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Combined effects of climate and land management on watershed vegetation dynamics in an arid environment

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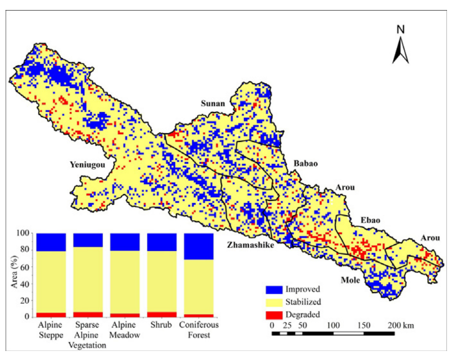
HIGHLIGHTS

- Determined relationships among leaf area index, topography, climate, and grazing in the Upper Heihe River Basin, China.
- Both climate change and grazing were responsible to the detected long term trend LAI trend during 2001-2012
- Extreme weather and ecological restoration contributed to the LAI variations in space and time.

GRAPHICAL ABSTRACT



Temporal trend of growing season leaf area index (LAI) during 2001–2012 in the Upper Heihe River Basin. Three distinct areas in LAI trend 'Improved", "Stabilized", and 'Degraded' are identified as a result of climate change and human activities (i.e., grazing and ecological restoration).

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ABSTRACT

Leaf area index (LAI) is a key parameter to characterize vegetation dynamics and ecosystem structure that determines the ecosystem functions and services such as clean water supply and carbon sequestration in a watershed. However, linking LAI dynamics and environmental controls (i.e., coupling biosphere, atmosphere, and anthroposphere) remains challenging and such type of studies have rarely been done at a watershed scale due to data availability. The present study examined the spatial and temporal variations of LAI for five ecosystem types within a watershed with a complex topography in the Upper Heihe River Basin, a major inland river in the arid and semi-arid western China. We integrated remote sensing-based GLASS (Global Land Surface Satellite) LAI products, interpolated climate data, watershed characteristics, and land management records for the period of 2001–2012. We determined the relationships among LAI, topography, air temperature and precipitation, and grazing history by five ecosystem types using several advanced statistical methods. We show that long-term mean LAI distribution had an obvious vertical pattern as controlled by precipitation and temperature in a hilly watershed. Overall, watershed-wide mean LAI had an increasing trend overtime for all ecosystem types during 2001–2012, presumably as a result of global warming and a wetting climate. However, the fluctuations of observed LAI at a pixel scale (1 km) varied greatly across the watershed. We classified the vegetation changes within the watershed as 'Improved', 'Stabilized', and 'Degraded' according their respective LAI changes. We found that climate was not the only driver for temporal vegetation changes for all land cover types. Grazing partially contributed to the decline of LAI in some areas and masked the positive climate warming effects in other areas. Extreme

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weathers such as cold spells and droughts could substantially affect inter-annual variability of LAI dynamics. We concluded that temporal and spatial LAI dynamics were rather complex and were affected by both climate variations and human disturbances in the study basin. Future monitoring studies should focus on the functional interactions among vegetation dynamics, climate variations, land management, and human disturbances.

1. Introduction

Leaf area index (LAI) is defined as the total green leaf surface area per unit land ground surface area (Chen and Black, 1992). LAI is a critical parameter of ecosystem structure for understanding vegetation growth and functional response to climate change (Daughtry et al., 1992; Gitelson and Merzlyak, 1996; Moran et al., 1995; Liu et al., 1997; Musau et al., 2016). In particular, LAI links plant photosynthesis and carbon sequestration, and water use (or evapotranspiration, ET), and eventually ecosystem productivity and water yield (Sun et al., 2011a, 2011b; Musau et al., 2016) and water supply to humans. Contemporary ecohydrological models such as Variable Infiltration Capacity (VIC), Systeme Hydrologique Europeen (MIKE SHE), and Xinanjiang model that simulate the climate-hydrology-ecosystem coupling relationships use LAI as a key input parameter (Tesemma et al., 2015; Dai et al., 2010; Kidmose et al., 2015; Li et al., 2009). Indeed, LAI reflects land surface characteristics that regulate the partitioning of sensible and latent heat fluxes (Sprintsin et al., 2011; Bonan, 2008; Hogg et al., 2002; Margolis and Ryan, 1997; Schwartz, 1992) and hydrological cycles at multiple scales, thus LAI is a critical parameter in understanding the vegetation and climate feedbacks, and water resources at the watershed level.

It is well known that the temporal and spatial distribution of vegetation and its characteristics are closely tied to micro- and macro-environmental factors such as water and energy availability (Li et al., 2012; Hao et al., 2014). For example, water stress alters leaf morphology as well as LAI. Xeric or dry conditions in dry regions or uplands have a low leaf area when compared to mesic environments in the humid or lowlands. A decrease in LAI due to human (i.e., grazing or deforestation) (Li et al., 2012; Hao et al., 2014) or natural disturbances (i.e., droughts) leads towards reduced ecosystem productivity and ET, but increase in water yield (Sun et al., 2011a, 2011b). Vegetation growth in lower elevation in the arid regions is usually limited by moisture availability, and increased precipitation can quickly promote increased vegetation growth (Guli Jiapaer et al., 2015). In areas with high elevations or high latitude, plant growth is often limited by thermal conditions such that temperature increases can facilitate vegetation growth (Zeng and Yang, 2008). Topography (e.g., slope aspects) is also an important factor influencing redistribution of air temperature, precipitation, and sunshine durations, that directly affect water and energy availability for plant growth (i.e., plant species composition, LAI) and ecosystem functions (i.e., water yield) (Bales et al., 2006).

Before the remote sensing technology is widely available, quantifying LAI at the watershed scale was limited because LAI can only be obtained through field measurements with special equipment (Bonhomme et al., 1974). However, the rapid development of remote sensing technology in the past decades provides powerful means that have made it possible to map regional and global LAI. For example, the level-4 MODIS global LAI and Fraction of Photosynthetically Active Radiation (FPAR) products are composited every 8 days at a 1000 m resolution on a Sinusoidal grid (Yang et al., 2006). These satellite-derived products have been used to map vegetation coverage, LAI, land use and land cover detections, vegetation growth, and most importantly understand the broad environmental controls to ecosystem structure, functions and services in different parts of the world (Hill et al., 2006; Heiskanen et al., 2012). For example, Liu et al. (2012) analyzed the LAI trend from 2001 to 2010 across China by using refined MODIS LAI products and concluded that the LAI changes were controlled by climate variation and extreme weather patterns. Similarly, Guli Jiapaer et al. (2015) analyzed the relationships between LAI and climate factors in the Xinjiang Autonomous Region, an arid region in northwestern China and found that climate change from warm-dry to warm-wet was the dominant factor causing the observed acceleration of vegetation growth. Studies in China have documented that climate has become warmer and more humid since the early 1980s in northwestern China, which includes arid and semi-arid areas. Variations in vegetation activities have been linked to variations in climate (Piao et al., 2010; Sun et al., 2015) and grazing (Hao et al., 2014). Climate change and variations have resulted in significant effects on vegetation dynamics due to the associated alterations to hydrological (Musau et al., 2016) and biogeochemical processes, such as plant photosynthesis (Hao et al., 2014), soil respiration, and mineralization of soil organic matters (Schlesinger and Andrews, 2000).

However, most of the existing studies were conducted at a very broad scale (Li et al., 2012; Musau et al., 2016), few studies have examined the satellite-derived LAI changes and have related the LAI variations to environmental factors at a finer spatial scale, such as a watershed with a complex topography (Hao et al., 2016). Previous large scale studies all suggest that the plant response to climate change varies spatially (Stocker et al., 2013; Raynolds et al., 2008; Song et al., 2005) and local information including land management is needed to fully understand effects of climate change on ecosystem functions. The spatial heterogeneity ecosystem responses to climate change within a watershed has been recognized as being extremely important especially for watersheds with rough topography in the Qinghai-Tibet Plateau regions in western China. For example, Deng et al. (2013) examined vegetation growth across the 2000–2400 m and 3900–4500 m elevation gradients and find a strong linkage between growing season mean NDVI and both temperature and precipitation in the Qilian Mountains. In general, because of the complex topography and associated diverse ecohydrological processes (Bales et al., 2006), it is often difficult to evaluate the influence of climate change and climate variability on vegetation at the watershed scale in mountain regions, in part due to climatic data availability and coarse resolution of vegetation data (Gao et al., 2016; Hao et al., 2016).

This study focuses on the upper part of the Heihe River Basin (HRB), the second largest inland river over the provinces of Qinghai, Gansu, and Inner Mongolia, western China (Gao et al., 2016; Hao et al., 2016) (Fig. 1). The HRB is located in the middle part of Hexi Corridor in an arid region of northwestern China that has experienced severe water shortages due to unregulated water use for irrigation-based agriculture and climate change. To alleviate water and related environmental problems, the Chinese government has invested 2.35 billion RMB (345 Million US Dollars) to carry out ecological restoration including reforestation and grazing management in the HRB since 2001. The ecohydology of HRB has been intensively studied in recent years to serve as one research model for understanding the interactions between water resources and socioeconomics in the arid region (Cheng et al., 2014; Gao et al., 2016). The Upper HRB is dominated by alpine ecosystems that are the source of the water supply for the middle and lower sections of the HRB, which are dominated by oasis and desert. Recent modeling studies suggest the upper part of the HRB generates nearly 70% total runoff for the entire HRB (Gao et al., 2016; Ruan et al., 2016) and the changes of vegetation in the basin were likely to affect not only the ecosystem productivity and other ecosystem functions locally but also affect water supply down streams. The middle part of the HRB is

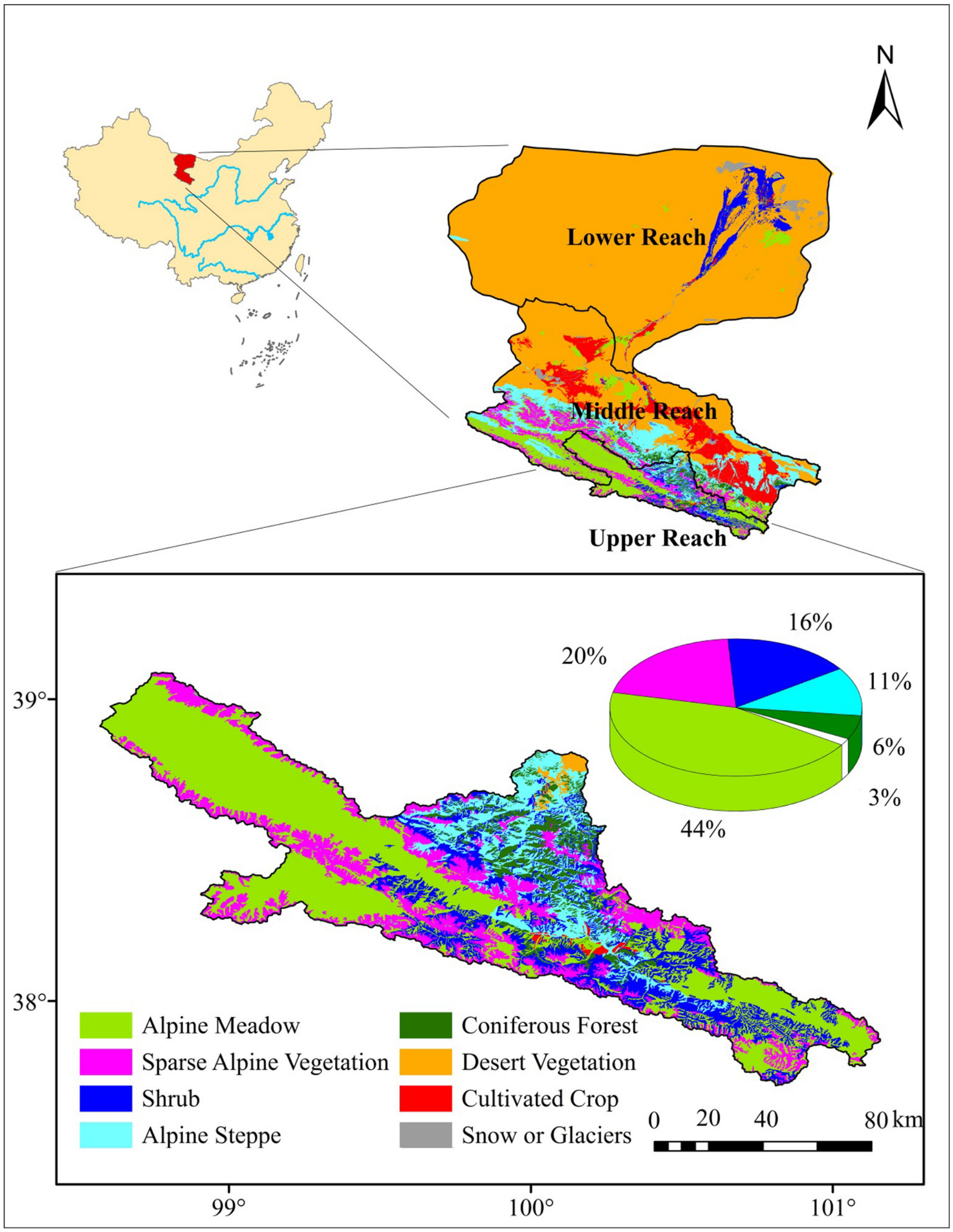

Fig. 1. Watershed location and vegetation distribution in the upper reach of the Heihe River Basin.

dominated by irrigation-based agriculture and the lower part by desert, and both regions solely rely on water supply from the Upper HRB through surface and groundwater systems (Cheng et al., 2014). Previous studies suggest that it is critical to quantify the LAI variations to better parameterize various watershed hydrological models (Gao et al., 2016; Ruan et al., 2016) that have been applied in the HRB for quantifying the potential changes in water supply in the Upper HRB under a changing environment.

Besides climate change, human activities such as cultivation, grazing, and reforestation also strongly affect ecosystem dynamics in the alpine regions resulting in irreversible ecosystem changes (Scherrer and Pickering, 2001). For example, grazing exclusion is one of the effective methods in ecological restoration for grasslands in arid regions (Hao et al., 2014). Zhang et al. (2015) compared overgrazing and climate warm effects and found that overgrazing was the main driver of change to the alpine grassland vegetation on the Qinghai-Tibetan Plateau, Therefore, fully understanding the LAI dynamics in the Upper HRB, and the influences of climate change and human activities must be examined collectively.

Therefore, the objectives of this study were to (1) quantify the long-term trends of growing season LAI at the watershed scale, (2) analyze relationships between environmental factors and LAI by ecosystem type, and (3) compare the different responses of LAI among all vegetation and climate variations. We hypothesized that changes in temperature and precipitation would influence long-term LAI trends, but human activities may mask the climatic impacts. The ultimate goal of this study is to better understand environmental controls and effects of human disturbances on LAI so watershed ecohydrological models may be improved to provide better quantitative information for assessing ecosystem services in the study watershed. In addition, land managers and policy makers can be better informed about the combined effects of climate and management options on ecosystem changes so that limited resources for ecological restoration efforts be more effectively allocated in the study region.

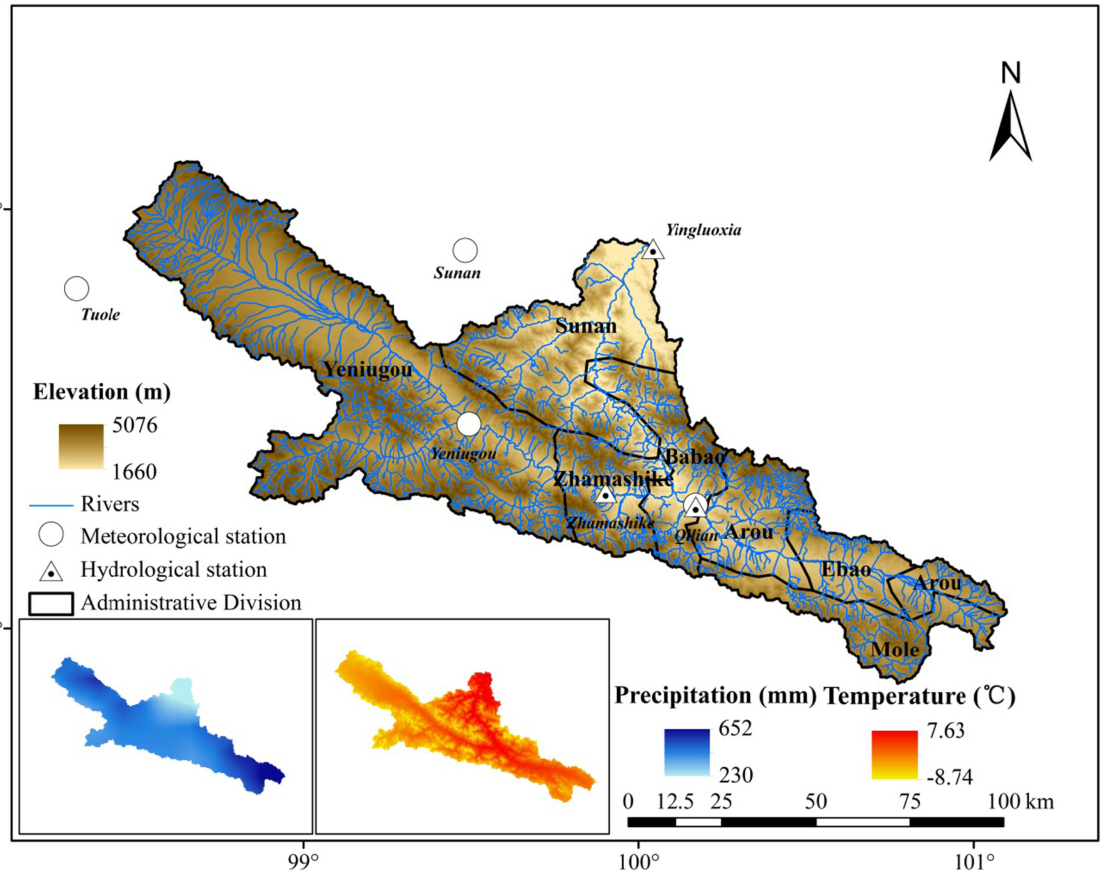

Fig. 2. Administrative boundary, elevation, and river network in the Upper Heihe River Basin.

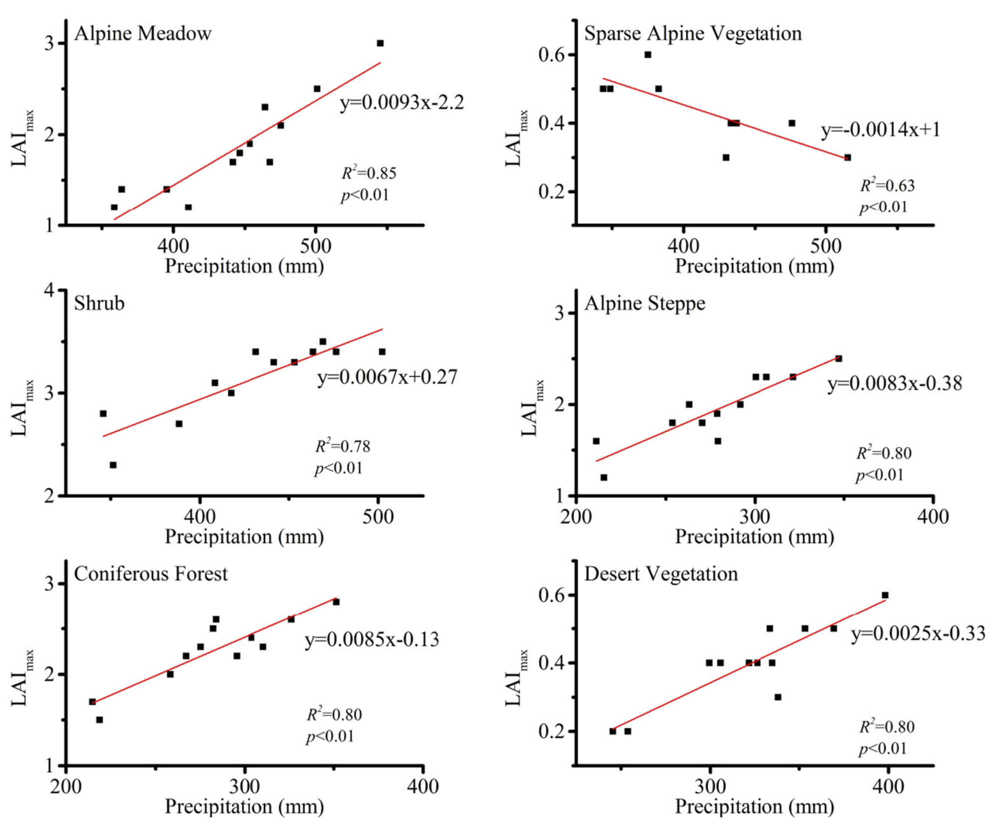

Fig. 3. Regression models between growing season LAI_{max} and precipitation.

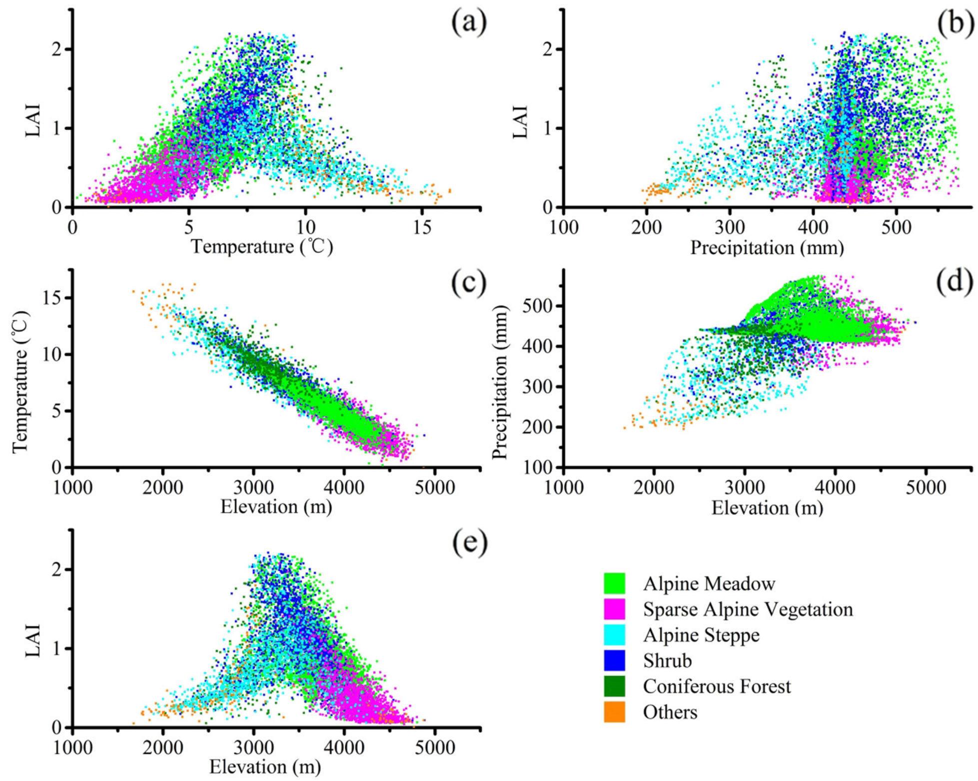

Fig. 4. Relationships among growing season leaf area index, elevation, precipitation and temperature for land covers.

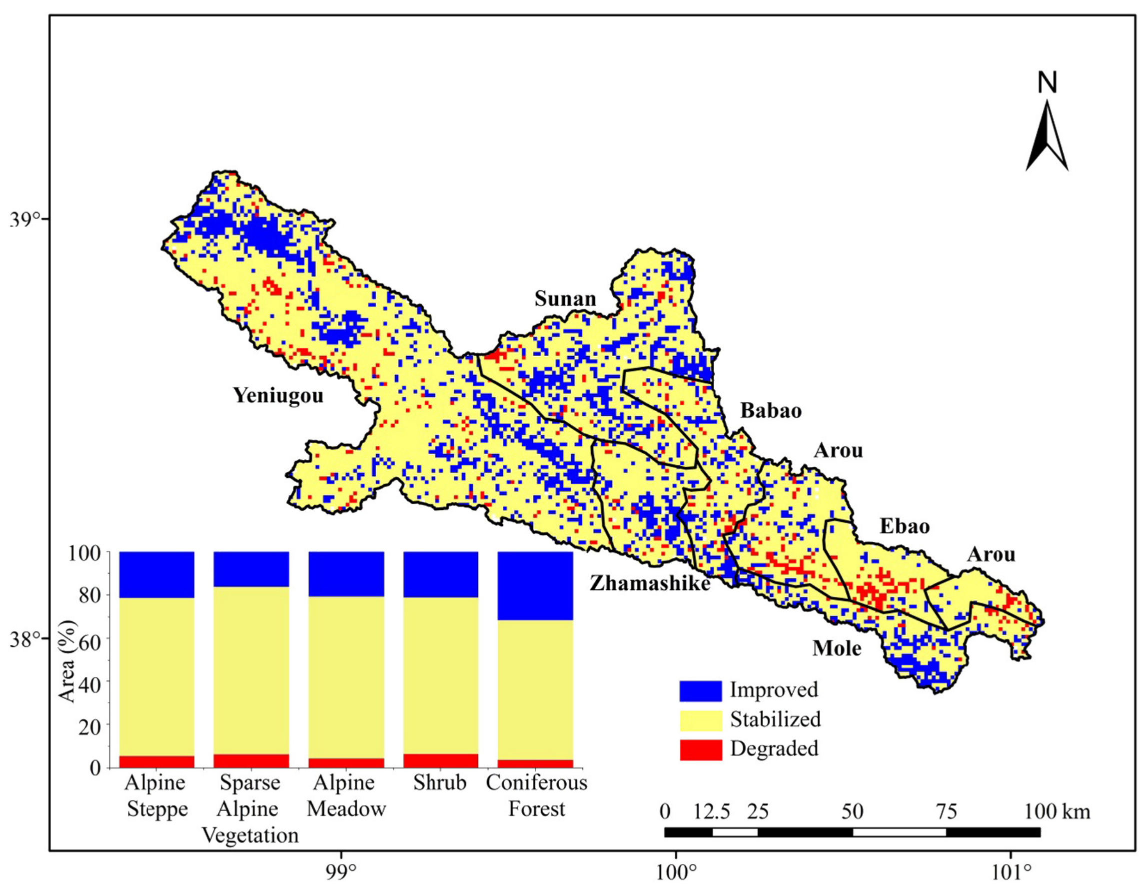

Fig. 5. Temporal trend of growing season LAI during 2001–2012 in the Upper Heihe River Basin.

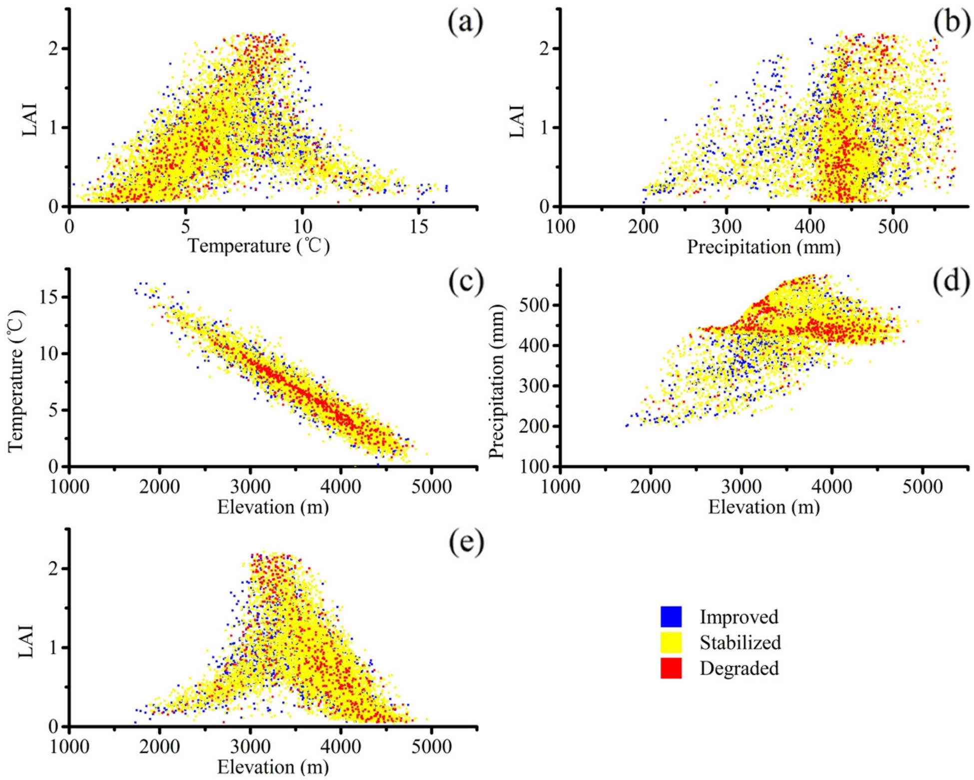

Fig. 6. Relationships among growing season LAI, elevation, precipitation and temperature in three LAI trends area.

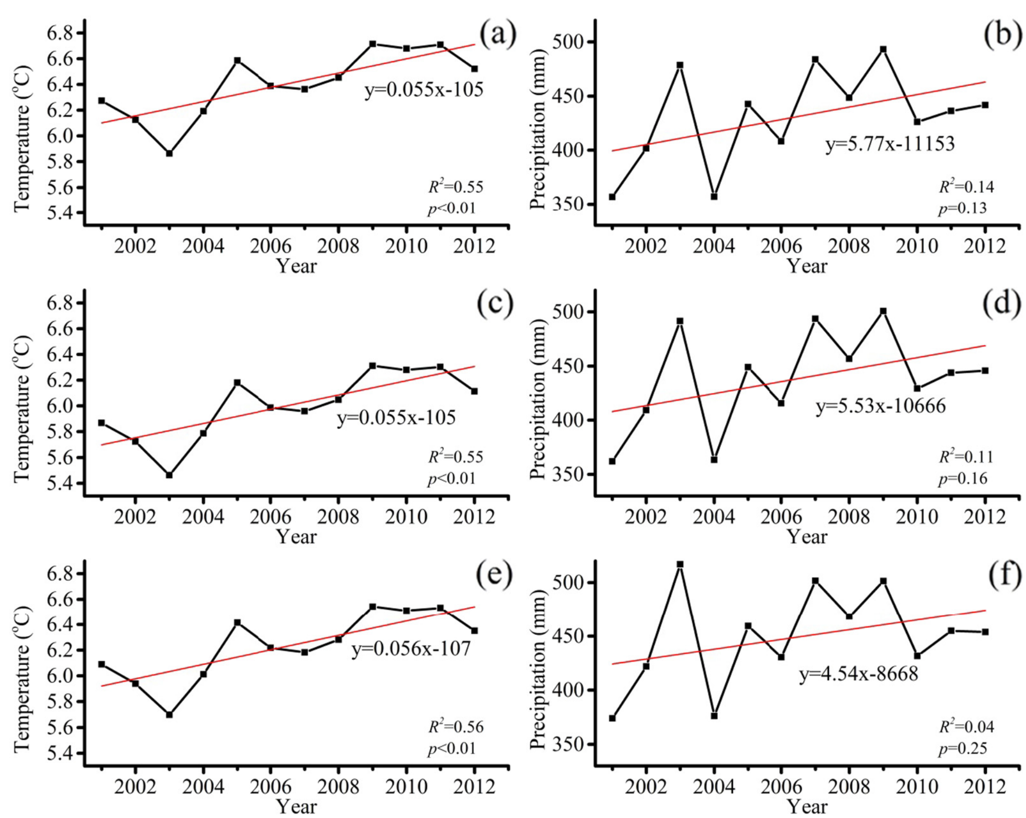

Fig. 7. Annual mean growing season temperature and precipitation variation showing upward trends by area with three different temporal trend in LAI: a–b) Improved, c–d) Stabilized, and e–f) Degraded, respectively.

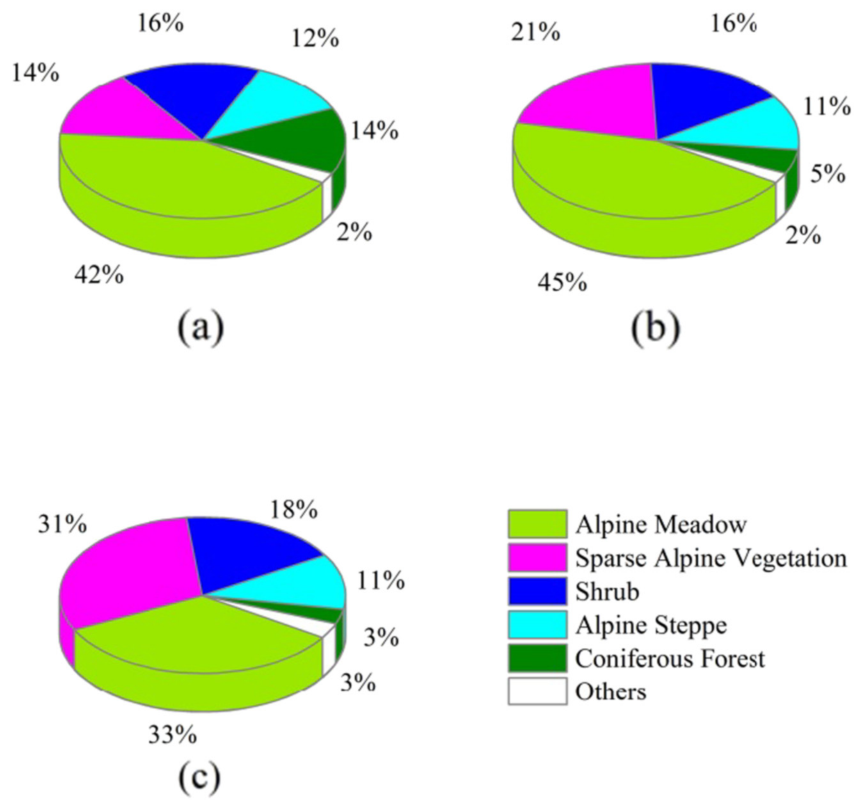

Fig. 8. Vegetation distributions in three LAI trend: a) Improved, b) Stabilized, and c) Degraded.

2. Methods

2.1. Study area

This study focuses on the upper part of the Heihe River Basin (98°34′–101°09′E and 37°43′–39°05′N). The HRB covers an area of approximately 14.1 × 10^4 km^2 that drains rivers originated from the mountainous areas of Qilian Mountain Range. The elevations of the upper reach vary from 1660 m to 5076 m with modern glaciers developed above the 4000 m elevation line. The upper reach of the HRB is higher, colder and wetter than middle and lower reaches which are groundwater recharge areas. This typical region in arid and semi-arid is dominated with a continental monsoon climate (Hao et al., 2016; Cao et al., 2016). The mean annual precipitation is about 450 mm with high variability in space as a result of topography. The annual mean temperature is 2 °C varying 6.2 °C in the low elevations to −9.6 °C in high elevations Fig. 2. Major vegetation cover types include Alpine Meadow, Shrub, Coniferous Forest, Alpine grassland, Sparse Alpine Vegetation, and Desert (Fig. 1). The vegetation growing season spans from April through to September and the growing season length is increasing in recent decades due to global warming (Yan et al., 2016).

In this paper, we mainly focused on five vegetation types that cover approximately 97% of the Upper HRB: Alpine Meadow (e.g. *Kobrecia parva*, *Kobresia humilis* and *Kobresia tibetica*), Sparse Alpine Vegetation (e.g. *Saussurea DC.*, *Cremanthodium DC.* and *Rhodiola rosea L.*), Shrub, Alpine Steppe, and Coniferous Forest (*Picea crassifolia*) (Table 1).

2.2. Remotely sensed LAI and climate database

The GLASS LAI products (version 3.0) (http://www.bnu-datacenter.com/) used in this study were acquired from Beijing Normal University (Xiao et al., 2014) who derived LAI datasets from the widely used global MODIS surface reflectance data. The datasets provided a sinusoidal projection at a spatial resolution of 1-km and temporal resolution of 8-days for the period 2001–2012. The GLASS LAI products were derived from general regression neural networks (GRNNs) trained by time series LAI values fused by MODIS and CYCLOPES LAI products and reprocessed time series MODIS reflectance during 2001–2012. The reprocessed MODIS reflectance values for the entire year were used as inputs to the GRNNs to estimate the one-year LAI profiles. The LAI datasets have been extensively evaluated using various high resolution remote sensing products for accuracies (Xiao et al., 2014). The vegetation type maps used in this study had a scale of 1:100,000 (Zhang et al., 2016). The gridded climate datasets with a 1-km spatial resolution were constructed from point measurements at local weather stations and had been used in hydrological modeling for the study watershed (Yang et al., 2015). More details about evaluations of LAI data accuracy/uncertainty and applications of the climate datasets can be found in Hao et al. (2016), Yang et al. (2015) and Gao et al. (2016), respectively. The elevation and stream network maps were extracted from the Digital Elevation Model (DEM, http://glovis.usgs.gov/). All data were scaled to 1-km for this analysis and presentations.

2.3. LAI trend analysis

The widely used Mann-Kendall (M-K) test was used to comprehensively examine temporal changes in the long-term climatic and LAI data series (2001 − 2012). The M-K test is a non-parametric statistical test method which is used to identify the existence of increasing or decreasing trend within a time series. The sample does not need to obey a certain distribution (Mann, 1945; Kendall, 1970). The M-K test has been widely used in climatological trend detection studies (Zhao et al., 2010; Chattopadhyay et al., 2012; Nalley et al., 2013; Yuan et al., 2013).

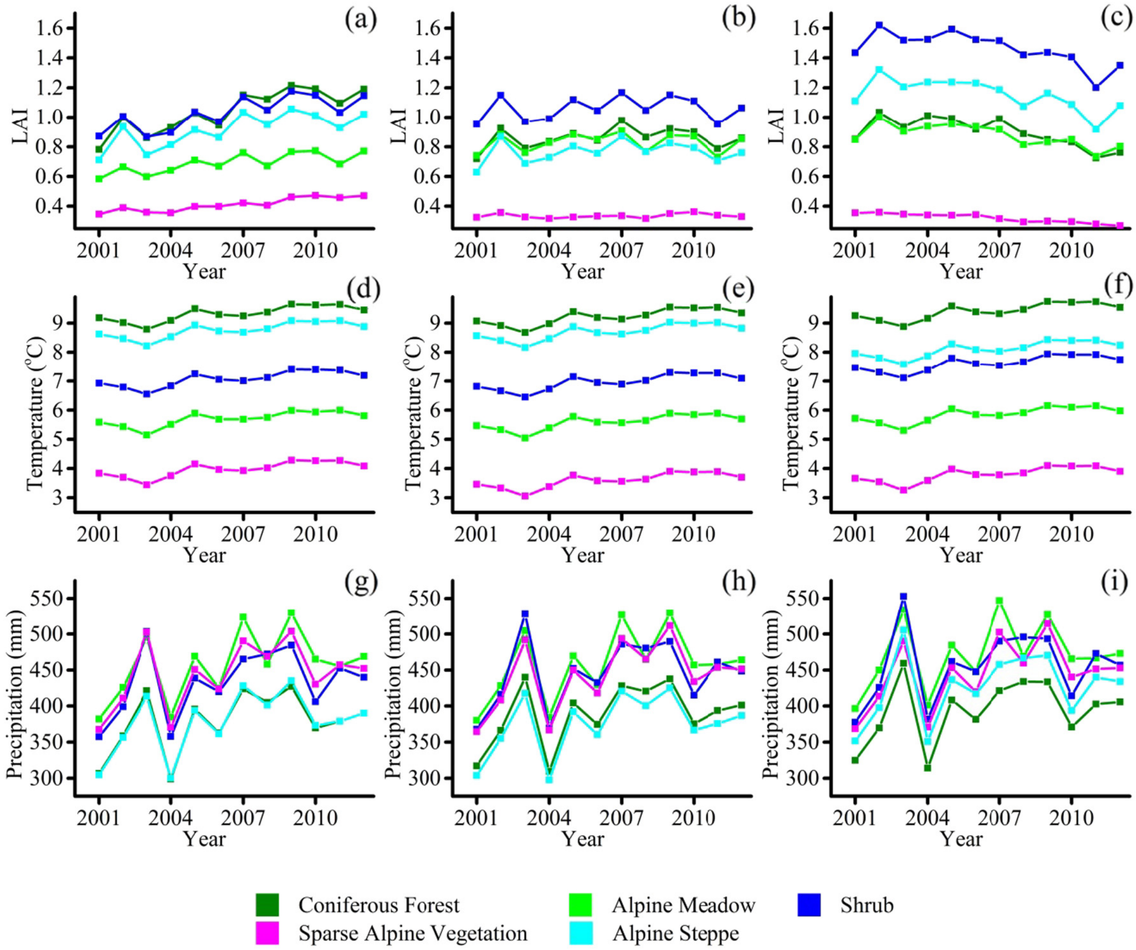

Fig. 9. Dynamics of growing season LAI, precipitation, and temperature by LAI trend areas of 'Improved', 'Stabilized', and 'Degraded' areas (from left to right panels) and by ecosystem type during 2001–2012.

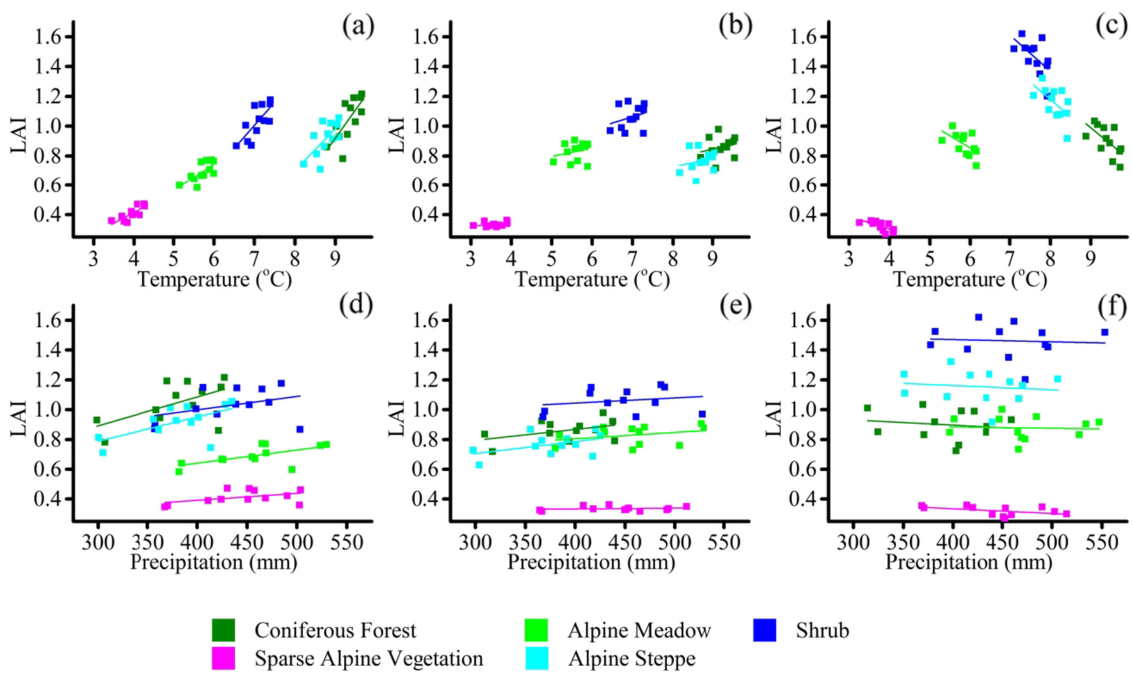

Fig. 10. Relationships between growing season LAI and Temperature (a–c) and Precipitation (d–f) in 'Improved', 'Stabilized' and 'Degraded' area (from left to right panels), respectively.

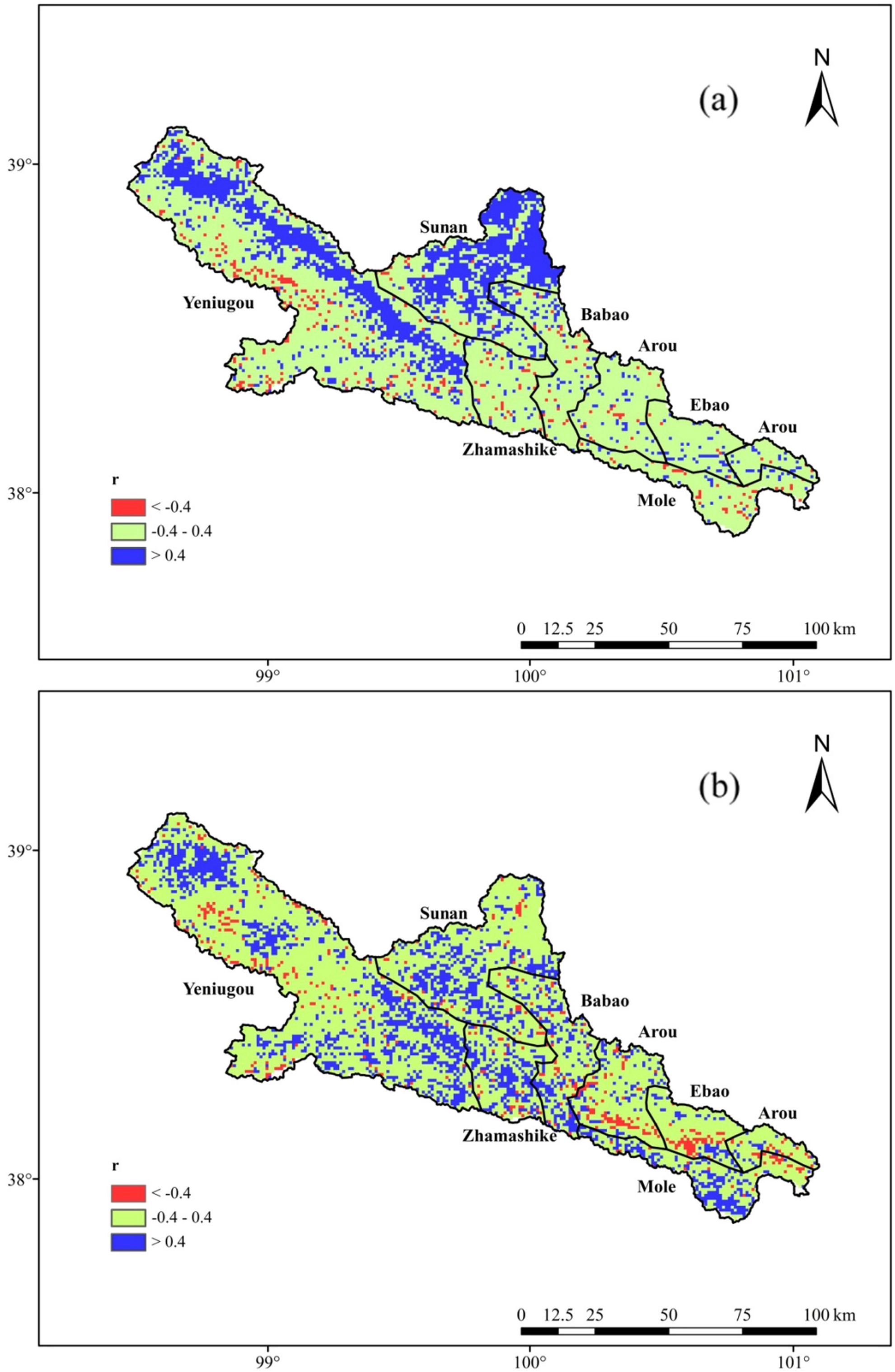

Fig. 11. Correlations between growing season LAI and a) precipitation, and b) temperature across the Upper Heihe River Basin.

The standard test statistic Z is:

$$Z = \begin{cases} \frac{s-1}{\sqrt{Vars}}, s>0 \\ 0, s=0 \\ \frac{s+1}{\sqrt{Vars}}, s<0 \end{cases}$$

where

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(LAI_j - LAI_i)$$

$$sgn(LAI_j - LAI_i) = \begin{cases} 1, LAI_j - LAI_i > 0 \\ 0, LAI_j - LAI_i = 0 \\ -1, LAI_j - LAI_i < 0 \end{cases}$$

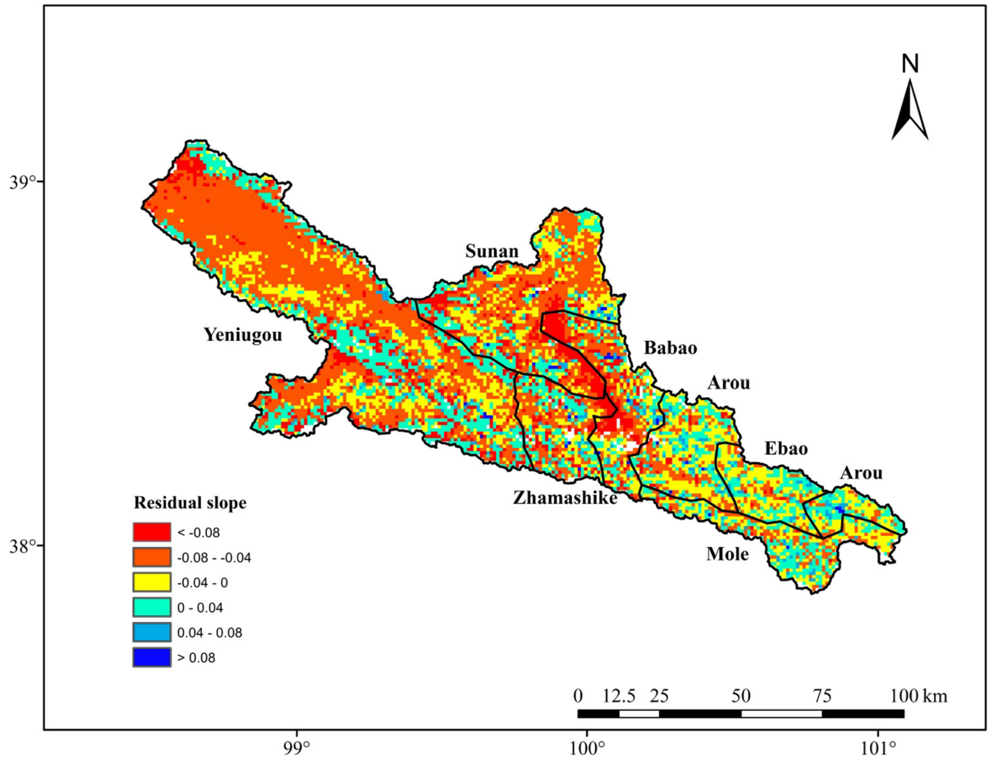

Fig. 12. Residual slope distribution across the Upper Heihe River Basin.

$$Var(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p-1)(2t_p+5)\right]$$

LAI_j and LAI_i represent the growing season (from April to September) mean LAI value of the jth and ith year. n means the length of time series. sgn is a sign function. q is the number of tied groups, and t_p is number of data values in pth group. The null hypothesis $H0$ is rejected if the absolute value of Z is larger than $Z_{\alpha/2}$, where $Z_{\alpha/2}$ is obtained from standard normal cumulative distribution tables. The α value indicates significance level (Zeleňáková et al., 2012).

In this paper, the significance of LAI trend was judged on a confidence level of $\alpha = 0.1$, where $Z_{\alpha/2} = 1.28$. We calculated Z value distribution for the growing season LAI (Z_{LAI}) and identified three trend types, 'Improved', 'Stabilized', and 'Degraded'. Meanwhile, we calculated Temperature (Z_T) and Precipitation (Z_P) by the same method for the same period 2001–2012 to LAI.

Three types of LAI trends for each of the pixels within the watershed were first determined according to their Z values with '>1.28', '−1.28–1.28', and '≤1.28' corresponding to 'Improved', 'Stabilized', and 'Degraded', respectively. Then, for each of the three LAI trend types, we examined Z_T and Z_P to determine the likely influence factors by correlating annual growing season LAI and climatic factors. All time series analysis results were conducted using the ArcGIS software.

2.4. The residual trend (RESTREND) analysis to isolate human influence

The fluctuations of vegetation LAI in the study region are controlled mainly by two factors: precipitation (positively) and livestock grazing (negatively). To quantitatively determine how human activities influence vegetation growth, influence of precipitation has to be isolated. The residual trend analysis (RESTREND) method (Wessels et al., 2007) is developed based on the general observations that ecosystem net primary productivity (NPP) under an arid and semi-arid climate is positively correlated with precipitation (Li et al., 2012). The RESTREND analysis (Evans and Geerken, 2004; Ibrahim et al., 2015; Li et al., 2011; Li et al., 2012) was thus adopted in this study to isolate the contributions of precipitation from that of other human factors in influencing vegetation. In this study we used LAI to substitute NPP, and the residuals (i.e. the differences between observed and predicted LAI values) for each pixel were then analyzed for detecting trends with respect to time. We chose six vegetation types (i.e., Alpine Meadow, Sparse Alpine Vegetation, Shrub, Alpine Steppe, Coniferous Forest, and Desert vegetation) to build regression relationships between LAI and precipitation and conduct RESTREND analysis in pixel scale.

We chose maximum LAI in the growing season (LAI_{max}) as the parameter representing vegetation growth. The RETREND method involves establishment of correlations between LAI_{max} and precipitation for each pixel by vegetation type. To find those pixels where vegetation growth were mainly influenced by precipitation not by grazing or other human disturbances, we chose those pixels that have the highest correlations between LAI and precipitation in the 12 sampling years. Regression models by vegetation type were developed at the highest correlation between LAI_{max} and growing season precipitation pixel:

$$\text{LAI}^{i'}_{\text{max}} = a^i P^i + b^i$$

$\text{LAI}^{i'}_{\text{max}}$ is the predicted LAI_{max} of the ith vegetation type, P^i is precipitation for the ith vegetation type and a^i and b^i are the undetermined coefficients of the ith vegetation. Then, we simulated LAI_{max} using the regression model (Fig. 3).

The model residual, statistic σ, was then calculated as:

$$\sigma^{ij} = \text{LAI}^{ij}_{\text{max}} - \text{LAI}^{ij'}_{\text{max}}$$

σ^{ij} represents the residuals between GLASS LAI_{max} ($\text{LAI}^{ij}_{\text{max}}$) and simulated LAI_{max} ($\text{LAI}^{ij'}_{\text{max}}$) for vegetation type i in the year j.

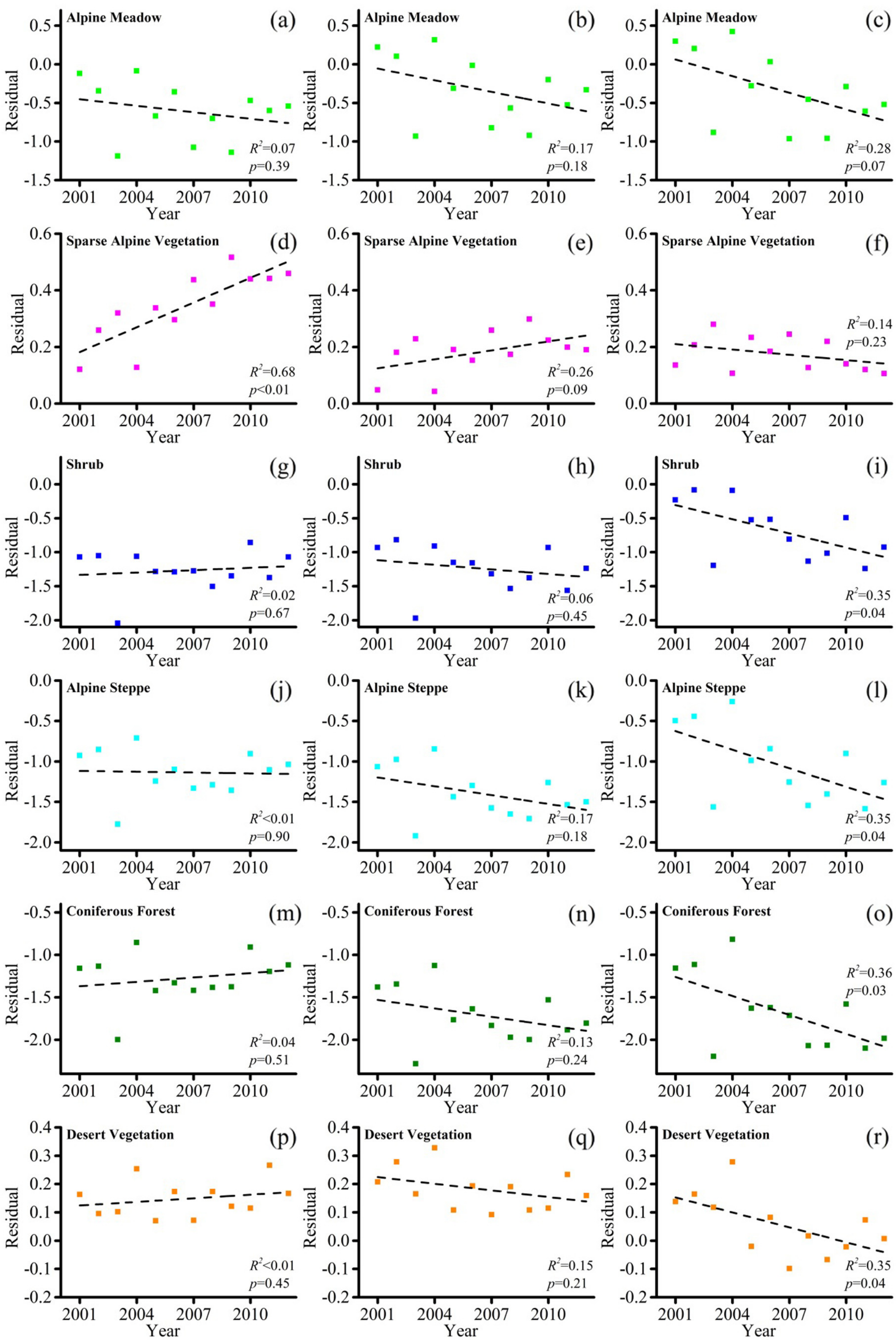

Fig. 13. Annual residual dynamic in the 'Improved', 'Stabilized' and 'Degraded' area of a–c) Alpine Meadow, d–f) Sparse Alpine Vegetation, g–i) Shrub, j–l) Alpine Steppe, m–o) Coniferous Forest, and p–r) Desert Vegetation, respectively.

Table 1
Spatial distribution of vegetation type and associated leaf area index (LAI) in the Upper Heihe River Basin.

Vegetation type	Area (km^2)	Area (%)	Elevation(m)	Mean growing season LAI (standard deviation)
Alpine Meadow	4572	44	2600–4860	0.8 (0.422)
Sparse Alpine Vegetation	2110	20	3070–5060	0.3 (0.265)
Shrub	1699	16	1900–5070	1.1 (0.455)
Alpine Steppe	1179	11	1740–4630	0.8 (0.435)
Coniferous Forest	583	6	1870–4560	0.9 (0.465)

The slope or change in annual residuals over time for vegetation type i is calculated as:

$$slope^i = \frac{n \times \sum_{j=1}^{n}\left(j \times \sigma^{ij}\right) - \sum_{j=1}^{n} j \sum_{j=1}^{n} \sigma^{ij}}{n \times \sum_{j=1}^{n} j^2 - \left(\sum_{j=1}^{n} j\right)^2}$$

A positive slope indicts positive human influence which may be attributed to conservation and reforestation efforts while a negative slope represents a negative human disturbance (e.g., overgrazing) during 2001–2012. A slope of zero indicates minor human influence compared to climatic influence.

3. Results

3.1. Growing season LAI, precipitation and temperature

We extracted long-term LAI, temperature, and precipitation data from April to September, a period which was considered as the growing season in this study. To understand the lateral and vertical LAI distribution patterns and their relationships with environmental factors, elevation, temperature, and precipitation distributions at the pixel scale were plotted against the mean growing season LAI separately (Fig. 4).

Most pixels in the study watershed had a growing season precipitation of 400–500 mm. Vegetation with a low LAI was found in two separate zones with an air temperature of 0–7 °C and 10–15 °C, respectively. Overall, vegetation that had a high LAI was found in a temperature zone of 7–10 °C. It appears that low temperature limited vegetation growth and high temperature promoted water stress (Fig. 4a). In contrast, vegetation with high LAI values (LAI > 1.5) was found in areas where precipitation exceeded 400 mm (Fig. 4b).

Precipitation increased with the increase of elevation, while temperature decreased linearly with the increase in elevation (-0.0048 °C m^{-1}, $p < 0.05$) (Fig. 4c, d). Areas with high precipitation (>500 mm) are located at an elevation higher than 3000 m (Fig. 4d). Overall, growing season LAI distributions showed an obvious vertical pattern as controlled by water and energy availability (Fig. 4e). LAI values increased with the increase in elevation in areas below the 3200 m elevation line likely due to the increase in precipitation. In contrast, the LAI in the area above the 3200 m line decreased with the increase of elevation, presumably due to the decrease in air temperature. The optimum growing season climate that promotes high vegetation coverage areas (LAI > 1.5) was mainly found in the altitude of 2700–3900 m where the air temperature was in the range of 4–11 °C and precipitation ranging from 300 to 580 mm.

The Alpine Meadow, the largest land cover type, was found mostly in the areas with elevations higher than 2600 m and growing season precipitation higher than 400 mm, and mean growing season temperature 0–11 °C. In contrast, the Sparse Alpine Vegetation which had a relatively low mean LAI, the second largest vegetation cover type in coverage, was found in areas with elevations >3000 m, and growing season air temperature cooler than 7 °C, and precipitation in the range of 330–580 mm. The Alpine Steppe developed in areas with low precipitation (<500 mm) but warm areas with temperature >7 °C. Coniferous Forests were found in riparian areas with a large range of elevation (1850–4560 m) receiving moderate precipitation (Fig. 4).

3.2. Trend of growing season LAI

The area with growing season LAI classified as 'Stabilized' accounted for about 74% of the total study area, while the rest was classified as 'Improved' (21%) and 'Degraded' (5%) (Fig. 5). The degradation area was considered minor when compared to the other two types of vegetation cover change, but was important to examine the coupling effects of climate and land management. By vegetation type, 32% and 16% of the Coniferous Forest and Alpine Steppe land covers had an increasing trend, respectively. For other vegetation types as a whole, 21% showed a significant increasing trend. All land cover types had similar areas classified as 'Degraded', about 4–6%.

Under the same temperature, the highest vegetation LAI was most always found in the 'Improved' area (Fig. 6a), and similar pattern was found for areas with annual precipitation <450 mm (Fig. 6b). LAI values for the 'Degraded' area had a large range (Fig. 6a) and the air temperature followed elevation linearly (Fig. 6c). The 'Degraded' area was found in areas with precipitation >400 mm, temperature <12 °C temperature, and elevation above 3000 m (Fig. 6).

3.3. Correlations between LAI and precipitation and temperature

To further analyze LAI variations as influenced by temperature and precipitation, we compared the trend of annual growing season temperature and precipitation over the three classified areas during 2001–2012. For all three areas, temperature showed a similar significant ($p < 0.01$) increasing trend with a rate of 0.055 °C/yr (Fig. 7). The precipitation had an upward, but not statistically significant ($p > 0.05$) trend for three areas with a slope of 5.8 mm/yr, 5.5 mm/yr and 4.5 mm/yr for the 'Improved', 'Stabilized', or 'Degraded' areas, respectively. The 'Degraded' area had the lowest slope and the improved area had the highest.

3.4. Contribution of vegetation cover to three types of LAI changes

For the area of 'Improved', Alpine Meadow contributed the most (42%), followed by Shrub (16%), Sparse Alpine Vegetation (14%), and Coniferous Forest (14%). For 'Stabilized' area, the contributions from each vegetation cover were almost identical to the vegetation cover compositions (Table 1). Alpine Meadow (31%) and Sparse Alpine Vegetation (31%) dominated the 'Degraded' area.

The growing season annual mean LAI values for Shrub, Alpine Meadow and Steppe in the 'Degraded' are much higher than the 'Improved' and 'Stabilized' areas (Fig. 9). In the 'Improve' areas, the LAI for Coniferous Forests increased most rapidly during a 12-year study period and has become the land cover that had the highest LAI after 2008. The LAI values for the Sparse Alpine Vegetation type were the lowest and fluctuated relatively small annually when compared to other vegetation types among the three LAI trends.

The growing season air temperature had similar and significant increasing trends in all three types of LAI change trends. However, LAI values for the Alpine Steppe in the 'Degraded' were >1 °C lower than other areas, whereas LAI values for Shrub were 0.5 °C higher the 'Degraded' area than other areas (Fig. 9d–f).

The precipitation trends for Shrub and Coniferous Forests were similar in the 'Improved' and 'Stabilized' areas, but the fluctuation patterns were different with a much higher amplitude in the Shrub than in the Coniferous Forests in the 'Degraded' area. Annual precipitation in the Alpine Steppe was the highest among all land covers and all the three types of LAI trend areas. In contrast, annual precipitation in the Sparse

Alpine Vegetation was similar among all three areas (Fig. 9g–i) in an environment with relative low air temperature (Fig. 9d–f).

3.5. LAI trend and climate variations

LAI increased with air temperature for all land covers in the 'Improved' and 'Stabilized' area. However, the relationships between LAI and temperature in the 'Degraded' area were just opposite to those of 'Improved' and 'Stabilized' areas for all vegetation types (Fig. 10a–c).

Similar to the air temperature-LAI relationship, LAI increased with precipitation for all land covers in the 'Improved' area and correlations were especially strong for Coniferous Forests, Alpine Steppe and Meadow. However, LAI was not significantly correlated to precipitation in the 'Stabilized' area and the 'Degraded' area (Fig. 10d–f).

Comparing Fig. 10 and Table 2, Alpine Meadow, Coniferous Forest and Alpine Steppe LAI showed significant relationships with both Temperature and Precipitation in the 'Improved' area, suggesting climate was the initial factor for vegetation growth and human activities was not affect the ecosystem seriously and even made environment restoration.

LAI was not significant related in the 'Stabilized' area and negative related in the 'Degraded' area to climate factors showed strange relationships. We suggest that human activities seriously affect the vegetation growth in these areas.

To further analyze environment controls on LAI dynamics by land cover type and LAI trend areas in space, mean growing season LAI values were correlated with mean temperature or total precipitation in the growing season (Fig. 11). By comparing Fig. 1, Fig. 5 and Fig. 11, we estimated that climate (temperature and precipitation) was responsible to about 63% of the LAI changes in the 'Improved' area, while other 37% was explained by human activities. In these human influenced areas, alpine meadow growth area accounted for about 45% and coniferous forest accounts approximate 7%, suggesting that vegetation management played a major positive role for vegetation augment. In 'Degraded' area, however, variations of LAI for all land covers did not significantly correlate to temperature or precipitation. In this case, Alpine Meadow area accounted for 38%, whereas coniferous forest only accounted for 3%. High correlations ($|r| > 0.4$) between LAI and precipitation were found in the north part of 'Stabilized' area. No significant relationships between LAI and temperature or precipitation were found in majority (80%) of the 'Stabilized' area.

3.6. Influences of human activities

About 75% and 25% of the watershed had a negative and positive residual slopes, respectively. Areas with high negative slope values concentrated on the southeast of Sunan and Western of Babao. Slope values in eastern part of the study watershed generally were higher than in Western and Center area (Fig. 12).

To further analyze how human activities affect the LAI, we compared the variations of annual residual with long-term trends of LAI for all land cover types (Fig. 13). In the 'Improved' area, residuals for the Alpine Meadow and Alpine Steppe were negative while other vegetation types showed a positive trend. Except the Sparse Alpine Vegetation, residuals for all land covers decreased in the 'Stabilized' and 'Degraded' area, while the residual slopes in the 'Degraded' area was much higher than in the 'Stabilized' area.

4. Discussion

This study integrates long term (12 yr) remote sensing-based LAI data and climate records for the Upper Heihe River Basin, an area considered relatively small when compared to similar studies (Guli Jiapaer et al., 2015). However, the spatial (both lateral and vertical in space) and temporal variation patterns of LAI dynamics were not uniform as influenced by both changes climate and land management such as grazing and ecological restoration activities. Our analysis indicates strong evidence that human activities could mask or aggravate the impacts of climate change.

4.1. Vertical LAI distribution and topography

As expected, vegetation distributions in mountainous regions are influenced by elevation land topography that affects the bioclimatology. In areas below the 2800 m line of elevation, the vegetation coverage was poor with low LAI values as result of relatively low precipitation but high air temperature and potential evapotranspiration (PET) in this semi-arid region. With the rise of elevation, vegetation LAI coverage was found to increase as a result of the increase in precipitation, decreased PET (Gao et al., 2016), and thus increased water availability. The altitude of 2700 m–3900 m that has relatively higher precipitation and moderate temperature appears to be the optimum elevation for local vegetation that had the highest LAI. For areas with an elevation higher than 3900 m, the precipitation was not a dominant factor, but low temperature became the limiting factor for plant growth. Above 4800 m elevation, snow packs, glaciers, and bare rocks dominated the watersheds (Fig.4). These findings were similar to results for the Shiyang River Basin, a watershed near the HRB (Tang et al., 2016). The Alpine Meadow is the largest (44% total) land cover type that receives the highest precipitation, and thus produces most water supply (Gao et al., 2016).

4.2. Variable climatic effects

Although the patterns of climatic change (i.e., air temperature) and variability (i.e., precipitation) were similar across the study basin, the LAI responses for different vegetation types were different. For example, Coniferous Forest was influenced by both temperature and precipitation, representing only 6% of the watershed. Alpine Steppe and Meadow in semi-arid and arid regions are predominantly influenced by precipitation (Zhao and Running, 2010), especially near the outlet of the upstream (Sunan and northeast of Yeniugou). However, the Sparse Alpine Vegetation and Shrub were not as sensitive to precipitation as grass. Similar to our result, Myerssmith et al. (2015) found that shrub is more sensitive to summer temperature than to precipitation.

Table 2
Correlation coefficient between growing season leaf area index (LAI) and Temperature and Precipitation in 'Improved', 'Stabilized' and 'Degraded' area respectively for each vegetation type.

Vegetation type	Improved		Stabilized		Degraded	
	Temperature	Precipitation	Temperature	Precipitation	Temperature	Precipitation
Alpine Meadow	0.70[a]	0.63[a]	0.22	0.33	−0.56	−0.06
Sparse Alpine Vegetation	0.81[b]	0.46	0.37	0.18	−0.69[a]	−0.47
Shrub	0.74[b]	0.38	0.28	0.21	−0.58[a]	−0.07
Alpine Steppe	0.67[a]	0.62[a]	0.21	0.47	−0.59[a]	−0.13
Coniferous Forest	0.72[b]	0.58[a]	0.23	0.44	−0.62[a]	−0.07

[a] Means significant at the 0.01 level.
[b] Means significant at the 0.05 level.

4.3. Extreme climate impacts on LAI

Comparing with precipitation, temperature was more influential in affecting growing season LAI in the 'Improved' area. In this area, vegetation growth was more responsive to climate warming. However, in the 'Degraded' area, LAI was negative correlated to temperature, suggesting precipitation was a dominant factor for controlling intra-annual variability of LAI in a dry environment (Fig. 10).

The growing season LAI had a sharp decrease in 2003, a relatively wet and cold year. Higher than normal precipitation did not result an increase in LAI in 2003, but LAI decreased as a result of low air temperature. We also saw a sharp drop in LAI in 2011 for most land covers although 2011 was not an extreme drought year. The sharp decrease in LAI was likely due to the drought episodes occurred in 2010 and 2011, and the decreasing trend of air temperature during 2009 to 2011. In this case, LAI was severely affected continued droughts (2010 − 2011) that might have lasting effects on plant growth (Fig. 9).

4.4. Influences of human activities on LAI for different vegetation type

Growing season LAI values around the north part of Yeniugou and Sunan areas showed significant positive relationships with precipitation ($r > 0.4$), while LAI did not show significant relationships with precipitation in other areas. We did not find any concentrated areas that had significant negative correlations ($r < -0.4$), suggesting that a precipitation increase generally resulted in a rise of LAI regardless of other factors (Fig. 11). This is common for ecosystems in an arid environment.

Areas with the growing season LAI being controlled by temperature were found in the south part of the study area. The LAI values for Zamashike, Mole, Babao, south of Sunan and east and northwest of Yeniugou areas showed a positive relationship with temperature, whereas LAI values in the south part of Arou and Ebao had negative relationship with temperature. In general, precipitation limited area concentrated in the north part of the study area while temperature controlled areas were scattered in the middle and south parts of the study basin (Fig. 11).

Although precipitation has been well recognized as an important limiting factor for plant growth in this study (Fig. 8) and other studies for an arid environment (Li et al., 2012; Hao et al., 2014; Guli Jiapaer et al., 2015), it was interesting to note that LAI did not have significant relationship with climate for the entire 'Degraded' area as a whole. Under the climate warming and no changes in precipitation (Fig. 7 and Fig. 9), the residuals of LAI_{max} in the upper HRB had a decreasing trend in majority of the area (Fig. 12 and Fig. 13). We argue that land management such as grazing and reforestation might help to explain the observed results in LAI changes in both upwards or downwards directions. This was consistent with notion that grazing had negative impacts on vegetation growth (Zhou et al., 2015).

Our RETREND analysis suggested that different vegetation covers had rather different response to grazing and other land management disturbances. For example, Sparse Alpine Vegetation with low LAI has not been grazed due to its remote location (high elevation, low temperature) (Fig. 4) (Wang et al., 2010). For this vegetation type, the annual LAI_{max} residuals were positive and increased during 2001–2012 in the 'Improved' and 'Stabilized' area as a result of warming trend (Fig. 13e). Comparing with other vegetation types in the 'Stabilized' area, LAI_{max} Residuals for Sparse Alpine Vegetation also increased significantly over time with the highest R^2 (0.26) and the lowest p (0.09) (Fig. 13e), indicating restoration activities might have been effective. In contrast, the LAI_{max} residuals for Alpine Meadow and Alpine Steppe that were subjected to grazing decreased for all three trend type areas. The results clearly indicated that overgrazing could significantly affect vegetation dynamics by reducing LAI. The potential increase in LAI due to warming and wetting might have been muted by overgrazing for Alpine Meadow and Alpine Steppe.

Annual residuals for Shrub, Coniferous Forest and Desert Vegetation in the 'Stabilized' and 'Degraded' areas were consistently negative and decreased as well, suggesting that human activities strongly influenced these three types of ecosystems. However, considering only few annual residual samples were available for Coniferous Forest and Desert Vegetation, future studies are needed to confirm the true causes of the dramatic changes in the residual slopes.

In the 'Improved' area, residuals for Shrub, Coniferous Forest and Desert Vegetation were positive showing an increasing trend (Fig. 13), indicating positive effects of ecological restoration activities. Although warmer climate and ecological restoration activities could help vegetation recovery, overgrazing remained in the study basin and perhaps canceled some the positive effects of climate. In the 'Improved' area, although residuals were different among the vegetation types, the mean annual residual for the area as a whole increased starting from 2010 and remained high during 2010–2012 (Fig. 13). This trend was likely due to the combined effects of a warming climate and ecological restoration that involved grazing control and afforestation. Therefore, we suggest that grassland management and forest protection measures contributed to the significant increase in LAI in the 'Improved' areas. Future research should examine how grazing and ecological restoration practices interact with climate to influence vegetation dynamics.

5. Conclusions

The spatial and temporal distributions of LAI dynamics were examined by integrating the GLASS LAI products and interpolated climate data. The optimum elevation for plant growth in the study watershed was estimated as 2700–3900 m where LAI researched the maximums. We identified three types of LAI trend including 'Improved', 'Stabilized', and 'Degraded' for the 2001–2012 study period. Vegetation has been stable with little change in LAI in majority of the Upper Heihe River Basin during 2001–2012. The vegetation improvement as detected by various statistical methods by this study was mostly related to climate warming and rise of precipitation while the vegetation degradation was caused by over grazing. Overgrazing might muted the positive effects of climate in some areas in the study basin. Different land covers responded differently to climate change and variability during 2001–2012.

LAI is an important parameter for evaluating watershed ecosystem structure, functions, and services. Our findings provide empirical evidence that climate and land management can influence vegetation dynamics in both directions at the watershed scale. Such information is useful to land managers to improve the ecosystem productivity and water supply in the upper Heihe River Basin in northwest China in the context of responding to future global climate and land cover changes. Future studies should focus on mapping grazing areas using high-resolution remote sensing techniques and also linking grazing data with vegetation changes (Li et al., 2012). Similarly, monitoring meteorology and climate change in a complex terrain in mountainous regions is important to understand the environmental controls over space, both laterally and vertically, and also build robust relationship between vegetation and climatic factors.

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