A remote sensing perspective of alpine grasslands on the Tibetan Plateau: Better or worse under “Tibet Warming”?

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Abstract

The Tibetan Plateau is a unique cold and dry highland widely known as the Earth’s 3rd Pole. Its fragile ecosystems, especially alpine grasslands comprising 60% of the plateau, are sensitive to climate change that has been experiencing a distinct warming trend in past decades. Due to limited in-situ accessibility, studies of alpine grasslands have been heavily relying on satellite observations since 1980s. This paper gives an overview of satellite remote sensing of alpine grasslands on the plateau, and controversial findings about their phenological trends and climatic impacts. Implications of cryospheric and hydrologic processes such as snow/glacier melting, lake area change and permafrost retreat on the warming plateau are also discussed. This study reveals that satellite-extracted spatio-temporal patterns of alpine grasslands should be interpreted with caution. Under the rapidly changing climate, alpine ecosystems and their evolution paths on the Tibetan Plateau need more comprehensive, integrated investigation.

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1. Introduction

The Tibetan Plateau in central Asia is the largest high-elevation geological structure on Earth. Covering an area of 2.5 million km² at elevation > 4000 m, it is recognized as
the “Roof of the World” and “the 3rd Pole of the Earth” (Zhang et al., 2002). The plateau is bordered by high mountains including the Himalaya along the south and the Kunlun, Arjin and Qilian in the north that extend to the Pamir highlands on the west end. Topographic features of the plateau are distinct on the Google Earth image in Fig. 1.

Climate of the interior plateau is characterized as cold and dry with annual mean temperature of 3–5 °C (Yu and Xu, 2009). The average monthly mean temperature reaches above 0 °C between April and October although it varies dramatically across the plateau (Liu and Chen, 2000). Precipitation is strongly affected by Asian and Indian summer monsoons (Wu, 2005), carrying precipitation in June–September with a gradient from over 1000 mm in the southeast to less than 100 mm in the northwest. Precipitation in winter is limited (Lu et al., 2007; Su et al., 2011). The long-term precipitation records at the plateau level did not have a clear trend although some studies reported various local trends in different periods and sub-regions (Lin and Zhao, 1996; Yu and Xu, 2009; Zhang et al., 2013). Recent studies also reported an overall increase of precipitation in selected months in the eastern plateau and decrease in the west (Xu et al., 2008; Wang et al., 2015a).

The plateau is undergoing rapid warming that is believed higher in winter than growing seasons (Yang et al., 2010), in agreement with that of the northern hemisphere (Myneni et al., 1997; Tucker et al., 2001). Upon the climatic records in 1955–1996, temperature increased 0.16 °C/decade for the annual mean and a doubled rate (0.32 °C/decade) for the winter mean (Liu and Chen, 2000). A more recent study over 90 meteorological stations in 1961–2007 found an unprecedented increase rate of 0.36 °C/decade (Wang et al., 2008). Yu and Xu (2009) reported a 1.7 °C increase of annual mean temperature since 1970. All these records were much higher than the global increase in the same period (IPCC et al., 2007). Under the SRES A1B scenario (a “middle of the road” estimate of future emission, IPCC et al., 2007), a 4 °C Warming on the plateau may occur in the next 100 years (Wang et al., 2008). Here we refer this strong warming trend as “Tibet Warming”.

Alpine ecosystems exist close to the biological limits and are extremely vulnerable to climate change (Grabherr et al., 1994). Alpine grasslands cover more than 60% of the Tibetan Plateau (Wang et al., 2015b) and therefore, it is of great importance to understand their responses to Tibet Warming. Due to physical difficulties in accessing the land, historical records and in-situ observations are limited especially in the vast, uninhabited interior plateau. From 1970s, around 100 meteorological stations have been established on the plateau (Chen et al., 2006). In spite of the dominant coverage of alpine grasslands, only 47 stations are located within this ecosystem, mostly in alpine meadows and steppes in the eastern and central plateau with relatively mild climate and better accessibility (Wang et al., 2015a).

Since 1980s, the spatially and temporally extensive satellite data have provided rich information for vegetation monitoring on the plateau. Both satellite observations and bioclimatic model simulations suggest that climate change and terrestrial responses are spatially unequivocal (Hansen et al., 1999; Beniston, 2003; Kawabata et al., 2010). This paper gives an overview of satellite-assisted monitoring of alpine grasslands on the Tibetan Plateau, and further discusses the influencing factors of their changes in the past decades.

![Fig. 1. The Tibetan Plateau in central Asia. The true-color image in the inset is from the Google Earth. The land cover map is modified from Wang et al. (2015b) and ACAS (2001). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)](image-url)
2. Distributions of alpine grasslands on the plateau

Controlled by local climates transiting from the Southern Himalaya Subtropical (warm, moist) in the southeast to the Kunlun High-cold (arid, frigid) in the northwest (Zheng et al., 1979), alpine grasses on the plateau transit from alpine meadows, alpine steppes to alpine desert grasses along the climatic gradient (Wang, 1988). Spatial distributions of these alpine grasses, however, are not clear due to insufficient in-situ observations. Several global land cover products have been developed, e.g. the 1-km AVHRR-derived IGBP DISCover (Loveland et al., 2000), the 8-km AVHRR land cover (Defries et al., 1998), the MODIS global land cover (Friedl et al., 2002) and the SPOT VEGETATION Global Land Cover (GLC-2000) (Bartholomé and Belward, 2005). Although valuable for global observations, these products fail to delineate alpine grasses on the Tibetan Plateau (Zhou et al., 2001; Nemani et al., 2003). With limited image scenes at coarse resolutions, cloud noises and mixed pixels may outperform their subtle spectral differences. In these products, the plateau is often grouped into the herbaceous and barren lands. In 2001, the Chinese National Vegetation Atlas (1:1,000,000) was published by the Academician of the Chinese Academy of Sciences (ACAS, 2001). The Vegetation Atlas on the plateau is a result of long-term efforts based on field surveys in 1960–70s and image classification from the Landsat MSS in 1970s and TM since 1980s. Although it reaches good accuracies in the eastern plateau that is fairly accessible (and therefore with good ground truth information), high uncertainties remain in the vast interior plateau that is barely inhabited.

Alpine grasses could be better identified from their growth cycles and timing of biological events along the growing season. de Beurs and Henebry (2004) defined the land surface phenology to measure the timing of periodic vegetation growth from frequent satellite observations. Alpine grasses have typical one-season growth cycles between May and September although their season lengths vary geographically.

Based on the phenological differences of alpine grasses, Wang et al. (2015b) extracted their spatial distributions that followed a distinct transition from the southeast to northwest of the plateau (Fig. 1). In comparison with the Landsat-classified map (ACAS, 2001), these spatial patterns of alpine meadows, alpine steppes and alpine desert grasses showed a much better agreement with climatic gradients on the plateau. Additionally, the southeastern plateau controlled by the Indian monsoon is primarily subtropical-montane evergreen/deciduous forests and scrubs (Zheng et al., 1979). Cultivated lands are scattered along the northeastern and southern ends where also occupy the majority of population on the plateau. These non-alpine lands are not considered in this review paper.

### Table 1

Satellite-assisted studies about the trends and driving factors of alpine grassland change on the Tibetan Plateau.

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3. Alpine grasslands in a changing climate

3.1. Trends of grassland changes on the Plateau

Biotic responses of climatic warming have been frequently observed in aspects of phenological variations of terrestrial ecosystems. Intensive investigation of land surface phenology on the plateau has been conducted since 1980s. Among the published literatures, commonly applied satellite image series include the 15-day, 8-km Global Inventory Modeling and Mapping Studies (GIMMS) AVHRR normalized difference vegetation index (NDVI) products (e.g., Zhang et al., 2007; Liang et al., 2007; Yu et al., 2010; Piao et al., 2011; Ding et al., 2007, 2011), the 10-day, 8-km Pathfinder AVHRR land (PAL) database (Yang et al., 2005; Mao et al., 2008; Hu et al., 2011; Xu and Liu, 2007), the 1-km SPOT VEGETATION NDVI data sets (Zhong et al., 2010; Shen et al., 2013; Zhang et al., 2013) and the 1-km Terra/Aqua MODIS series (Wang et al., 2008, 2015a, 2015b). In smaller study areas such as the Tri-River Source region (TRS, headwaters of Yellow River, Yangtze River, and Lancang (the upper reaches of Mekong) River), the 30-m Landsat TM/ETM+ images have been used to reveal the temporal changes of grasslands (Song et al., 2009; Wang et al., 2011).

Changes of alpine grasslands in past decades have been commonly recognized. Their trends across the plateau, however, are not in good agreement. Due to different data sources at varying spatial/temporal resolutions, geographic locations, time periods and area extents of these studies on the plateau, controversy findings have been documented. Table 1 lists a group of satellite-assisted studies showing different trends of alpine grasslands and their influencing factors. Both biophysical (e.g., greenness, grass cover, net primary production (NPP), biomass) and phenological (e.g., start of season (SOS), end of season (EOS), season length) changes of alpine grasslands are summarized in the table.

Interestingly, some studies reported an improved vegetation greening on the plateau while others found the general trend of degradation. Some studies claimed that the change of alpine grasslands was fragmented and not statistically significant. Many studies also recognized the spatially and temporally varying patterns of alpine grassland changes across such a large geographic region. As shown in Table 1, however, the spatial and temporal trends do not agree in these studies.

3.2. Climatic impacts on alpine grasslands

The relationships between Alpine grassland changes and climatic factors have been commonly examined to identify the driving forces on the change (also listed in Table 1). Human settlement on the plateau remains low. Therefore most studies treat climate as the primary influencing factor in this region.

Climatic impacts on the change of alpine grasslands, however, are unclear on the plateau level. Nemani et al. (2003) predicted that both temperature and precipitation were potential climatic constraints to plant growth in central Asia (where the Tibetan Plateau is located). As listed in Table 1, most studies suggested temperature as the primary driver of alpine vegetation growth, although some studies found a positive trend (Hu et al., 2011; Liu et al., 2006; Zhang et al., 2013), while others attributed the degradation of alpine grasslands to a drier and warmer climate (Mao et al., 2008; Song et al., 2009). As an interesting example, Yu et al. (2010) suggested that the increased winter temperature caused the delay of spring green-up and shorter growing season in alpine meadows/steppes, possibly explained by the later fulfillment of winter chilling. Chen et al. (2011) rebutted their study by relating the delayed spring phenology to grassland degradation coupled with soil thawing-freezing processes on the plateau. In permafrost regions, Zhou et al. (2015) found that grass cover change responding to climate warming was complicated by soil water released from permafrost thawing. Yi and Zhou (2011) also suggested that the delayed spring phenology may be related to increased contamination on the plateau. Shen (2011) concluded that the effect of winter warming on spring phenology did not follow a simple correlation.

Some studies claimed precipitation as the primary control of grassland change. In a scenario of 2 °C increase on the plateau, Li et al. (2000) simulated the potential evapotranspiration of alpine meadows and found that it cannot be balanced until the precipitation reached a 15% increase. Piao et al. (2003) suggested that increased snowfall and rainfall may shorten growing season and reduce the incoming solar radiation, and thus reduce vegetation greenness on the plateau. Ding et al. (2007) claimed that the spatial distributions of annual maximum NDVI trends in 1982–1999 agreed with the change of the annual effective precipitation. With finer-resolution MODIS time series in 2000–2010, Wang et al. (2015a) reported the geographically opposite trends of alpine phenology between the western and eastern plateau that cannot be explained by the unidirectional climate warming, but the pattern agreed well with the subtle precipitation change at station level. Specifically, stations in the eastern plateau revealed an increase of monthly precipitation and a decrease in the west. While significant at station levels, their study also claimed that the trends did not satisfy at all stations, and were not significant for annual precipitation.

Under the umbrella of Tibet Warming, the geographically different precipitation trends in alpine grasslands may be explained by the change of atmospheric circulations (Yao et al., 2012). In consistency with the decreased precipitation in the southwestern plateau (Wang et al., 2015a), the Global Precipitation Climatology Project (GPCP) reported a large-scale decrease of precipitation in 1979–2010 in the Himalayas Mountain, which was closely related to the weakening trend of the Indian monsoon as reported in recent studies (Wu, 2005; Thompson et al., 2006). Numerical models of atmospheric general circulation showed that Tibet Warming may be interrelated with the increased summer rainfall in East Asia (Wang et al., 2008), which was in consistency with the improved growth and advanced spring greening in the northeast (Wang et al., 2015a). By examining climatic data records at the 66 weather stations above 2000 m, Liu and Yin (2001) found that the precipitation anomalies on the eastern Plateau were closely associated with the North Atlantic Oscillation. With the ERA-40 reanalysis in a
coupled climate model (ECHAM5/MPIOM), Bothe et al. (2010) found that summer drought and wetness events on the Tibetan Plateau were associated with the large-scale high pressure anomalies of atmospheric circulations in the North Atlantic/European sector concurrent with increasing sea surface temperatures in the Indo-Pacific Tropics. These studies suggested that macro-scale atmospheric circulations should be further studied to explore the determinant factors of climatic variability across such a large orography as the Tibetan Plateau.

Other influencing factors to alpine grasslands were found to be the increased evapotranspiration (Song et al., 2009) and solar radiation (Piao et al., 2006), permafrost retreat (Wang et al., 2011), and human activities including overgrazing (Zhang et al., 2007) as well as the implementation of national key projects to restore alpine ecosystems (Song et al., 2009). Applying a process-based Terrestrial Ecosystem Model, Jin et al. (2013) found that alpine phenology was more correlated to soil’s localized physical conditions than air temperature and precipitation. Nevertheless, extrapolation based on currently limited evidence should be treated carefully, and long-term data set is needed to address the climatic control of alpine grasslands.

4. Implications of cryospheric/hydrologic processes

The warming plateau accelerates its hydrological processes such as freeze-thaw cycling, deglaciation and permafrost retreat, which in turn affect soil thermal regimes and growth of alpine grasslands (Wang et al., 2006; Cheng and Wu, 2007; Yi et al., 2013). Investigations of these processes could help us better understand the complicated processes and their underlying consequences on alpine grasslands in this unique region.

4.1. Snow and glacier melting

Persistent snow cover on the plateau is primarily located in the southern and western edges within large mountain ridges with elevation higher than 6000 m (Pu et al., 2007). The largest inter-annual variations of snow cover fractions occurs in the late fall and winter months. Different from previous suggestions (e.g. Piao et al., 2003), Pu et al. (2007) suggested that increased snowfall in winter may not have significant impacts on alpine grasslands. Wang et al. (2015) explored the MODIS snow cover products in 2001–2010 and found that snow in December–February and March–May played a significant role on alpine grasslands; however the impacts could be negative or positive depending on different geographic areas on the plateau.

The Tibetan Plateau has the largest area of glaciers out of the Polar Regions. Similar to snow covers on the plateau, they are mostly located in the high mountains. Tibetan glaciers provide headwaters of most of Asia’s great river systems (Yao et al., 2012; Immerzeel et al., 2010). The retreat of glaciers in the Himalayas has been observed from satellite imagery (Liu et al., 2010; Zhang et al., 2011; Bolch et al., 2012), although those in central Plateau were relatively stable (Yao et al., 2012; Xu et al., 2009). Glacier melting affects water supplies to alpine grasslands in the catchment. However, few studies have been done to estimate the long-term contribution of glacier melting to water balance in the plateau, and high uncertainties remain because of the difficulties in quantifying the changing glacial mass (Lei et al., 2012).

4.2. Permafrost retreat

Permafrost covers more than 1.5 million km² on the Plateau (Zhao et al., 2004; Yang et al., 2010). Continuous permafrost occupies about one third of permafrost area, mostly in central and northwestern Plateau. Other permafrost areas are predominantly discontinuous island permafrost and sporadic island permafrost across the Plateau (Nan et al., 2005; Cheng and Wu, 2007). Frozen soils are distributed in a range of 10–312 m in depth across the plateau, and water held in the permafrost is estimated twice of that in glaciers (Wu et al., 2010; Zhao et al., 2010). Past studies (Ji, 1996) reported that the upper permafrost layers had warmed 0.2–0.3 °C in average since 1970s, leading to large-scale thawing and disappearance of permafrost. Drilling records reveal the lower elevation limit of permafrost moved up to 25 m in the north and 50–80 m in the south in the past 20–30 years (Zhao et al., 2004; Cheng and Wu, 2007; Yang et al., 2010). Ni (2000) modeled the potential changes of permafrost under the warming climate, and estimated that the boundary between continuous and discontinuous permafrost on the plateau would shift toward the north by up to 1–2° in latitude.

With permafrost retreat and thinning, groundwater table drops, root-zone soil moisture decreases and soil temperature increases. In transitional permafrost zone, however, water released from frozen soil during permafrost thawing actually favors vegetation growth (Zhou et al., 2015). Therefore permafrost plays an important role in regulating the distributions of alpine vegetation, especially the succession of alpine meadows into steppes and desertification (Wang, 1998; Wang et al., 2006). Alpine meadows are found more sensitive to permafrost changes than alpine steppes (Wang et al., 2011). For example, the source region of the Yangtze River is primarily covered with permafrost. Yang et al. (2005) found that alpine grasslands in this area were extremely sensitive to soil temperature and moisture in the 0–40 cm depth.

Reciprocally, grassland degradation affects soil surface temperature (Yi et al., 2013) and thus accelerates the impact of thermal regime in the active layer of soil (Wang et al., 2010). Soil with high grass cover had later thawing-freezing and lower annual variability than that with low grass cover. While some studies (e.g. Yu et al., 2010) attributed the delayed spring phenology to temperature increase, the thawing-freezing processes in the active layer of permafrost may also affect the seasonal growth of alpine grasslands (Yang et al., 2003). Hu et al. (2009) reported that grassland degradation on the plateau resulted in advanced and shorter processes of soil freezing and thawing, which in turn shortens the growing season of grasslands. Therefore, permafrost retreat and grassland degradation may interact with each other and deserve
further investigation in different permafrost areas on the plateau.

4.3. Lake area change

The Tibetan Plateau has more than 1000 lakes, most of which belong to inland drainage systems (Li et al., 2014). Lake area change certainly reflects the change of water availability in alpine grasslands of the catchment. Climate change directly affects the extent of Tibetan lakes. Some studies found that most lakes in the plateau were expanding (Zhang et al., 2011). Others reported that the inland lake water had widespread decline in the source region of the Yellow River (Lin et al., 2011), and expansion in the western and northern source region of the Yangtze River (Huang et al., 2011). Along with Tibet Warming, evaporation rate on the plateau is about 2–3 times higher than precipitation (Li et al., 2007). Therefore lake area change of this region is influenced by water recharge from other sources than precipitation (Zhang et al., 2011).

Some studies claimed that lake area expansion in southern plateau was a direct result of glacier melting (Wu and Zhu, 2008; Liu et al., 2010). Ma et al. (2010) also claimed the 60 newly appeared lakes in the plateau to the accelerated glacier melting. Similar results were reported in the source regions of the Yellow and Yangtze Rivers by comparing the TM images in 1986 and 2000 (Wang et al., 2004). Oppositely, a recent study debated that, instead of glacier retreat, water supply in the Tibetan lakes was actually primarily attributed by permafrost degradation along with Tibet Warming (Li et al., 2014). With the Landsat/ICESat satellite time series in 1970–2010, the study found a southwest-northeast transition of lake areas from shrinking, stable, to rapidly expanding, in consistence with the pattern of permafrost degradation that was retrograding from south and southeast (isolated permafrost) to northwest (continuous permafrost). Shrinking inland lakes were also found in other studies (e.g. Lin et al., 2011; Huang et al., 2011) as a common feature in the discontinuous permafrost regions.

Associated with snow/glacier melting, permafrost retreat and lake extent change, the dynamics of water availability in soil inevitably affect alpine grasslands in both short-term change and long-term succession. Understanding the interaction among these processes is critical for better prediction of future water availability in alpine grasslands on the plateau, as well as water sources and hydropower supplies for more than 1.5 billion people in South and East Asia.

5. Summary and research needs

Due to limited physical access to the Tibetan Plateau, large-coverage frequent satellite imagery is becoming the predominant data source to monitor this unique environment. This paper gives a comprehensive review of satellite-assisted studies in aspects of alpine grassland mapping and phenological changes, their climatic consequences and the implication of snow/glacier/permafrost/lake changes along with Tibet Warming. Although spatially explicit, plateau-level information could be easily extracted from satellite time series, the controversy findings amongst past studies indicate that the satellite-derived patterns should be interpreted with caution. Time series of vegetation index extracted from satellite imagery is often contaminated by temporal variation of meteorological conditions and soil background, which may outperform the spectral signatures in alpine environments. As reviewed in this paper, inconsistencies of the plateau-level trends and driving forces were reported. For satellite remote sensing of alpine grasslands on the plateau, the following aspects deserve further investigation:

1. Spatial/temporal scales of satellite data
   Many studies on the plateau relied on coarse-resolution satellite imagery such as the 8-km, 15-day AVHRR GIMM database that became available since the 1980s. Due to the harsh climates, alpine grasslands are sparse with low biomass and short growing season, especially in alpine steppes and alpine deserts in western plateau. With reduced spatial and temporal resolutions, these data fail to reveal detailed growth curves of alpine grasses and their inter-annual trends. Patterns of vegetation growth extracted from these data turn to be highly fragmented across the plateau, which could easily be mis-interpreted in geospatial analysis. The km-scale, 8-day MODIS composite data, available since 2000, reduced the uncertainties of the spatial patterns in alpine grassland mapping. The short period of MODIS data acquisition, however, limits its capability of extracting phenological trends and examining climate dependencies. Trends in such a short period could be falsely significant with a small degree of freedom in statistical tests. Further research may be conducted to integrate multi-source satellite observations (spatially and temporally) to take advantage the merit of continuous satellite observations for long-term assessment of alpine grasslands in a changing climate.

2. The accelerated anthropogenic impacts
   Population on the Tibetan Plateau is low and clustered in the eastern and southern plateau. Constrained by the harsh climate, human impacts on this fragile environment should not be ignored. Taking the Qinghai-Xizang Highway/Railway systems as an example, negative effects such as the imbalanced thermal regime in the active layer of permafrost along the road infrastructure are inconvertible. Comprising about one third of pasturelands in China, alpine grasslands on the plateau are under accelerated grazing in recent decades. Overgrazing and the associated infestation of plateau pika (Ochotona curzoniae), the rapidly established highway/railway systems and the intensified touring activities, all cast strong impacts on this fragile ecosystem. Started in 1998, a series of key national projects have been initiated on the plateau to combat grassland degradation. Recovery of alpine grasslands, however, is much slower than those in temperate climates. Long-term implementation and evaluation of these programs are needed.

3. New satellite data on Tibetan Plateau
   Soil moisture controls water availability in alpine grasslands, but has not been well documented on the
plateau. While more satellite sensors have been available in past decades, their soil moisture products are at coarse resolutions (40–100 km), and uncertainties remain high in examining the contribution of soil moisture to alpine grasses. For example, Su et al. (2011) compared the soil moisture products of the NASA AMSR-E (Njoku et al., 2003; Owe et al., 2008) and European ASCAT-L2 (Wagner et al., 2003; Bartalis et al., 2007) in three networks composing the Tibetan Plateau Observatory. The study found that, at the plateau level, both products overestimated soil moisture by 0.2–0.3 m³ m⁻³ in monsoon season, and were basically not reliable in winter. Better products such as the new SNAP mission (launched in February 2015) reach up to 10-km grid size (http://smap.jpl.nasa.gov), although the product may be affected by the failure of the L-band radar in July 2015. Such data layers could improve our investigation of the plateau’s land surface conditions in alpine ecosystems.

In short, by far we are still in lack of sufficient understanding of current socio-ecological systems on the Tibetan Plateau. Additional work is necessary to integrate the physiological, ecological and hydrological data from satellite observations to better understand the complicated processes on the plateau, and the evolution of alpine grasslands under the persistent Tibet Warming.

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Beniston, M., 2003. Climatic change in mountain regions: a review of current socio-ecological systems on the Tibetan Plateau. Additional work is necessary to integrate the physiological, ecological and hydrological data from satellite observations to better understand the complicated processes on the plateau, and the evolution of alpine grasslands under the persistent Tibet Warming.

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