasing trend. The significance level (p) of 0.05 was used for the linear trend analysis. The significance level represents the level of confidence in the trend value, independent of the rate of change.

2.2.2. Contribution assessment

This study assumed that the trend of ET was only affected by climate change and LUCC:

$$\Delta ET^{unit} = \Delta ET^{unit}_{\text{climate}} + \Delta ET^{unit}_{LUCC} \tag{2}$$

where ΔET^{unit} is the change in ET in a unit area; $\Delta ET^{unit}{}_{climate}$ and $\Delta ET^{unit}{}_{LUCC}$ are ET changes in the unit area due to climate change and LUCC, respectively.

If neither climate nor LUCC change over a period of time, ET in a region remains constant over the period. If the climatic characteristics of a region are basically the same, the effect of climate change on ET in this region should be the same regardless of the land use and cover types. We divided China into six regions according to different ecological geography (Jin et al., 2016) and climatic zones (Zheng et al., 2013), ensuring that the climate characteristics in each region are basically the same but land use patterns differ in the region (Fig. 1).

First, we assumed that if land cover types in a region were unchanged during the period 2001–2013, then any change in ET in that region was caused by climate change. There are many climatic factors that can affect ET, and different regions have different climatic characteristics. We needed to know which climatic factors primarily influenced ET. Four important factors that influence ET, which are provided by the MOD16 algorithm, are TA, WD, RH, and SD. ET changes with time (t) were decomposed by the partial differentiation equation method (Zheng et al., 2009; Liu et al., 2011; Yang and Yang, 2012):

$$\frac{d\overline{ET}_{c\text{ limate}}}{dt} = \frac{\partial ET_{c\text{ limate}}}{\partial TA}\cdot\frac{dTA}{dt} + \frac{\partial ET_{c\text{ limate}}}{\partial WD}\cdot\frac{dWD}{dt} + \frac{\partial ET_{c\text{ limate}}}{\partial RH}\cdot\frac{dRH}{dt} + \frac{\partial ET_{c\text{ limate}}}{\partial SD}\cdot\frac{dSD}{dt} + \varepsilon \tag{3}$$

where $\mathcal{E}$ represents the systemic error. The four terms on the right-hand side of the equation represent the positive (increases in ET) and negative (decreases in ET) contributions of the four climate factors (TA, WD, RH, and SD) to the long-term ET trend, respectively. The dominant climatic factors influencing the change in ET can be identified by comparing the absolute values of the contributions of each factor.

Second, we assumed that if land cover types were changed and then changes in ET were attributable to the combined effect of climate change and LUCC. Therefore, the effects of LUCC on ET in a region can be quantitatively identified by removing the effects of climate change on ET in that region (refer to Eq. (2)) since the effects of climate change on ET in a region are the same. Through two variation transfer matrices (Tables 1 and 2), the directions of changes in the proportions of land cover types and the effect of each LUCC on ET can be determined.

Finally, as a first-order approximation, the total change in annual total ET in a region can be calculated as (Ma et al., 2008; Zhang et al., 2016b):

$$\overline{\Delta ET}_{total} = \overline{\Delta ET}_{c\text{ limate}} \times C_{c\text{ limate}} + \overline{\Delta ET}_{LUCC} \times C_{LUCC} \tag{4}$$

So the change in mean ET in a region can be expressed as:

$$\overline{\Delta ET}_{total} = \overline{\Delta ET}_{c\text{ limate}} \times C_{c\text{ limate}} + \overline{\Delta ET}_{LUCC} \times C_{LUCC} \tag{5}$$

where $\overline{\Delta ET_{total}}$ is the total change in mean ET (mm) in a region; $\overline{\Delta ET_{\text{climate}}}$ and $\overline{\Delta ET_{LUCC}}$ is the mean ET change due to climate change and LUCC, respectively; A_{total}, $A_{climate}$, and A_{LUCC} is total area within a region, area affected by climate, and area with land cover change, respectively; Since climate affects the whole region, so $A_{climate} = A_{total}$; C_{LUCC} and $C_{climate}$ represents the area proportion of contribution of LUCC and climate change to ET in a region, respectively. $C_{climate}$ is 1.0 and C_{LUCC} is calculated by $\frac{A_{LUCC}}{A_{total}}$.

3. Results

3.1. The temporal and spatial distribution of ET

Average annual ET in China for the period 2001–2013 was 553 mm/yr. Generally, the ET trend was decreasing with the average rate of decrease −0.6 mm/yr, but it fluctuated inter-annually (Fig. S1).

Spatially, average annual ET in China was lower in the western and northern regions with spare vegetation, and higher in the eastern and southern regions with abundant vegetation. Average annual ET increased gradually from the northwest inland area to the southeast coastal area (Fig. 2a). During the period 2001–2013, the ET trend was decreasing in about 68% of China with a significant decrease in 17% of areas, distributed in the northwest of XB and the central region of XN, and most regions of ZN and HD. In contrast, areas with significant increases in ET were sporadically distributed in the southeast of XB and the west of DB (Fig. 2b, Fig. S2).

3.2. Changes of climatic factors and their contributions to ET trends

Fig. 3 shows the change trends of four climatic factors and their contributions to changes in ET. TA increased in most parts of China during the period 2001–2013 (Fig. 3a). Among meteorological sites used in China, 32% of sites showed a significant increase ($p < 0.05$), and only 12% of sites showed a significant reduction in TA ($p < 0.05$). TA contributed positively to changes of ET in >85% of China. Only in the central part of XB that had the least annual ET which was most barren (Fig. 3a), did TA contribute negatively. SD decreased in >60% of sites but showed significant decrease in only 15% of sites ($p < 0.05$). SD contributed negatively to change in ET in >75% of China, with the greatest effect in eastern and western parts of XB and the western part of XN (Fig. 3b). In the majority of sites studied, WD was declining. A significant decrease was found in 36% of sites and a significant increase in 16% of

Table 1
The transfer matrix of areas between land use types in China during the period 2001–2013 (km^2).

2001	2013					
	Forests	Grasslands	Wetlands	Croplands	Bare lands	Total
Forests	*1,747,546*	184,573	6684	182,569	25,477	2,146,849
Grasslands	228,350	*2,236,456*	2805	243,943	118,091	2,829,645
Wetlands	15,735	294	*946*	4559	50.3	21,583
Croplands	194,440	97,752	7449	*981,006*	4216	1,284,863
Bare lands	53,993	244,237	586	16,510	*1,837,752*	2,153,078
Total	2,240,064	2,763,311	18,470	1,428,587	1,985,585	

Note: italic numbers on diagonal line are areas kept as the same land cover type during the period of 2001 to 2013.

sites ($p < 0.05$). WD contributed negatively to changes in ET in >80% of China, which were distributed mostly in the eastern part of XB (Fig. 3c). A significant decrease in RH was found in 30% of all sites of which 8% showed a significant increase ($p < 0.05$). RH contributed positively to changes in ET in >85% of China, but the contribution was relatively small (Fig. 3d).

Overall, the average regional contributions of TA, WD, SD, and RH to ET were 0.9 mm/yr, −1.2 mm/yr, −1.5 mm/yr, and 0.3 mm/yr, respectively. Comparisons of the contributions of each climatic factor to ET showed that ET changes in different regions were attributable to different factors (Fig. 4). SD was the dominant factor in 48% of China, which included XB, the northeastern part of HB, and some parts of DB and ZN. WD was the dominant factor for changes in ET in 27% of China, mainly concentrated in the middle-west part of DB and XN. TA and RH were the dominant factors for changes in ET in 15% and 11% of China, respectively, scattered over different regions. These results indicate that changes in ET are mainly due to TA, WD, and SD, and that the combined negative effects of WD and SD were significantly greater than the positive effects of TA. This may explain why ET decreased despite of the increase in TA.

3.3. Changes of land use/cover and their effects on ET

In addition to climate change, human activity can also affect the surface water cycle and thereby affect ET in a region. LUCC indirectly reflects the level of human activity in an area. The effect of LUCC on regional ET mainly results from physical changes to the land surface which affects the efficiency of ET as a process (Douglas et al., 2009; Dias et al., 2015). The reclassified 2001 MODIS land cover map of China (Fig. 5a) shows that: most forests were located in the eastern part of DB and the southern region of HD, ZN, and XN; croplands were mainly in the northern part of HD, the northeast of ZN, and XN, and the western part of DB; and grasslands and bare lands covered the western part of XN and most of the areas of HB and XB.

Comparing the multi-year mean ET of each land cover type from 2001 to 2013 (Figs. 2a, 5b), the change rules of perennial mean ET for the various land cover types were as follows: wetlands > forests > croplands > grasslands > bare lands.

Table 1 shows the direction of changes in the proportions of land cover types in China during the period 2001–2013. The total area of forests increased by 93,214.7 km^2 in the study period, with the main sources from grasslands and croplands. Croplands were the larger source because of the policy of returning croplands to forests in China since 2000 (Feng et al., 2005). The total area of grasslands in the period decreased by 66,333.2 km^2, most of which became forests and croplands. The total area of croplands increased during the period, mainly from grasslands.

Table 2 shows the contributions of each LUCC to changes in ET. We found that the conversion of forests and wetlands to other land uses caused a decrease in ET, and that conversion of croplands to grasslands also resulted in a decrease in ET, and conversion of grasslands to croplands resulted in an increase in ET. However, the contribution to change in ET of LUCC in one direction (change from use A to use B) was not matched by the contribution of LUCC in the opposite direction (change from use B to use A). For example, the conversion of forests to grasslands and to croplands decreased ET by −25.2 mm/yr and −4.7 mm/yr, respectively. However, conversion of grasslands and of croplands to forests increased ET only by 6 mm/yr and 6.4 mm/yr, respectively. These results indicate that the conversion of forests to grasslands had more effect on the change in ET than the conversion of forests to croplands, but that increases in the afforestation or reforestation of grasslands and croplands had similar effects on the change in ET. On the other hand, conversion from croplands to grasslands caused a decrease in ET by −3.7 mm/yr, a much larger magnitude that of ET change from the reverse direction (1.1 mm/yr). This result indicates that it is better not to convert croplands to grasslands (perhaps through abandonment) if an increase ET is hoped for. Apart from the effects of climate change, during 2001–2013, the largest contributory factor to the decrease in ET in the period 2001–2013 was LUCC of forests to bare lands, which reduced ET by −38.5 mm/yr. The largest contribution to total ET in China during the period 2001–2013 was from LUCC of forests to grasslands because of the larger areas that were converted (from Table 1).

3.4. ET response to climate change and LUCC

The annual fluctuations in the effects of climate change and LUCC on ET are shown in Fig. 6. In the DB, HD, and ZN regions, the fluctuations in the effects of LUCC on ET were significantly smaller than fluctuations in the effects of climate change on ET. This result was mainly due to relatively small changes in the land use types of these three regions during the period 2001–2013.

The cumulative response of annual average ET to climate change and LUCC in different regions of China is shown in Fig. 7. We found that the changes in ET in different regions of China during the period 2001–2013 were relatively consistent with the trends in climate change impact, but the regional annual average ET also changed significantly in some years due to the influence of LUCC. Comparing the effects of LUCC and climate change on ET, our study shows that the impact of climate change on ET in China was greater than that of LUCC, and that the response of ET to climate change in China was more significant during the period of 2001–2013. Thus, climate change had a dominant effect on change in ET in China as a whole during the period 2001–2013.

Table 2
The average contribution rate of LUCC to ET in China from 2001 to 2013 (mm/yr).

2001	2013				
	Forests	Grasslands	Wetlands	Croplands	Bare lands
Forests		−25.2	5.9	−4.7	−38.5
Grasslands	6		13.4	1.1	−7.4
Wetlands	1.4	−17		−4.7	−9.3
Croplands	6.4	−3.7	17.6		−10.9
Bare lands	8.6	0.2	2.6	28.5	

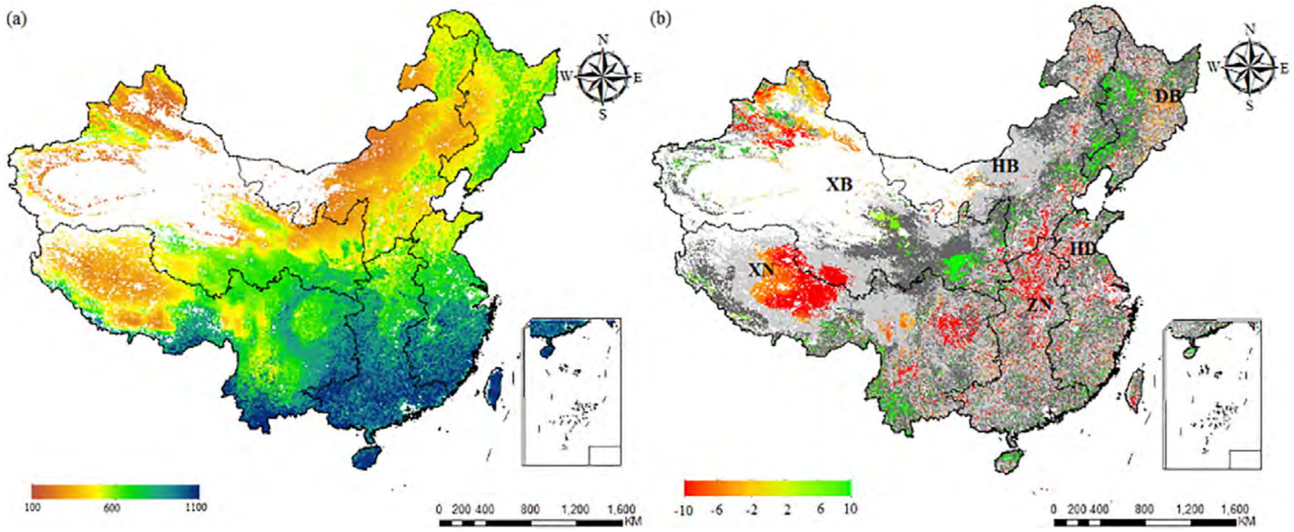

Fig. 2. a) The spatial distribution of mean annual evapotranspiration (ET) (mm) in China during the period 2001–2013, and b) Trend of ET change. The white color indicates non-vegetated areas, the light gray and dark gray indicate areas without significant decrease and increase ET changes, respectively ($p > 0.05$).

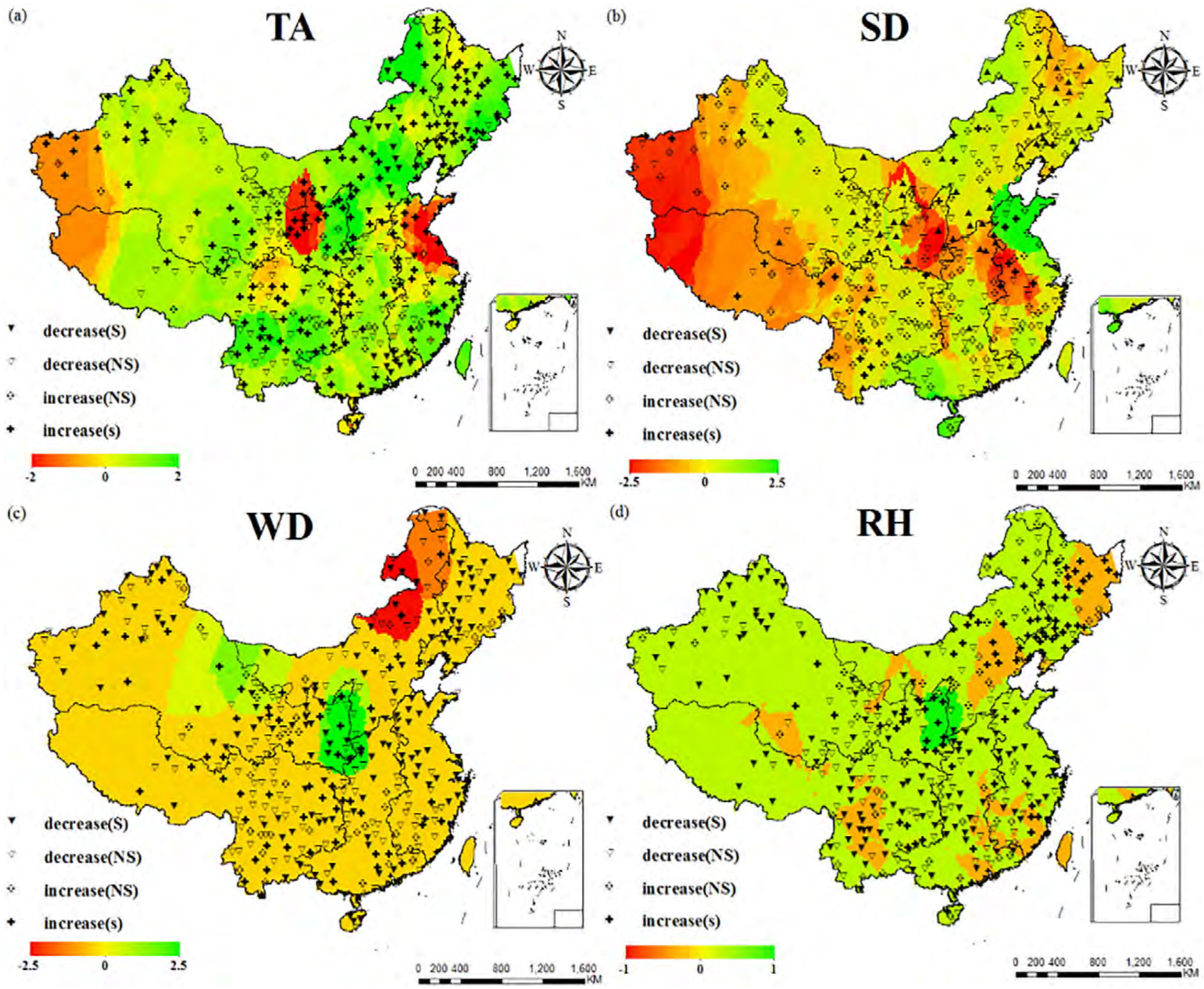

Fig. 3. Spatial distributions of contribution rates from four meteorological factors ((a) average temperatures (TA), (b) sunshine duration (SD), (c) wind speeds (WD), (d) relative humidity (RH)) to evapotranspiration (ET) with their change trends at station used in this study during the period 2001–2013. Inverted triangle and crosses indicate a decreasing and increasing trend, respectively (solid indicate that the trend is significant (S), $p < 0.05$; and open inverted triangle and crosses indicate that the trend is not significant (NS), $p > 0.05$); color ramps represent the contribution rates (mm/yr).

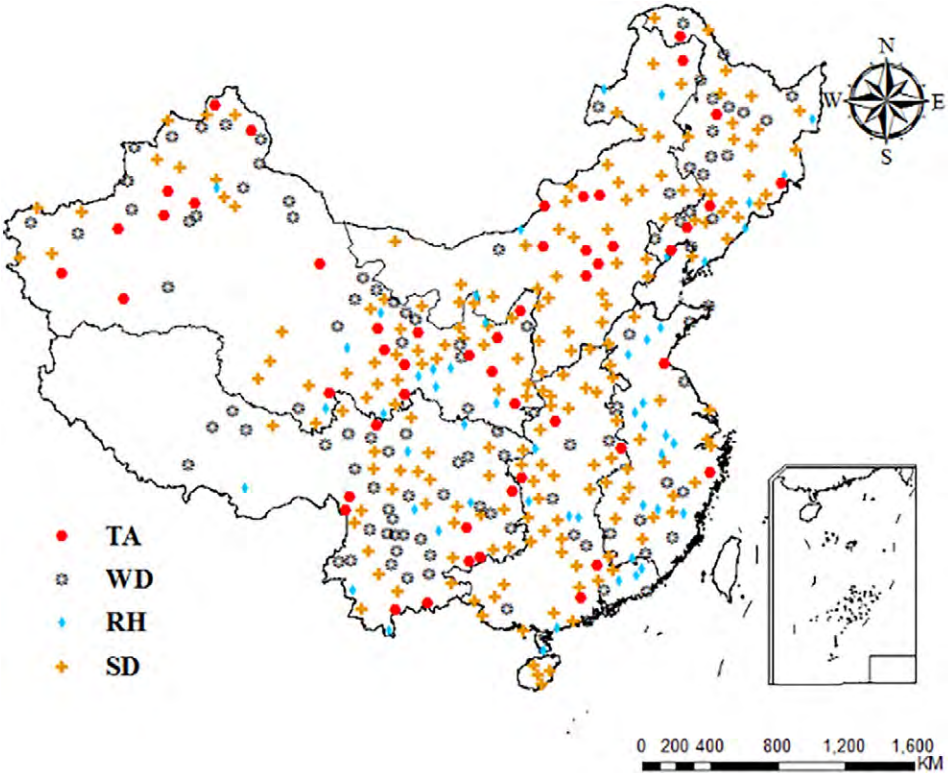

Fig. 4. The spatial distribution of dominant contribution from climate factors. TA: average temperatures; SD: sunshine duration; WD: wind speeds; RH: relative humidity.

4. Discussion

4.1. Climatic factors influencing ET

In recent decades, many researchers worldwide have studied the relationships between ET and climatic factors (Golubev et al., 2001; Ohmura and Wild, 2002; Eslamian et al., 2011; Nam et al., 2015). In considering the regional distributions of the dominant climatic factors that contribute to change in ET, our results are similar to those obtained by others (Thomas, 2000; Gao et al., 2006). SD was the most important climatic factor that influenced ET in China. WD affected water vapor transport during the evaporation process. In China, as in other countries or continents such as Australia, Europe, and North America (Tuller, 2004; Roderick et al., 2007; McVicar et al., 2008; Donohue et al., 2010), WD, which has a significant effect on ET, has been decreasing in recent years. Some studies suggest that the decrease in wind speed in China is mainly due to the weakening of atmospheric circulation and the lessening intensity of the monsoon (Xu et al., 2006b), and that the significant increases in wind speed in a few areas may be associated with LUCC and underlying land surface changes. Any change in RH is closely related to a change in dry or wet surface conditions. In this study, we found that RH contributed only slightly to change in ET, and thus RH was not the dominant factor affecting ET in China.

The *evaporation paradox* has been a subject of much concern in recent years (Roderick and Farquhar, 2002). The IPCC (2013) reported that global surface temperatures have increased significantly over the

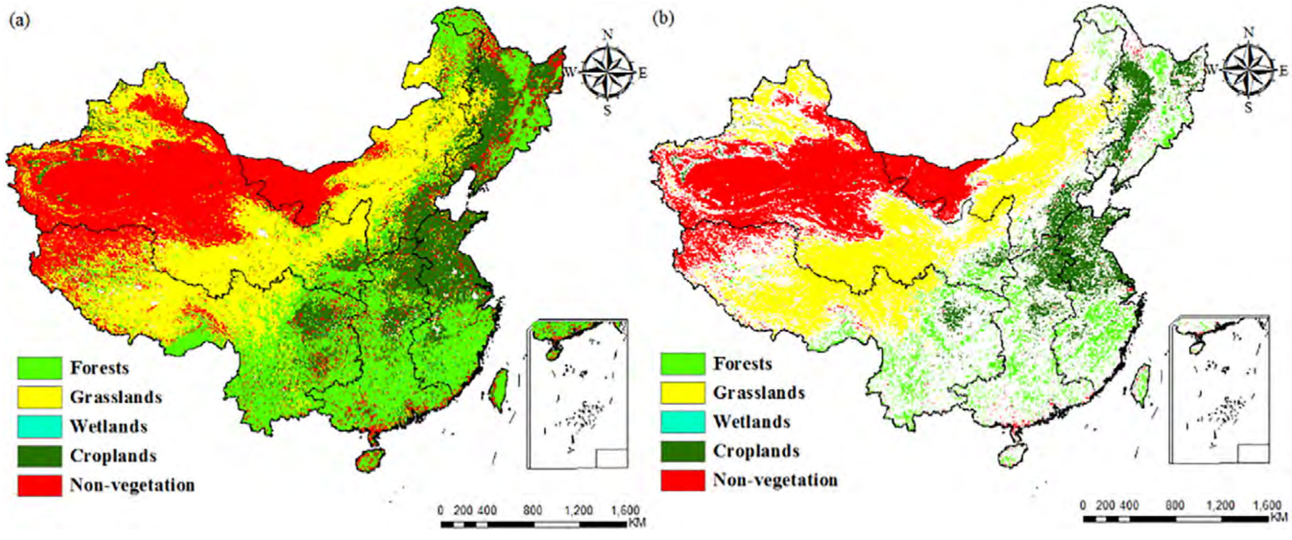

Fig. 5. (a) The reclassified land cover map in 2001; (b) the land cover map unchanged from 2001 to 2013.

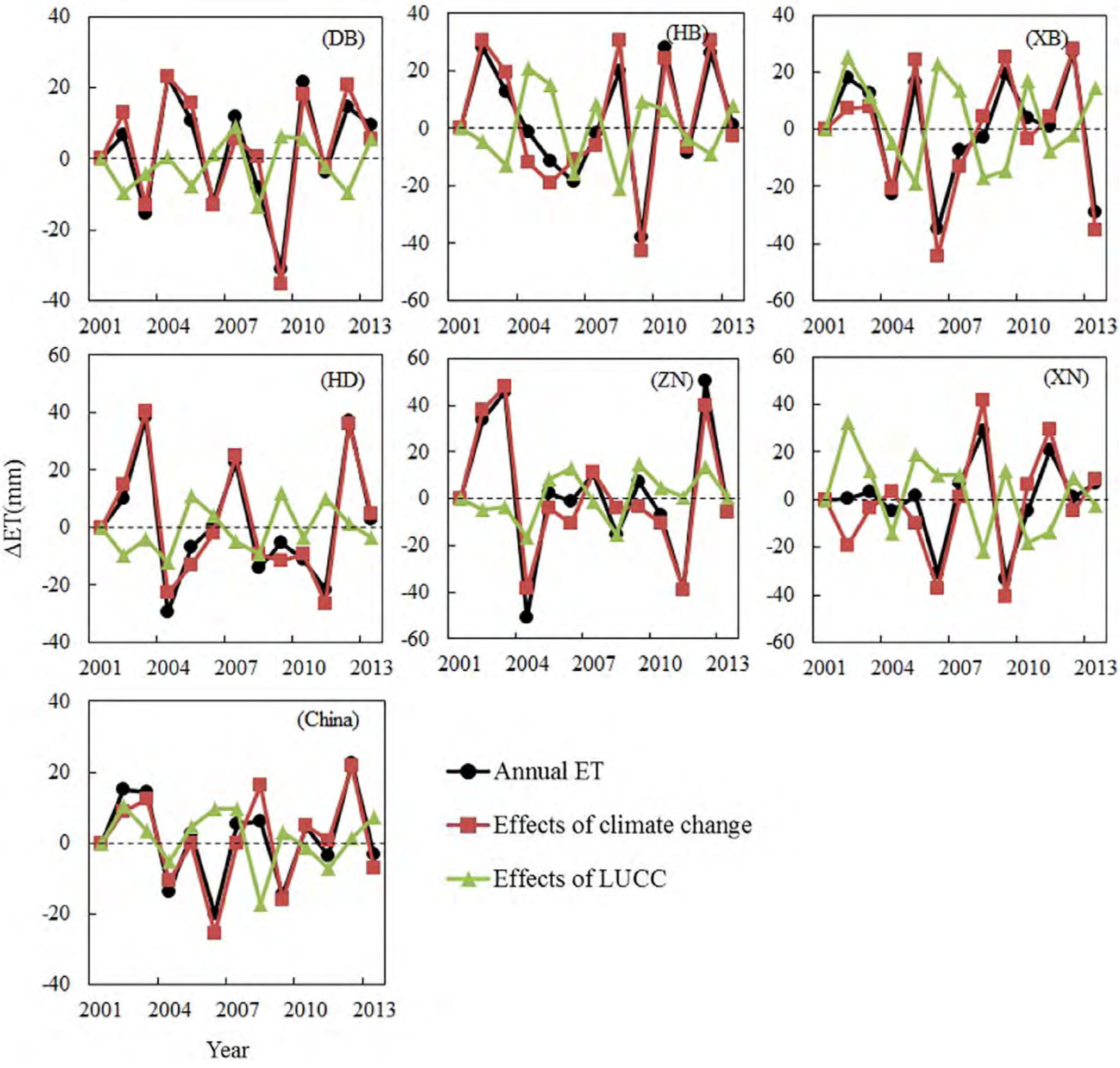

Fig. 6. The annual fluctuations in the effects of climate change and LUCC on average ET.

past century. China has experienced a significant increase in TA, which has risen by 0.23 °C every 10 years in the last 60 years (National Assessment Report on Climate ChangeII, 2011), which is almost twice the world average. Our study shows that TA in China has contributed positively to ET changes since the beginning of the twenty-first century, but that the negative contributions of WD and SD outweighed the positive influence of TA. Thus, ET still showed a decreasing trend even in the context of obvious global warming. We conclude that the *evaporation paradox* is to some extent an illustration of the effect of isolating the positive contribution of TA to change in ET which ignores the (mainly negative) contributions of other factors.

4.2. Effects of climate variability

Precipitation is one of the most important components of the hydrological cycle and determines the water supply conditions, further to an extent controlling ET (Walter et al., 2004). When precipitation is not a limiting factor for change in ET, the energy conditions and atmospheric demand factors that controlled by TA, WD, SD and RH) will be decisive. However, under drought conditions, ET can be affected by precipitation (Yang et al., 2006; Han et al., 2014). Thus, low ET in 2009 in DB and HB region is attributed to the fact that the most severe drought occurred, with precipitation reduced by 50%–80% of that in more normal years (Guo and Guo, 2010). In the HD and ZN regions, the differences between a hot and rainy 2003 and the high temperatures and low rainfall in 2004 (Fig. S3) resulted in strong opposite effects on ET in these regions between each of the two years. LUCC had a negative effect on ET, which decreased rapidly in the regions,. In 2011 there was a drought, followed in 2012 by waterlogging, in the HD and ZN regions (Li et al., 2012; Wang et al., 2013), which resulted in a decrease in ET in 2011 but an increase in ET in 2012.

4.3. Implications of ecological restoration on water resources

Changes from forests and natural vegetation to other land use types can increase water yield and decrease ET (Brown et al., 2005; Hayhoe et al., 2011; Dias et al., 2015; Yao et al., 2015). Deforestation and afforestation are the most influential types of LUCC that affect ET on a global scale (Bronstert et al., 2002). Olchev et al. (2008) found that transpiration and the evaporation of intercepted rainfall were reduced after tropical rainforests were converted to croplands in Indonesia. Although the land use conversion also increased soil evaporation there was overall a decrease in mean ET. Oliveira et al. (2014) found that deforestation reduced ET by 36% in Brazil because the leaf area index and vegetation

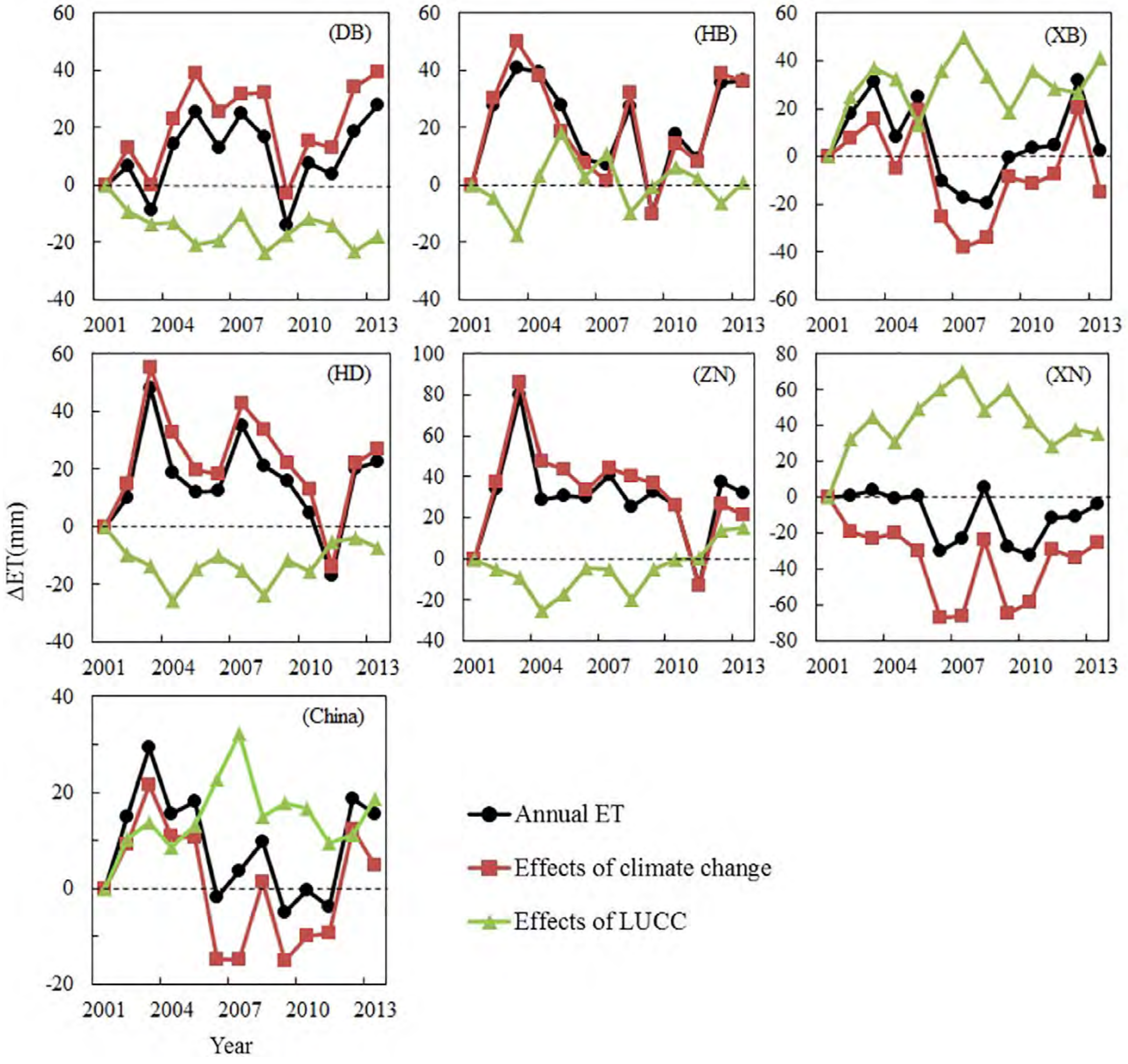

Fig. 7. Response of annual average ET cumulative to climate change and LUCC during the period 2001–2013.

coverage of croplands are relatively smaller than those of forests. In our study, when we compared the effects of the conversions of three land use types (forests, grasslands, croplands) on ET, we found that changes in ET due to forests being converted to other land use types were not equal to changes in ET due to other land use types being converted to forests (Table 2). The former were much greater than the latter. This might be due to the large differences between the growth cycles of forests and those of other vegetation types. Our study suggests that, in a certain area, the effects of deforestation on ET cannot be offset by the effects of afforestation or reforestation.

When comparing the effects of both climate change and LUCC on ET, we found that LUCC had a relatively greater effect than climate change did in certain areas. However, LUCC had no obvious effect on change in ET at the regional level because the area of LUCC was relatively small within the region. For example, land desertification in the XB region increased annually before 2003 (Yang, 2004). After 2003, China began to enforce the policy of returning croplands to forests and returning pasture to grasslands in the XB region, which made this region greened well (Bao, 2006). In 2007, to further improve the outcomes of the policy, desertification became more controlled and the area of vegetation coverage area in the region increased. Thus, during the period 2001–2003, changes in ET were mostly affected by land desertification in the XB region. ET was gradually less affected by LUCC after 2003, and the effects of climate change on ET gradually dominated.

4.4. Uncertainty and future studies

This study quantitatively analyzed the effects of both climate change and LUCC on ET based on MODIS products. The use of remotely-sensed data will inevitably bring some error and uncertainty into the analysis. We examined climate change and LUCC separately to identify their individual effects on ET, but climate change and LUCC interact. Climate factors can influence LUCC boundaries, and in turn LUCC also can affect regional climate. The interactions between the two factors can lead to considerable uncertainty in their roles in influencing ET. Land surface models that take account of the feedbacks between climate change and vegetation dynamics and LUCC may be used to study these issues in future research.

5. Conclusions

In this study, we analyzed the temporal and spatial variations of ET in China in the period 2001–2013 and the contributions both of climate change factors and LUCC to changes in ET. The annual ET decreased at a rate of −0.6 mm/yr from 2001 to 2013 in spite increase in air temperature. Spatially, average annual ET increased gradually from the northwest inland areas to the southeast coastal areas. The significant decrease in ET was mainly confined to the northwest China, the central of southwest China, and most regions of south central and east China. During 2000–2013, the overall area of forests and croplands increased, and the area of grasslands decreased. The ET effects from changes from forests to other land cover types were much greater than those from other land cover types to forests.

The changes in ET were mainly controlled by climate change in different regions of China. The effects of climate change on ET were more significant than the effects of LUCC on ET, although LUCC was more influential in some years than in other years. Among four climatic factors, SD was the dominant influence on changes in ET in China, but WD and SD were responsible to the detected ET decrease in some areas without LUCC.

This continental-scale study concludes that air temperature is not the only climatic variable when considering the climate change effects on hydrological cycle. When projecting effects of climate change on water resources in the future, climatic variables other than temperature and precipitation must be considered to realistically reflect future hydrometeorological conditions. This study suggests that LUCC induced by urbanization and ecological restoration influenced ET and the hydrological cycle locally. However, the regional effects of LUCC including reforestation through affecting atmospheric moisture, cloud formation, precipitation, and energy balances in different regions are unclear without additional studies using regional land surface models (Ellison et al., 2012). Future studies on the regional interactions between climate change, LUCC, and energy balances may offer more insights on the likely effects of vegetation-based ecological restoration on local water resources in China.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2017.04.080.

References

Allen, R.G., Pereira, L.S., Howell, T.A., Jensen, M.E., 2011a. Evapotranspiration information reporting: i. factors governing measurement accuracy. Agric. Water Manag. 98 (6), 899–920.

Allen, R.G., Pereira, L.S., Howell, T.A., Jensen, M.E., 2011b. Evapotranspiration information reporting: ii. recommended documentation. Agric. Water Manag. 98 (6), 921–929.

Autovino, D., Minacapilli, M., Provenzano, G., 2016. Modelling bulk surface resistance by MODIS data and assessment of MOD16A2 evapotranspiration product in an irrigation district of Southern Italy. Agric. Water Manag. 167, 86–94.

Bao, L.M., 2006. A summary of the study on the policy of grain for green in China. I. Agric. Econ. 8, 62–65 (in Chinese).

Bao, Z., Zhang, J., Wang, G., Fu, G., He, R., Yan, X., Jin, J., Liu, Y., Zhang, A., 2012. Attribution for decreasing streamflow of the Haihe river basin, northern China: climate variability or human activities? J. Hydrol. 460, 117–129.

Bronstert, A., Niehoff, D., Bürger, G., 2002. Effects of climate and land-use change on storm runoff generation: present knowledge and modelling capabilities. Hydrol. Process. 16 (2), 509–529.

Brown, A.E., Zhang, L., Mcmahon, T.A., Western, A.W., Vertessy, R.A., 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. J. Hydrol. 310 (1–4), 28–61.

Brutsaert Amp, W., Parlange, M.B., 1998. Hydrologic cycle explains the evaporation paradox. Nature 396 (6706), 30.

Burn, D.H., Hesch, N.M., 2007. Trends in evaporation for the Canadian prairies. J. Hydrol. 336 (1–2), 61–73.

Croitoru, A.E., Piticar, A., Dragotă, C.S., Burada, D.C., 2013. Recent changes in reference evapotranspiration in Romania. Glob. Planet. Chang. 111, 127–137.

Dias, L.C.P., Macedo, M.N., Costa, M.H., Coe, M.T., Neill, C., 2015. Effects of land cover change on evapotranspiration and streamflow of small catchments in the upper Xingu river basin, central Brazil. J. Hydrol. 4 (Part B), 108–122 (Regional Studies).

Dinpashoh, Y., Jhajharia, D., Fakheri-Fard, A., Singh, V.P., Kahya, E., 2011. Trends in reference crop evapotranspiration over Iran. J. Hydrol. 399 (3–4), 422–433.

Donohue, R.J., Mcvicar, T.R., Roderick, M.L., 2010. Assessing the ability of potential evaporation formulations to capture the dynamics in evaporative demand within a changing climate. J. Hydrol. 386 (1), 186–197.

Douglas, E.M., Jacobs, J.M., Sumner, D.M., Ray, R.L., 2009. A comparison of models for estimating potential evapotranspiration for Florida land cover types. J. Hydrol. 373 (3), 366–376.

Ellison, D.N., Futter, M., Bishop, K., 2012. On the forest cover–water yield debate: from demand-to supply-side thinking. Glob. Chang. Biol. 18 (3), 806–820.

Eslamian, S., Khordadi, M.J., Abedi-Koupai, J., 2011. Effects of variations in climatic parameters on evapotranspiration in the arid and semi-arid regions. Glob. Planet. Chang. 78 (3–4), 188–194.

Feng, Z., Yang, Y., Zhang, Y., Zhang, P., Li, Y., 2005. Grain-for-green policy and its impacts on grain supply in west china. Land Use Policy 22 (4), 301–312.

Feng, X., et al., 2016. Revegetation in China's Loess plateau is approaching sustainable water resource limits. Nat. Clim. Chang. 6, 1019–1022.

Friedl, M.A., Sulla-Menashe, D., Tan, B., Schneider, A., Ramankutty, N., Sibley, A., Huang, X.M., 2010. MODIS Collection 5 global land cover: algorithm refinements and characterization of new datasets. Remote Sens. Environ. 114, 168–182.

Gao, G., Chen, D., Ren, G., Chen, Y., Liao, Y., 2006. Spatial and temporal variations and controlling factors of potential ET in china: 1956-2000. J. Geogr. Sci. 16 (1), 3–12.

Golubev, V.S., Lawrimore, J.H., Groisman, P.Y., Speranskaya, N.A., Zhuravin, S.A., Menne, M.J., Peterson, T.C., Thomas, C., Malone, R.W., 2001. Evaporation changes over the contiguous united states and the former USSR: a reassessment. Geophys. Res. Lett. 28 (13), 2665–2668.

Guo, Q.H., Guo, Z.F., 2010. 2009 top ten weather and climate events in China. Meteorol. Knowl. 1, 24–25 (in Chinese).

Han, S., Tian, F., Hu, H., 2014. Positive or negative correlation between actual and potential evaporation? Evaluating using a nonlinear complementary relationship model. Water Resour. Res. 50 (2), 1322–1336.

Hao, L., Zhang, X., Gao, J., 2011. Simulating human-induced changes of water resources in the upper Xiliaohe river basin, China. Environ. Eng. Manag. J. 10, 787–792.

Hao, L., et al., 2015. Urbanization dramatically altered the water balances of a paddy field-dominated basin in southern China. Hydrol. Earth Syst. Sci. 19, 3319–3331.

Hayhoe, S.J., Neill, C., Porder, S., Mchorney, R., Lefebvre, P., Coe, M.T., Elsenbeer, H., Krusche, A.V., 2011. Conversion to soy on the Amazonian agricultural frontier increases streamflow without affecting stormflow dynamics. Glob. Chang. Biol. 17 (5), 1821–1833.

Hu, G., Jia, L., Menenti, M., 2015. Comparison of MOD16 and LSA-SAF MSG evapotranspiration products over Europe for 2011. Remote Sens. Environ. 156, 510–526.

IPCC, 2013. In: Dennis, L., et al. (Eds.), Climate change 2013. The physical science basis, working group I contribution to the fifth assessment report of the intergovernmental panel on climate change. WMO/UNEP Cambridge Univ. press, Cambridge UK.

Irmak, S., Kabenge, I., Skaggs, K.E., Mutiibwa, D., 2012. Trend and magnitude of changes in climate variables and reference evapotranspiration over 116-yr period in the Platte river basin, central Nebraska–USA. J. Hydrol. 420 (4), 228–244.

Jia, Z., Liu, S.M., Xu, Z.W., Chen, Y., Zhu, M.J., 2012. Validation of remotely sensed evapotranspiration over the Hai River Basin, China. J. Geophys. Res. 117, D13113.

Jin, J.X., Wang, Y., Jiang, H., Kong, Y., Lu, X.H., Zhang, X.Y., 2016. Improvement of ecological geographic regionalization based on remote sensing and canonical correspondence analysis: a case study in China. Sci. China Earth Sci. 59, 1745–1753.

Kim, J., Choi, J., Choi, C., Park, S., 2013. Impacts of changes in climate and land use/land cover under ipcc rcp scenarios on streamflow in the Hoeya river basin, Korea. Sci. Total Environ. 452–453 (C(5)), 181–195.

Li, Z., Liu, W.Z., Zhang, X.C., Zheng, F.L., 2009. Impacts of land use change and climate variability on hydrology in an agricultural catchment on the loess plateau of china. J. Hydrol. 377 (1–2), 35–42.

Li, Y., Gao, G., Ye, D.X., Chen, Y., Zou, X.K., Ai, W.X., Zhang, P.Q., Wang, P.L., 2012. Climatic Characters over China in 2011. Meteorol. Monthly 38 (4), 464–471 (in Chinese).

Liu, X., Luo, Y., Zhang, D., Zhang, M., Liu, C., 2011. Recent changes in pan evaporation dynamics in China. Geophys. Res. Lett. 38, L13404.

Loveland, T.R., Belward, A.S., 1997. The IGBP-DIS global 1km land cover data set, DISCover: First results. Int. J. Remote Sens. 18 (15), 3289–3295.

Ma, Z., Kang, S., Zhang, L., Tong, L., Su, X., 2008. Analysis of impacts of climate variability and human activity on streamflow for a river basin in arid region of northwest china. J. Hydrol. 352 (3–4), 239–249.

McVicar, T.R., et al., 2008. Wind speed climatology and trends for Australia, 1975–2006: capturing the stilling phenomenon and comparison with near-surface reanalysis output. Geophys. Res. Lett. 35, L20403.

Monteith, J.L., 1965. Evaporation and the environment. The State and Movement of Water in Living Organisms XIXth Symposium. Cambridge Univ. Press, Swansea, Wales. Cambridge, UK, pp. 205–234.

Mu, Q.Z., Zhao, M.S., Running, S.W., 2011. Improvements to a MODIS global terrestrial evapotranspiration algorithm. Remote Sens. Environ. 115, 1781–1800.

Nam, W.H., Hong, E.M., Choi, J.Y., 2015. Has climate change already affected the spatial distribution and temporal trends of reference evapotranspiration in south korea? Agric. Water Manag. 150 (150), 129–138.

National Assessment Report on Climate ChangeII, 2011. Editorial Board, National Assessment Report on Climate ChangeII. Science Press, Beijing, pp. 23–38.

Ohmura, A., Wild, M., 2002. Is the hydrological cycle accelerating? Science 298 (5597), 1345–1346.

Olchev, A., et al., 2008. Effects of land-use changes on evapotranspiration of tropical rain forest margin area in Central Sulawesi (Indonesia): modelling study with a regional SVAT model. Ecol. Model. 212 (1–2), 131–137.

Oliveira, P.T.S., Nearing, M.A., Moran, M.S., Goodrich, D.C., Wendland, E., Gupta, H.V., 2014. Trends in water balance components across the Brazilian Cerrado. Water Resour. Res. 50 (9), 7100–7114.

Peterson, T.C., Golubev, V.S., Groisman, P.Y., 1995. Evaporation losing its strength. Nature 377 (6551) (687–588).

Qiu, G.Y., Yin, J., Tian, F., Geng, S., 2011. Effects of the “Conversion of Cropland to Forest and Grassland Program” on the water budget of the Jinghe River Catchment in China. J. Environ. Qual. 40 (6), 1745–1755.

Roderick, M.L., Farquhar, G.D., 2002. The cause of decreased pan evaporation over the past 50 years. Science 298 (5597), 1410–1411.

Roderick, M.L., Farquhar, G.D., 2004. Changes in Australian pan evaporation from 1970 to 2002. Int. J. Climatol. 24 (9), 1077–1090.

Roderick, M.L., Rotstayn, L.D., Farquhar, G.D., Hobbins, M.T., 2007. On the attribution of changing pan evaporation. Geophys. Res. Lett. 34, L17403.

Sun, G., Alstad, K., Chen, J., Chen, S., Ford, C.R., Lin, G., Liu, C., Lu, N., Mcnulty, S.G., Miao, H., 2011a. A general predictive model for estimating monthly ecosystem evapotranspiration. Ecohydrology 4, 245–255.

Sun, G., Caldwell, P., Noormets, A., Mcnulty, S.G., Cohen, E., Moore, M.J., Domec, J.C., Treasure, E., Mu, Q., Xiao, J., 2011b. Upscaling key ecosystem functions across the conterminous United States by a water-centric ecosystem model. J. Geophys. Res. Biogeosci. 116, 2011.

Sun, G., Mcnulty, S.G., Myers, J.A.M., Cohen, E.C., 2008. Impacts of multiple stresses on water demand and supply across the Southeastern United States. J. Am. Water Resour. Assoc. 44 (6), 1441–1457.

Tang, B., Tong, L., Kang, S., Zhang, L., 2011. Impacts of climate variability on reference evapotranspiration over 58 years in the Haihe river basin of north China. Agric. Water Manag. 98 (10), 1660–1670.

Thomas, A., 2000. Spatial and temporal characteristics of potential evapotranspiration trends over China. Int. J. Climatol. 20 (4), 381–396.

Tuller, S.E., 2004. Measured wind speed trends on the west coast of Canada. Int. J. Climatol. 24 (11), 1359–1375.

Vörösmarty, C.J., Green, P., Salisbury, J., Lammers, R.B., 2000. Global water resources: vulnerability from climate change and population growth. Science 289 (5477), 284–288.

Walter, M.T., Wilks, D.S., Parlange, J.Y., Schneider, R.L., 2004. Increasing evapotranspiration from the conterminous united states. J. Hydrometeorol. 5 (3), 405–408.

Wang, Y.M., Ye, D.X., Ai, W.X., Wang, L., Wang, C.K., Gao, R., Xiang, Y., Zhao, L., 2013. Climatic Characters over China in 2012. Meteorol. Monthly 39 (4), 500–507 (in Chinese).

Xiao, J.F., Zhou, Y., Zhang, L., 2015. Contributions of natural and human factors to increases in vegetation productivity in China. Ecosphere 6 (11), 233.

Xie, X., Liang, S., Yao, Y., Jia, K., Meng, S., Li, J., 2015. Detection and attribution of changes in hydrological cycle over the three-north region of China: climate change versus afforestation effect. Agric. Forest Meteorol. 203, 74–87.

Xu, F., Bao, H.X.H., Li, H., Kwan, M.P., Huang, X., 2016. Land use policy and spatiotemporal changes in the water area of an arid region. Land Use Policy 54, 366–377.

Xu, M., Chang, C., Fu, C., Qi, Y., Robock, A., Robinson, D., Zhang, H.M., 2006b. Steady decline of East Asian monsoon winds, 1969–2000: evidence from direct ground measurements of wind speed. J. Geophys. Res. Atmos. 111 (D24), 906–910.

Xu, C.Y., Gong, L., Jiang, T., Chen, D., Singh, V.P., 2006a. Analysis of spatial distribution and temporal trend of reference evapotranspiration and pan evaporation in Changjiang (Yangtze river) catchment. J. Hydrol. 327 (1–2), 81–93.

Yang, R.R., 2004. Grazing withdrawal and management of grassland: issues over meaning and technological standards. Pratacult. Sci. 21 (2), 41–44 (in Chinese).

Yang, D., Sun, F., Liu, Z., Cong, Z., Lei, Z., 2006. Interpreting the complementary relationship in non-humid environments based on the Budyko and penman hypotheses. Geophys. Res. Lett. 33, L18402.

Yang, H., Yang, D., 2012. Climatic factors influencing changing pan evaporation across China from 1961 to 2001. J. Hydrol. 414, 184–193.

Yao, Y., Cai, T., Ju, C., He, C., 2015. Effect of reforestation on annual water yield in a large watershed in northeast China. J. For. Res. 26, 697–702.

Yu, P.S., Yang, T.C., Chou, C.C., 2002. Effects of climate change on evapotranspiration from paddy fields in southern Taiwan. Clim. Chang. 54 (1), 165–179.

Zeng, T., Zhang, Z., Zhao, X., Wang, X., Zuo, L., 2015. Evaluation of the 2010 MODIS collection 5.1 land cover type product over China. Remote Sens. 7 (2), 1981–2006.

Zhang, Y., Liu, C., Tang, Y., Yang, Y., 2007. Trends in pan evaporation and reference and actual evapotranspiration across the Tibetan plateau. J. Geophys. Res. Atmos. 112 (D12), 1103–1118.

Zhang, T., Peng, J., Liang, W., Yang, Y., Liu, Y., 2016a. Spatial-temporal patterns of water use efficiency and climate controls in China's Loess plateau during 2000-2010. Sci. Total Environ. 565, 105–122.

Zhang, Y., Zhang, C., Wang, Z., Chen, Y., Gang, C., An, R., Li, J.L., 2016b. Vegetation dynamics and its driving forces from climate change and human activities in the Three-River Source Region, China from 1982 to 2012. Sci. Total Environ. 563-564, 210–220.

Zhang, Y., et al., 2015. Multiple afforestation programs accelerate the greenness in the ‘Three North’ region of China from 1982 to 2013. Ecol. Indic. 61, 404–412.

Zhao, A., Zhu, X., Liu, X., Pan, Y., Zuo, D., 2016. Impacts of land use change and climate variability on green and blue water resources in the Weihe river basin of northwest china. Catena 137, 318–327.

Zheng, J.Y., Bian, J.J., Ge, Q.S., Hao, Z.X., Yin, Y.H., Liao, Y.M., 2013. The climate regionalization in China for 1981–2010. Chin. Sci. Bull. 58, 3088–3099 (Chin Ver). (in Chinese).

Zheng, H., Liu, X., Liu, C., Dai, X., Zhu, R., 2009. Assessing contributions to panevaporation trends in Haihe River Basin, China. J. Geophys. Res. 114, D24105.