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# Mapping degraded grassland on the Eastern Tibetan Plateau with multi-temporal Landsat 8 data — where do the severely degraded areas occur?

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ABSTRACT

The Tibetan Plateau in Western China is the world's largest alpine landscape, sheltering a rich diversity of native flora and fauna. In the past few decades, the Tibetan Plateau was found to suffer from grassland degradation processes. Grassland degradation is assumed to not only endanger biodiversity but also to increase the risk for natural hazards in other parts of the country which are ecologically and hydrologically connected to the area. However, the mechanisms behind the degradation processes remain poorly understood due to scarce baseline data and insufficient scientific research.

We argue that remote sensing data can help to better understand degradation processes and patterns by: (1) identifying the distribution of severely degraded areas and (2) comparing the patterns of key spatial attributes of the identified areas (altitude above sea level, aspect, slope, administrative districts) with existing theories on degradation drivers. Therefore, we applied four Landsat 8 images covering large portions of the three counties Jigzhi, Baima and Darlag in the Eastern Tibetan Plateau. The dates of the Landsat scenes were selected to cover differing phenological stages of the ecosystem. Reference data were collected with a remotely piloted aircraft and a standard consumer RGB camera. To exploit the phenological information in the Landsat data as well as deal with the problem of cloud cover in multiple images, we developed a straightforward PCA-based procedure to merge the Landsat scenes. The merged Landsat data served as input to a supervised support vector machine classification which was validated with an iterative bootstrap procedure and an additional independent validation set. The considered classes were "high-cover grassland", "grassland (including several stages of grassland vitality)", "(severely) degraded grassland", "green shrubland", "grey shrubland", "urban areas" and "water bodies". Kappa accuracies ranged between 0.84 and 0.93 in the iterative procedure, while the independent validation led to a kappa accuracy of 0.76. Mean producer's and user's accuracies for all classes were higher than 80%, and confusion mainly occurred between the two shrubland classes and between the three grassland classes.

Analysis of the slope, aspect and altitude values of the vegetation classes revealed that the degraded areas mostly occurred at the higher altitudes of the study area (4300–4600 m), with no strong connection to any specific slope or aspect. High-cover grassland was mostly located on sunny slopes at lower altitudes (less than 4300 m), while shrubland preferred shady, relatively steep slopes across all altitudes. These observations proved to be stable across the examined counties, while the proportions of land-cover classes differed between the examined regions. Most counties showed 5–7% severely degraded land cover. Darlag, the county located at the edge of the permafrost zone, and featuring the highest average altitude and lowest annual temperature and precipitation, was found to suffer from larger areas of severe degradation (14%).

Therefore, our findings support a strong connection between degradation patterns and climatic as well as altitudinal gradients, with an increased degradation risk for high altitude areas and areas in colder and drier climatic zones. This is relevant information for pastoral management to avoid further degradation of high altitude pastures.



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## 1. Introduction

Grasslands are amongst the largest terrestrial ecosystems on the Earth, covering about a quarter of the total land surface. Grasslands also provide important services, including not only foods and goods but also non-economic services such as by sustaining hydrological systems and preventing degradation. Currently, approximately one billion mostly low-income people depend directly on grassland economies (Boval and Dixon, 2012).

The Tibetan Plateau Grassland (TPG) is the highest grassland ecosystem in the world with an average altitude of 4500 m above sea level. Due to its high elevation and harsh environment, domestic animal keeping, and yak herding in particular, became the dominant industry for local people. The current landscape of TPG is formed by a long history of nomadic pastoralism (Miehe et al., 2009). Tibetan communities developed an adaptive land-use system to survive the harsh environment of the plateau. For instance, nomads separated grassland into cold and warm season pastures to protect certain areas from overgrazing; meanwhile, the use right of pastures was fluid and could be adjusted or transferred according to family herd sizes (Goldstein and Beall, 1991). However, like many other grassland ecosystems of the world, privatization of livestock and seasonal pastures has prevailed on the TPG since the middle 1980s for the purpose of improving management efficiency and avoiding the "tragedy of the commons" (Cao et al., 2013; Hardin, 1968). To improve the welfare of nomads, the government launched a comprehensive program subsidizing establishments of stockyards and permanent settlements on winter pastures. The corresponding changes in pastoral management have resulted in steadily high stocking rates since the 1980s and declining mobility of pastoral nomads due to the rigid boundaries of privatized land and intensive usage of winter (cold season) pastures (Gruschke, 2008).

Simultaneously with these land-use changes, increases in grassland degradation and desertification have been observed across the TPG (Harris, 2010; Lehnert et al., 2014; Wang et al., 2006). It has been reported that the heavily degraded area of the TPG has exceeded 500,000 km$^2$ and the annual desertification rate is 8% (Zhang, 2006). This degradation not only damages the livelihoods of local Tibetans but also threatens biodiversity and the ecological services of the plateau. For example, degradation was found to increase the risk of hazards connected to hydrological disturbances, dust storms, and commodity scarcity (Harris, 2010). Recent studies suggest that the degradation on the TPG is caused by complex interactions between environmental and management changes, including intensified pasture usage, overgrazing and permafrost degradation caused by climate warming (Dong et al., 2013; Li et al., 2013; Shang and Long, 2007). In the Yellow River Source region of the eastern Tibetan Plateau, Liu et al. (2006) found that high degradation rates can be observed over all slope and aspects in the relative low elevation zone (3800–4100 m), which is often used as heavily-grazed winter pasture. From 4100 to 5000 m the degradation rate was found to be higher on sunny slopes and inversely proportional to altitude, which also shows a spatial correlation with the land-use intensity pattern in this elevation zone. Furthermore, due to the high elevation and low temperatures, the TPG is considered to be especially sensitive to climate warming (You et al., 2014). Significant warming has already resulted in extensive degradation of permafrost (Yang et al., 2010). This degradation is mainly evidenced by an increased thickness in the active layer, which is subject to repeated freezing and thawing and is thus more vulnerable to weathering, erosion, and subsequent reductions of vegetation (Yang et al., 2004). Wang et al. (2006) found that the alpine cold swamp meadow has decreased by 28% since 1990, and predicted that the alpine cold meadow located in the low mountain and plateau area will suffer from moderate to serious degradation under a 50 year scenario with a temperature increase of 2 °C. The other widely-mentioned factor causing degradation is rodents, particularly the plateau pika (*Ochotona curzoniae*) which was often considered as a pest causing grassland damage. However, more recent studies interpret the increasing density of small mammals as a result rather than the cause of the degradation (Harris, 2010; Lai and Smith, 2003; Smith and Foggin, 1999).

In general, the causes of the documented degradation processes are still not understood properly. This is due to a number of factors, including the poor ecological and socio-economic baseline information for such a vast area, the lack of long-term monitoring projects, and the absence of studies on driver interactions and feedback processes. We think that remote sensing can help to improve the understanding of degradation patterns by identifying degraded grassland areas and by allowing their geospatial attributes to be analyzed. By locating these degraded areas, existing hypothesis on degradation drivers can be strengthened or weakened. Although this seems to be a straight forward approach, studies following a similar workflow to characterize degradation areas on the TPG are rare. Most of the remote sensing studies to date in the Himalayan and Tibetan region focused on change analysis concerning climatic variables (Agrawal et al., 2014; Tseng et al., 2011), phenology shifts (Chen et al., 2009 ; Jin et al., 2008 ; Li et al., 2014a) and processes related to some type of grassland productivity (Gang et al., 2010; Li et al., 2014b; Zhang et al., 2014). In addition to the preceding satellite-based studies, a few studies making use of field spectroscopy data have been conducted. Shen et al. (2008) examined the feasibility of field spectrometer data for estimating grassland biomass, and Lehnert et al. (2014) developed an indicator system to assess rangeland degradation from field spectroscopy data with the aim to transfer the method to spaceborne hyperspectral data.

Methodologically, the natural properties of the TPC pose some challenges for spaceborne remote sensing applications. Some parts of the TPC are frequently affected by cloud-cover, the pronounced terrain leads to large proportions of shadowed pixels, and the strong phenological amplitudes of the grasslands complicate the successful detection and quantification of changes. In addition, the collection of ground reference information is difficult due to the limited accessibility and large extent of the TPC. An example of this is the study of Yu et al. (2011), who presented a land-cover mapping approach in the Lhasa river basin based on Landsat data and an expert system classification. As their number of field samples was too small, they made use of pre-existing vegetation and zonation maps and relied on field experience, which of course adds uncertainty. It was amongst the objectives of this study to address these challenges.

Therefore, this study focuses on the following objectives:

1. Development of a classification workflow to obtain reliable vegetation classifications (including degraded areas) from multi-temporal Landsat 8 data in a study area with multiple cloud occurrences, strong terrain shadow effects and complicated terrain accessibility.
2. Identification and interpretation of differences within the considered vegetation and degradation classes concerning the three spatial attributes slope, aspect and altitude above sea level, in the three counties Jigzhi, Baima and Darlag which cover the majority of the study area
3. Calculation and comparison of the land area balances of all counties that notably intersect the examined area covered by the satellite data