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Snow cover phenology affects alpine vegetation growth dynamics on the Tibetan Plateau: Satellite observed evidence, impacts of different biomes, and climate drivers

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ABSTRACT

Alpine vegetation plays a crucial role in global carbon cycle. Snow cover is an essential component of alpine land cover and shows high sensitivity to climate change. The Tibetan Plateau (TP) has a typical alpine vegetation ecosystem and is rich of snow resources. With global warming, the snow of the TP has undergone significant changes that will inevitably affect the growth of alpine vegetation, but observed evidence of such interaction is limited. In particular, a comprehensive understanding of the responses of alpine vegetation growth to snow cover variability is still not well characterized on TP region. To investigate this, we calculated three indicators, the start (SOS) and length (LOS) of growing season, and the maximum of normalized difference vegetation index ($NDVI_{max}$) as proxies of vegetation growth dynamics from the Moderate Resolution Imaging Spectroradiometer (MODIS) data for 2000–2015. Snow cover duration (SCD) and melt (SCM) dates were also extracted during the same time frame from the combination of MODIS and the Interactive Multi-sensor Snow and Ice Mapping System (IMS) data. We found that the snow cover phenology had a strong control on alpine vegetation growth dynamics. Furthermore, the responses of SOS, LOS and $NDVI_{max}$ to snow cover phenology varied among different biomes, eco-geographical zones, and temperature and precipitation gradients. The alpine steppes showed a much stronger negative correlation between SOS and SCD, and also a more evidently positive relationship between LOS and SCD than other types, indicating a longer SCD would lead to an earlier SOS and longer LOS. Most areas showed positive correlation between SOS and SCM, while a contrary response was also found in the warm but drier areas. Both SCD and SCM showed positive correlations with $NDVI_{max}$, but the relationship became weaker with the increase of precipitation. Our findings provided strong evidence between vegetation growth and snow cover phenology, and changes in snow cover should be also considered when analyzing alpine vegetation growth dynamics in future.

1. Introduction

During the past three decades, the Northern Hemisphere has very likely experienced the warmest 30-year period on the record (IPCC, 2014). Such abrupt warming can affect many aspects of vegetation, such as plant composition and diversity, phenology, productivity, biomass, and vegetation fraction (Liu et al., 2017; Ozanne et al., 2003; Thomey et al., 2011; Thompson et al., 2015; Wu et al., 2016; Zhang et al., 2010). These changes in vegetation may also feedback to climate system (Zhao et al., 2006). High latitude and altitude ecosystems such as alpine regions are facing the greatest warming. As an important component of terrestrial ecosystem, alpine vegetation plays a crucial role in seasonal carbon, water, and energy cycles (Inouye and Wielgolaski, 2013; Körner, 2005; Shen et al., 2015). Thus, investigating the responses of alpine vegetation to global warming is of great significance for understanding the global climate change.

In alpine regions, snow is a major source of fresh water for vegetation activities (Beniston et al., 1997). Furthermore, snow cover

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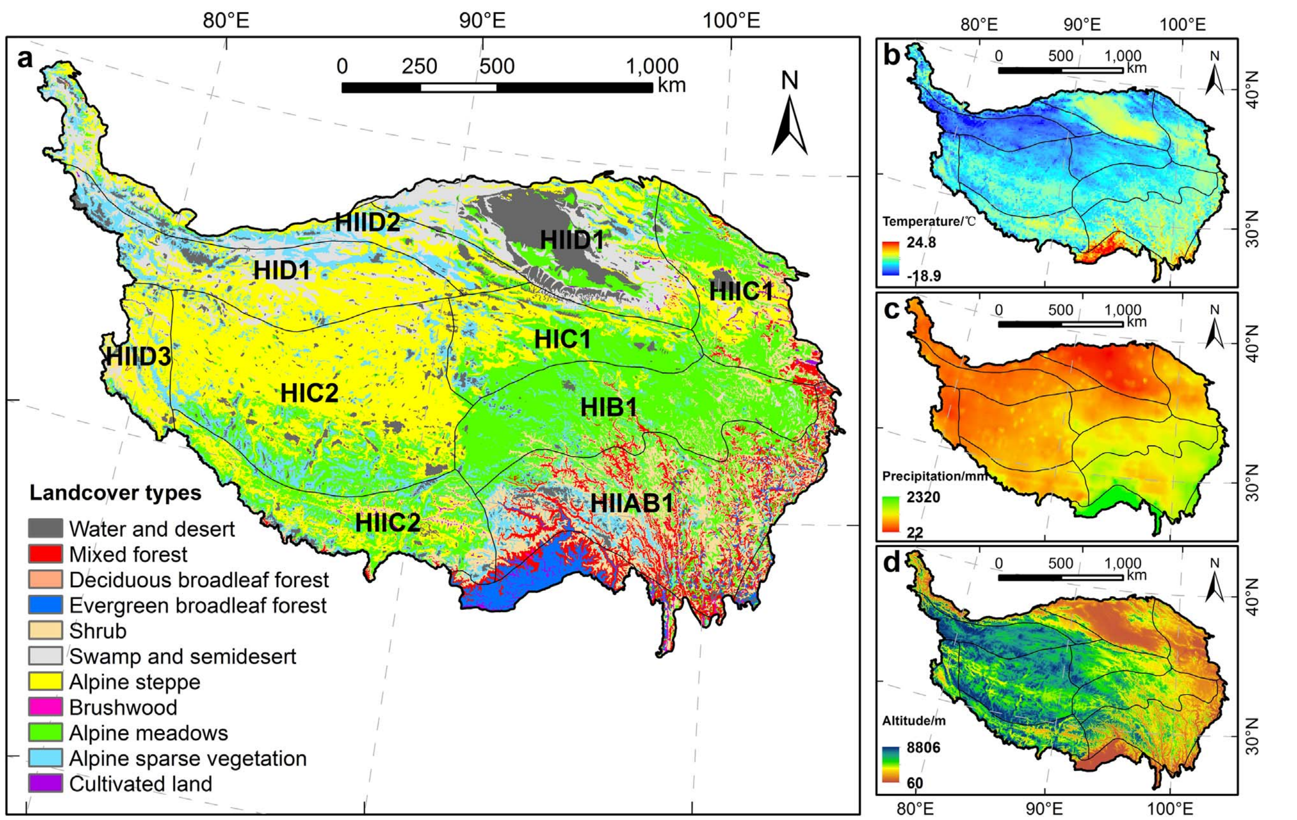

Fig. 1. Description of the (a) land cover types and eco-geographical zones, (b) annual mean temperature, (c) annual total precipitation, and (d) elevation of the study area.

protects soil from wind and low temperature, which is beneficial to the growth of vegetation (Nobrega and Grogan, 2007). Although the response of snow cover to global warming is complicated, as snow formation and melt are closely related to a temperature threshold of 0 °C, snow cover is the most predictable climate indicator among several other land, ocean, and cryosphere climate variables (Gonsamo et al., 2016b). With global warming, snow cover has significantly changed as evidenced from multiple in-situ observations and satellite data (Chen et al., 2015a; Gonsamo et al., 2016b; Peng et al., 2013). Previous studies have shown that changes in snowpack could alter energy flow and water cycle, which has significant implications on vegetation growth. Buus-Hinkler et al. (2006) analyzed the relationship between the normalized difference vegetation index (NDVI) and snowmelt date in Northeast Greenland through digital camera images. Their results revealed that vegetation vigor was linked to the initiation time of the snow-free period rather than air temperature. Groffman et al. (2001) also suggested that the decrease in snowpack, as may occur in a warmer climate, would result in the increase in soil freezing and cause microbial mortality, hydrologic and gaseous losses of nitrogen, which could impact vegetation growth. Paudel and Andersen (2013) analyzed the response of rangeland vegetation to snow cover dynamics and suggested that snow cover phenology played more important roles in snow-fed and drier regions for vegetation phenology.

The Tibetan Plateau (TP), the largest and highest plateau on the Earth, is regarded as the third pole of the Earth. There are typical alpine vegetation ecosystems and abundant snow resources on the plateau. Moreover, due to its fragile and instable ecosystems and natural environment, TP is believed to be more vulnerable to global warming (Wang et al., 2017b). Thus TP is an ideal area for investigating the snow cover effect on vegetation activities. The TP has experienced significant warming trends over the past three decades. In parallel to this warming signal, snow cover has changed significantly and may influence runoff amounts and spring time land surface phenological trend over this region (Wang et al., 2013). In recent years, site level experiments were conducted on a specific vegetation type or in a small area of TP to describe the interrelation between vegetation dynamics and snow cover (Chen et al., 2014; Chen et al., 2008). These conclusions are important but cannot be deemed representative of the whole area. Other studies like Wan et al. (2014), investigated the impact of snow depth, retrieved from passive microwave data, on alpine vegetation over the whole plateau. However, the coarse spatial resolution of microwave data (25 km) cannot sufficiently reflect the interior heterogeneity of such influence given the complex geographical features of TP. Wang et al. (2017a) analyzed the response of spring phenology to snow cover dynamics on the TP. However, only the spring phenology cannot adequately reflect the condition of alpine vegetation growth, and the driving mechanisms of different response need to be further explored.

Based on the Moderate Resolution Imaging Spectroradiometer (MODIS) 500 m data during 2000–2015, we first calculated the start of growing season (SOS), the length of growing season (LOS) and the maximum of NDVI ($NDVI_{max}$) as the main indicators of growth dynamics of alpine vegetation. Snow cover duration (SCD) and snow cover melt date (SCM) were also determined from MODIS and IMS data to represent the snow cover phenology variability. We then examined spatial variability in the responses of SOS, LOS and $NDVI_{max}$ to SCD and SCM over the whole plateau. Correlations in different biomes, eco-geographical zones, and temperature and precipitation gradients were also investigated to better understand the dependence of such impacts. The overall questions we address are whether the phenological changes of snow cover can affect the growth of vegetation dynamics on the TP, and how such influence varies by biomes and climate drivers in a spatially explicit way over the vast areas.

2. Data and method

2.1. Study area

The Tibetan Plateau (TP) is located in the southwest of China