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Retrieval of grassland plant coverage on the Tibetan Plateau based on a multi-scale, multi-sensor and multi-method approach

Lukas W. Lehnert [a,*], Hanna Meyer [a], Yun Wang [b], Georg Miehe [a], Boris Thies [a], Christoph Reudenbach [a], Jörg Bendix [a]

[a] Faculty of Geography, Philipps-University of Marburg, Deutschhausstr. 10, 35037 Marburg, Germany
[b] Senckenberg Museum of Natural History, Am Museum 1, 02826 Görlitz, Germany

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ABSTRACT

Plant coverage is a basic indicator of the biomass production in ecosystems. On the Tibetan Plateau, the biomass of grasslands provides major ecosystem services with regard to the predominant transhumance economy. The pastures, however, are threatened by progressive degradation, resulting in a substantial reduction in plant coverage with currently unknown consequences for the hydrological/climate regulation function of the plateau and the major river systems of SE Asia that depend on it and provide water for the adjacent lowlands. Thus, monitoring of changes in plant coverage is of utmost importance, but no reliable tools have been available to date to monitor the changes on the entire plateau. Due to the wide extent and remoteness of the Tibetan Plateau, remote sensing is the only tool that can recurrently provide area-wide data for monitoring purposes. In this study, we develop and present a grassland-cover product based on multi-sensor satellite data that is applicable for monitoring at three spatial resolutions (WorldView type at 2–5 m, Landsat type at 30 m, MODIS at 500 m), where the data of the latter resolution cover the entire plateau. Four different retrieval techniques to derive plant coverage from satellite data in boreal summer (JJA) were tested. The underlying statistical models are derived with the help of field observations of the cover at 640 plots and 14 locations, considering the main grassland vegetation types of the Tibetan Plateau. To provide a product for the entire Tibetan Plateau, plant coverage estimates derived by means of the higher-resolution data were upscaled to MODIS composites acquired between 2011 and 2013. An accuracy assessment of the retrieval methods revealed best results for the retrieval using support vector machine regressions (RMSE: 9.97%, 7.13% and 5.51% from the WorldView to the MODIS scale). The retrieved values coincide well with published coverage data on the different grassland vegetation types.

1. Introduction

Plant coverage is a key proxy used to estimate and monitor important ecosystem parameters and functions by remote sensing, particularly for such expanses as the grasslands on the Tibetan Plateau. Important cover-related parameters and functions are primary production (PP; Seaquist, Olsson, & Ardö, 2003), evapotranspiration (ET; Mu, Heinsch, Zhao, & Running, 2007) and leaf area index (LAI; Soudani, Francois, le Maire, Le Dantec, & Dufrene, 2006), where PP is commonly used as a proxy of CO_2 fluxes (Wylie et al., 2003) and ET is used to investigate interactions among vegetation, hydrology and climate (Murray et al., 2013). In addition, plant coverage and its changes over time have been directly used as an indicator for grassland degradation in several studies (*e.g.*, Gao et al., 2010). The Tibetan Plateau hosts the world's largest high-mountain grassland ecosystem, and it significantly influences the hydrology of East and South-East Asia (Piao et al., 2010). The plateau, with its extended pastures, serves as a globally important "water tower", providing water for nearly 40% of the world's population (Barnett, Adam, & Lettenmaier, 2005; Xu, Lu, Shi, & Gao, 2008), and it plays an important role in monsoon generation (Ding & Chan, 2005; Mölg et al., 2014). Despite their great importance, the pastures of the plateau are threatened by environmental change. To date, there is strong evidence that degradation of the grassland due to climate change and overgrazing may alter the phenology of the vegetation, thus adversely affecting ecosystem stability on the plateau (Harris, 2010; Zhang, Zhang, Dong, & Xiao, 2013). Consequently, monitoring the state changes of the Tibetan grasslands under conditions of global environmental change is of utmost importance.

* Corresponding author. Tel.: +49 6421 28 24 227.
E-mail addresses: lukas.lehnert@staff.uni-marburg.de (L.W. Lehnert), hanna.meyer@geo.uni-marburg.de (H. Meyer), yun.wang@senckenberg.de (Y. Wang), miehe@staff.uni-marburg.de (G. Miehe), thies@staff.uni-marburg.de (B. Thies), reudenbach@geo.uni-marburg.de (C. Reudenbach), bendix@staff.uni-marburg.de (J. Bendix).

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Information about plant coverage of the grasslands on the Tibetan Plateau is important for various stakeholders. On the local scale (covered by WorldView-type satellite data), a plant coverage monitoring product would improve the early detection of over-grazing and would allow adjustment of the carrying capacities of the spacious rangeland ecosystems (Cao, Yeh, Holden, Yang, & Du, 2013). On the regional scale (covered by Landsat-type satellite data), knowledge of changes in plant coverage is essential for county administrators who assign rangeland to the farmers (Banks, Richard, Li, & Yan, 2003). On the plateau scale (MODIS data), detailed knowledge on pasture degradation is particularly interesting for scientists, *e.g.*, to simulate the effect of land-use changes on hydrological and atmospheric processes (Cui & Graf, 2009).

Because of the enormous spatial extent and remoteness of the Tibetan pastures, it is obvious that remote sensing is the only tool for assessing and monitoring the plateau's plant coverage. To be suitable for the different stakeholders mentioned above, a remotely sensed plant coverage product for the grasslands of the Tibetan Plateau must have a spatial resolution fine enough to cover local terrain effects and to differentiate the pastures belonging to a village. To warrant its suitability for monitoring purposes, the temporal resolution must be high enough to allow comparisons between seasons and to investigate differences among years. Thus, satellite systems offering continuous and consistent data over a long time are a precondition for an operational monitoring product.

Previous attempts at plant coverage monitoring on the Tibetan grasslands using remote sensing have mainly been based on the analysis of normalized difference vegetation index (NDVI) data, either by inspecting NDVI time-series (Zhang et al., 2013) or conducting change-detection analysis (Gao et al., 2010). However, the link between plant coverage and NDVI is sometimes ambiguous because the index is highly sensitive to the soil background signal, particularly in arid (and/or degraded) environments with low vegetation cover (Huete, Liu, Batchily, & vanLeeuwen, 1997). Thus, to make the plant coverage product suitable for estimation and monitoring purposes regarding, *e.g.*, the provisioning of ecosystem services by pastures, the satellite reflectance values must be transformed into plant coverage. This transformation can be achieved using field-derived transfer functions, which have been established for single sites (*e.g.*, Liu, Shen, Lin, Li, & Yue, 2014) but not for the entire plateau. Other possibilities to derive plant coverage from remotely sensed images are the application of linear spectral unmixing (LSU, Göttlicher et al., 2009) and spectral angle mapper (SAM; Yang & Everitt, 2012) techniques. One simple and fast method to translate reflectance values or SAM distances into plant coverage values is linear-regression analysis. This method has been applied in a variety of studies (Meyer, Lehnert, Wang, Reudenbach, & Bendix, 2013; Psomas, Kneubuehler, Huber, Itten, & Zimmermann, 2011; Zha et al., 2003). More advanced multivariate methods used to retrieve plant coverage from satellite data encompass partial least squares regressions (PLSR) and machine-learning algorithms such as support vector machines (SVM), which have been evaluated as a valuable tool to cope with non-linear relations and highly correlated predictor variables. Thus, SVM might be advantageous in studies of complex interacting systems. For instance, Schwieder, Leitão, Suess, Senf, and Hostert (2014) recently highlighted the high potential of SVM for the determination of fractions of land cover types in satellite images.

However, none of the previous studies have answered the question of which method is most suitable for deriving plant coverage, particularly on the Tibetan Plateau. Consequently, reliable and area-wide information on plant coverage and its changes over time is lacking to date. Therefore, the paper has two objectives:

- Objective one is to compare different methods to derive the summer plant coverage of the grasslands on the Tibetan Plateau. In this context, plant coverage information is derived along a cascade of satellite data with three spatial resolutions. This allows for a direct link between locally observed plant coverage and satellite-derived values. The methods to be compared are (i) LSU, (ii) SAM in combination with linear regression, (iii) PLSR and (iv) SVM regression based on the same feature space comprised by vegetation indices (VI) and normalized difference indices (NDI).
- Objective two is to apply the method with the highest accuracy to generate a summer (JJA) plant coverage dataset for the grasslands of the Tibetan Plateau for the years with field data at hand (2011–2013), based on Moderate Resolution Imaging Spectroradiometer (MODIS) imagery.

First, a short overview of the considered grassland vegetation types on the Tibetan Plateau is given. Then, the upscaling methodology to compare the different estimation methods to derive plant coverage on three spatial scales is described. In the third part, we present and discuss the results, including the finally generated grassland cover data set.

2. Grasslands on the Tibetan Plateau

Plant coverage on the Tibetan Plateau is calculated for the most widespread and grazed grassland vegetation types. For further processing, grassland areas were pre-assigned to the five major grassland vegetation types on the Tibetan Plateau as proposed by Hou (2001): (1) *Kobresia pygmaea* pastures, (2) *Kobresia humilis* pastures, (3) swamps and salt marshes, (4) montane and (5) alpine steppes. The distribution of the grassland vegetation types under investigation is shown in Fig. 1.

K. humilis pastures (Fig. 2a) are widespread in the north-eastern Tibetan Plateau between 3300 and 3600 m, and they grow under 400–600 mm of mainly summer precipitation. The plant cover normally exceeds 80%, and a typical *Kobresia* pasture is composed of 30 to 40 species. In less-grazed areas, grasses up to 40 cm of height overgrow the widespread Cyperaceae, which reach 10 to 20 cm in height. If pastures are intensively grazed, grazing weeds (*Stellera chamaejasme*, *Ligularia tangutica*, *Iris* spp., *Cryptothladia kokonorica*), which are generally taller than the Cyperaceae, may cover up to 30% of the area. Since the mid-Holocene optimum (8000 BP), these grasslands have replaced forests of *Picea crassifolia* and *Juniperus przewalskii* due to human impact (Miehe et al., 2014).

Montane steppe is also a secondary grassland vegetation type. It occurs in areas with lower rainfall and terrain altitude. Tussocks of *Stipa splendens* and the poisonous bunch grass *Achnatherum inebrians* grow up to 80 cm tall in a grazing lawn of 2–5 cm consisting of matted *Sibbaldianthe adpressa*, *Potentilla bifurca*, *Heteropappus* spp., and annual *Artemisia* spp. The total cover of the steppe, with its approximately 20 species, ranges between 30 and 60%. The number and cover of matted and rosette grazing weeds is highest in comparison to the other grassland vegetation types considered in this study.

K. pygmaea pastures cover the humid south-eastern quarter of the Tibetan Plateau (450,000 km^2; Fig. 2b). The altitudinal range of this alpine plant community is globally unique, forming the world's highest alpine vegetation (up to 5960 m) on sunny slopes. In the core area, the tiny sedge *K. pygmaea* (2–4 cm in height, Fig. 2c) forms a nearly monotypic pasture on a felty turf with up to 98% cover, dominating the plant composition by 90% abundance. The closed grasslands are generally species-poor (average 10 species). In areas of *K. pygmaea* pastures with higher disturbance and in the ecotone toward the Alpine steppe (Fig. 2d), the mosaics of *K. pygmaea* turfs are surrounded by vegetation on open sands and gravels composed of rosette plants and alpine cushions (average 24 species).

Alpine steppes are Central Asian short-grass steppes in the arid northwest of the Tibetan Plateau associated with alpine cushions plants. This grassland vegetation type covers an area of approx. 800,000 km^2. The less diverse *Carex moorcroftii* desert steppe normally consists of 2–8 species. Cushion plants dominate at 50–100 mm of summer precipitation at elevations between 4500 and 5400 m in the remote north of