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

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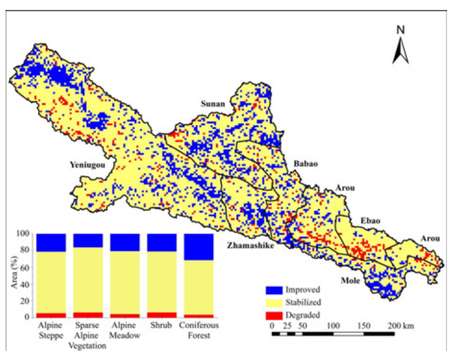
HIGHLIGHTS

- 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