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Modeling alpine grassland cover based on MODIS data and support vector machine regression in the headwater region of the Huanghe River, China

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A B S T R A C T

Monitoring changes in grassland cover is essential in assessment of grassland health as well as the effects of anthropogenic interventions and global climate change on grassland ecosystems. Remote sensing is an effective approach for providing rapid and dynamic monitoring of vegetation cover over large grassland areas. In this study, four types of remote sensing retrieval models (i.e., pixel dichotomy models, univariate vegetation index (VI) regression models, multivariate regression models, and a support vector machine (SVM) model) are built to derive grassland cover based on moderate resolution imaging spectroradiometer (MODIS) data and the measured grassland cover data collected (by unmanned aerial vehicle) during the grassland peak growing season from 2014 to 2016. The optimal model is then used to map the spatial distribution of grassland cover and its dynamic change in the headwater region of the Huanghe River (Yellow River) (HRHR) of the northeastern Tibetan Plateau over the 16 years period (2001 to 2016). The results show that (1) the pixel dichotomy models based on MODIS VI data are inappropriate for estimating grassland cover in the HRHR when their endmembers (VI_{oil} and VI_{veg}) are determined based only on the MODIS data; (2) the multivariate regression models present better performance than the univariate VI (normalized difference vegetation index (NDVI) or enhanced vegetation index (EVI)) models; (3) MODIS NDVI outperforms MODIS EVI for modeling grassland cover in the study area; (4) the SVM model based on nine factors is the optimal model (R^2: 0. 75 and RMSE: 6.85%) for monitoring alpine grassland cover in the study area; and (5) majority of the grassland area (59.9%) of the HRHR showed increase in yearly maximum grassland cover from 2001 to 2016, while the average yearly maximum grassland cover for the 16 years exhibited a generally increasing trend from west to east and from north to south. This study provides a more suitable remote sensing inversion model to greatly improve the accuracy of modeling alpine grassland cover in the HRHR, and to better assess grassland health status and the impacts of warming climate to grasslands in regions of remote and harsh environments.

1. Introduction

Vegetation cover refers to the percentage of aboveground vegetation in relation to the total ground surface area (Purevdorj et al., 1998), and is a valuable parameter for reflecting vegetation growth status and a sensitive indicator of ecosystem change (Jiapaer et al., 2011). Monitoring vegetation cover of an extensive grassland is of great significance for assessing grassland resources and preventing grassland degradation. Accurate information on grassland cover status and changes can support government decisions regarding grassland management and livestock production (Wang et al., 2017; Purevdorj et al., 1998). Remote sensing is the only available and effective approach for estimating grassland cover and monitoring its dynamic changes over a long time series in harsh environments of vast spatial extents. There are two approaches for deriving grassland cover based on satellite remote sensing data: spectral mixture analysis (SMA) and empirical model methods.

SMA provides an important method for deriving vegetation cover from multispectral and hyperspectral satellite data at a regional scale. Under this approach, each pixel in a satellite image is decomposed into a linear component of a reference spectrum, referred to as an endmember (Jiapaer et al., 2011; Elmore et al., 2000; Guerschman et al.,

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2009; Wu and Murray, 2003). The pixel dichotomy model is a simplified linear SMA model (Wittich and Hansing, 1995) that includes two vegetation index endmembers consisting of a VI_{veg} value from the 100% green vegetation area and a VI_{soil} value contributed by the bare soil area (Li et al., 2014; Qi et al., 2000; Gutman and Ignatov, 1998; Zeng et al., 2000). Due to its simplicity and interpretability, the pixel dichotomy model is rapid and effective in simulating dynamic changes in vegetation cover over a long time series at regional and even global scales. To the best of our knowledge, previous studies have concentrated on estimating sparse vegetation in arid and semiarid areas, and the selection of vegetation and non-vegetation endmembers has been based on satellite images with a 30 m or higher spatial resolution or in situ data (Li et al., 2014; Xiao and Moody, 2005; Liu et al., 2009; Jiapaer et al., 2011). However, at large regional scales, the utilization of high-resolution satellite images is constrained by high costs and weather conditions, and field surveys are further limited by additional factors. Moderate-resolution satellite images (e.g., MODIS imagery) may be more suitable for use at large regional scales because they present not only wide spatial coverage, but also a high temporal resolution. However, few studies have systematically evaluated the accuracy of pixel dichotomy models at a moderate spatial resolution (such as MODIS) in pastoral areas with relatively dense alpine grasslands, such as those found on the Tibetan Plateau (TP).

Empirical models have been widely adopted in recent years for determining vegetation cover. Good results have been achieved through establishing empirical relationships between satellite remote sensing and field-measured data, and then extrapolating vegetation cover estimates to a regional scale using such empirical formulas (Kergoat et al., 2015; Jakubauskas et al., 2000; North, 2002; Gitelson et al., 2002). The satellite data used in an empirical model can come from a single band, a combination of bands, or vegetation indices (VIs). Existing studies have shown that VIs are highly reliable and effective data sources for assessing vegetation cover. In this context, the normalized difference vegetation index (NDVI), enhanced vegetation index (EVI), ratio vegetation index, soil-adjusted vegetation index and modified soil-adjusted vegetation index have performed particularly well (Patel et al., 2007; Purevdorj et al., 1998; Rundquist, 2002; North, 2002; Lehnert et al., 2015). However, several existing studies have utilized empirical models based on a single VI without considering the ecological context and the spatial heterogeneity of grasslands. Moreover, each VI has its own limitations and uncertainties, which cause the models to produce good results only for the specified measurement areas while inappropriately describing the vegetation cover in other regions (Yang et al., 2017). Therefore, building multivariate models by adding other environmental factors (i.e., geographical location, terrain data and meteorological data) that are closely related to grassland cover is a more effective method that decreases the prediction error of single VI-based retrieval models and improves the stability and universality of grassland cover inversion models (Meng et al., 2018). Furthermore, according to different statistical methods, empirical models can be divided into categories including linear regression analysis (Zha et al., 2003; Psomas et al., 2011), nonlinear regression analysis (Gitelson et al., 2002), support vector machine (SVM) regressions (Schwieder et al., 2014; Lehnert et al., 2015), decision tree (DT) regressions (Hansen et al., 2002a, 2002b; Goetz et al., 2003), and artificial neural networks (ANN) (Boyd et al., 2002).

Compared to traditional linear and nonlinear regressions, the SVM method is a more advanced and intelligent statistical method. SVM is a supervised and nonparametric machine learning algorithm that is used for classification and regression analyses (Vapnik et al., 1996). This method offers many unique advantages in coping with small samples and nonlinear and high dimensional pattern recognition, presenting a high correlation with predictor variables (Mountrakis et al., 2011; Verrelst et al., 2015). Schwieder et al. (2014) compared the capability of three machine learning models to estimate shrub vegetation cover and showed that all algorithms (SVM, partial least squares regression (PLSR), and random forest regression) presented good predictive power, while the SVM model outperformed the others with an average R^2 value of 0.64 and a root mean square error (RMSE) of only 12%. Lehnert et al. (2015) obtained similar results when they studied the performance of four different methods (i.e., SVM, spectral angle mapper, PLSR, and linear spectral unmixing) used for estimating grassland cover on the TP, with an R^2 of up to 0.64, while RMSE was only 5.59% for the SVM model at the MODIS imagery scale.

Accurate field measurement data of grassland cover are important for developing and/or validating the two modeling approaches mentioned above. On the one hand, accurate measurement data are the basis for establishing high-quality empirical models. On the other hand, the results predicted by both pixel dichotomy models and empirical models need to be validated with accurate field-measured data (Zhou and Robson, 2001; Delamater et al., 2012). Field measurements are acquired by visual estimations, sampling, and photographic methods (Okin et al., 2013). These traditional measurement methods are generally conducted at a quadrat scale (i.e., 0.5 m × 0.5 m or 1 m × 1 m) and are often time consuming and labor intensive. Moreover, a major gap in spatial resolution exists between satellite remote sensing pixels and sample quadrats. Sampling representativeness is greatly influenced by the limited number and size of sampling quadrats, especially in complex natural grasslands with high spatial heterogeneity. Although substantially increasing the number of quadrats can solve this problem, a large number of quadrats implies larger consumption of time, manpower, and cost. This is therefore not suitable for sampling surveys over large areas, particularly in the Tibetan Plateau of high elevation and harsh environment. Unmanned aerial vehicle (UAV) is a powerful tool for effectively addressing the problem of spatial matching between surface ground measurements and satellite remote sensing due to the high resolution and large area coverage of UAV images (Rango et al., 2006; Salamí et al., 2014; Qin, 2014). Compared to satellite remote sensing, UAV images are collected closer to the ground, so the observation data are less disturbed by the atmosphere and other factors. UAVs also have the advantages of small size, light weight, low operating costs, convenient transportation, real-time image transmission and high flexibility, and can be employed to map vegetation cover in inaccessible areas by feet (Colomina and Molina, 2014; Yi et al., 2016; Capolupo et al., 2015). Rango et al. (2006, 2009) described the application of a UAV to acquire the canopy cover of woody vegetation in the experimental mixed rangeland of Jornada and obtained good results. Chen et al. (2016) used both the UAV photographic method and surface quadrat investigations to obtain fractional vegetation cover (FVC) data from alpine grassland of the Tibetan Plateau and then evaluated the accuracy of these two methods. The research ultimately reached the conclusion that the UAV provided more accurate FVC estimations at the pixel scale of satellite remote sensing image and was more effective than traditional surface measurements.

Therefore, utilizing MODIS VI data and grassland cover data collected by UAV, the objectives of this study are to (1) assess accuracy and applicability of different models (pixel dichotomy model, univariate linear and nonlinear regression, multivariate linear and nonlinear regression, and SVM regression) for alpine grassland cover inversion and (2) analyze the spatial distribution and temporal change in grassland cover over the peak growing season between 2001 and 2016 in the headwater region of the Huanghe River (HRHR) over Tibetan Plateau.

2. Data and methods

2.1. Study area

The HRHR (N33°02′58″–36°07′43″, E95°53′47″–102°15′22″) lies in northeastern TP (Fig. 1) and is a critical ecological barrier on the TP and one of the most important freshwater resources in China (Chu et al., 2016). The HRHR covers an area of approximately 105,190 km^2, with

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