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Monitoring fractional green vegetation cover dynamics over a seasonally inundated alpine wetland using dense time series HJ-1A/B constellation images and an adaptive endmember selection LSMM model

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ABSTRACT

Time series fractional green vegetation cover (FVC) is crucial for monitoring vegetation cover status monitoring, simulating growth processes and modeling land surfaces. Through the integration of remotely sensed data and FVC estimation models, FVC can be routinely and periodically monitored using remote sensing images over large areas. However, due to frequent cloud contamination and trade-offs in satellite sensor design, the FVC estimates from remote sensing data are not continuous, either spatially or temporally, and cannot simultaneously depict details in spatio-temporal variation. Taking the seasonally inundated Zoige alpine wetland in China as a case area, the objective of this paper is to develop a practical and effective approach to quantifying the explicit vegetation FVC details with both high spatial and temporal resolution. In this approach, 30-m multi-spectral images from the Chinese HJ-1A/B (HuanJing (HJ), which means environment in Chinese) satellite constellation with a 2-day revisit time were first composited at 16-day intervals to improve spatio-temporal continuity. Then, a new adaptive endmember selection linear spectral mixture model (ASLSMM) was proposed to improve the accuracy of FVC estimation by considering the endmember dynamics for each pixel. FVC time series were finally estimated by applying the ASLSMM to the cloudless HJ composites. The performance of the model and the spatio-temporal representational capability of the FVC estimation results were comprehensively evaluated using Unmanned Aerial Vehicle (UAV) reference images and ground measurements from an integrated, multi-scale remote sensing experiment. A traditional LSMM with fixed endmembers and the Multiple Endmember Spectral Mixture Analysis (MESMA) model were also used for model performance comparison. The results showed that the R^2 and RMSE values between the FVC estimated from the proposed model and the UAV reference were 0.7315 and 0.1016 (unitless) respectively, which was better than the results from the linear spectral mixture model with a fixed number of endmembers, with R^2 of 0.5924 and RMSE of 0.3821. The R^2 and RMSE values between the FVC estimated from MESMA and the UAV reference were 0.6327 and 0.1578, which was comparable with the ASLSMM. The accuracy evaluation using multi-temporal *in situ* measurements indicated the consistently high performance of the ASLSMM. This study highlights the feasibility of using HJ satellite constellation images to generate the temporally dense and fine spatial resolution FVC estimations for wetland and wetland-like heterogeneous landscape monitoring. The proposed approach can be viewed as a reference for generating FVC datasets from the on-going HJ constellation and similar constellation missions such as Sentinel-2A/B.

1. Introduction

Fractional Vegetation Cover (FVC), which refers to the percentage of the vertical projected area of vegetation to the total ground area, is an important quantitative measurement of vegetation coverage status. FVC is also a sensitive indicator for evaluating ecosystem degradation and desertification processes (Camacho et al., 2013; Li et al., 2015; Jia et al., 2016). It is a critical parameter for many environmental and climate-related modeling applications, such as land surface models, hydrological models, soil erosion models, and weather prediction models (Gutman and Ignatov, 1998; Zeng et al., 2000; Roujean and Lacaze, 2002; Mallick et al., 2013; Zhao et al., 2014). Deriving the spatial distribution and variation pattern of FVC is therefore of significant importance to discovering the ecosystem functions and their variations and to evaluating ecosystem health under the influence of global change

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and human pressure (Camacho-De Coca et al., 2004; Yang et al., 2013; Li et al., 2014; Jia et al., 2015; Wang et al., 2016).

Remotely sensed data have become the primary data sources for generating FVC at regional to global scales. Due to the long history of available data and both large-scale and periodic coverage, satellite images from a variety of sensors have been applied extensively for FVC mapping and dynamic monitoring (Hansen et al., 2002; Baret et al., 2013; Camacho et al., 2013; Sexton et al., 2013; Li et al., 2014; Jia et al., 2016). However, due to the presence of clouds, sensor failures or suboptimal imaging conditions, FVC estimation results have shown spatial and temporal discontinuity, limiting FVC's application in land surface process simulations and ecosystem modeling research. Consequently, there is a need for continuous high-quality data that can be used easily by researchers (Fang et al., 2008). Temporal compositing, in which supplementary temporal information from images at different periods is selected based on criteria such as the maximum/minimum band value or NDVI (van Leeuwen et al., 1999; Roy et al., 2010), has been used extensively to fill the gaps in remotely sensed data. To routinely monitor the FVC at regional or global scales in the long term, temporally composited images such as MODIS and SPOT VEGETATION have often been used for the development of FVC time series products (Hansen et al., 2002; Atzberger and Rembold, 2013; Baret et al., 2013; Camacho et al., 2013; Xiao et al., 2016). However, the composited images have only been available at coarse and medium spatial resolutions (*e.g.*, 250 m–1 km) and are not capable of providing the necessary spatial details for fully characterizing highly heterogeneous areas, such as seasonally inundated wetlands or multiple cropping areas (Gao et al., 2015; Mu et al., 2015).

Recently, the compositing of Landsat data to generate the spatio-temporal continuous 30-m images has emerged from a unique confluence of scientific and operational developments (Roy et al., 2010; Griffiths et al., 2013; White et al., 2014). The composited 30-m spatial resolution images (*e.g.*, Web-Enabled Landsat Data, WELD) have been successfully employed in many studies for crop field extraction (Yan and Roy, 2016), leaf area index estimation (Chen et al., 2015) and land cover change mapping (Hansen et al., 2014). However, due to the low-frequency of the Landsat-like fine spatial resolution images, composited images at monthly or season temporal scales are not frequent enough to reflect the rapid evolution of details during the growing season (Flood, 2013). Thus, a compositing method considering the "best available pixels" from all data within a couple of years is a practical way to generate products that characterize land surface dynamics (Griffiths et al., 2013; White et al., 2014). Satellite constellations, whose payloads often include identical sensors on each satellite, can shorten the revisit time and as a result enhance the temporal density of the remotely sensed data. Satellite constellations such as HJ-1A/B (Wang et al., 2010) and Sentinel-2A/B (Drusch et al., 2012) open a new era in Earth observation capability. They provide a potential way to get the spatio-temporal continuous FVC data with a high resolution in both time and space for characterizing surface dynamics in heterogeneous landscapes.

Numerous remote sensing-based FVC estimation algorithms have been proposed over the past few decades, including classification methods (Foody et al., 1992), spectral mixture analysis (SMA) (Adams et al., 1986; Adams et al., 1995; Roberts et al., 1998; Dennison and Roberts, 2003), regression models (DeFries et al., 1997; Hansen et al., 2002) and physical model-based methods (Jia et al., 2016). Among these methods, SMA is widely used due to its substantial flexibility in practical applications and physically meaningful measures of fractional cover. SMA methods assume that each pixel is composed of several components (which are called endmembers), and a pixel value can be decomposed into a proportional representation of the endmembers that contribute to the overall pixel signal (Montandon and Small, 2008). Thus, the proportion of the vegetation component can be considered to be FVC. One common SMA method, the linear spectral mixture model (LSMM), has been widely used by many researchers. Previous studies have illustrated that, to some extent, the LSMM is superior to other remote sensing inversion approaches and can achieve more accurate results (Cui et al., 2013; Zhang et al., 2016a).

Selecting the appropriate endmembers is a critical component in successfully unmixing sub-pixel spectra (Fan and Deng, 2014). Traditional LSMM methods are implemented using a fixed set of endmembers for every pixel to map an entire region. While LSMM has proven effective for mapping FVC, it fails to account for the within-class spectral variability and the number of endmembers for each pixel (Roberts et al., 1998; Chang and Du, 2004; Fernandez-Manso et al., 2016). The endmembers in a pixel, such as seasonally inundated wetland, may vary with time due to the variation of vegetation phenology and land surface conditions. Thus, the application of the actual endmembers for unmixing pixels will result in an increase in unmixing accuracy (Powell et al., 2007; Zhang et al., 2010; Li et al., 2015). Recently, an expanded version of the LSMM, the Multiple Endmember SMA (MESMA), has been explored to address endmember variability and similarity (Roberts et al., 1998; Dennison and Roberts, 2003; Roberts et al., 2015). Furthermore, in LSMM models, the number of endmembers is constrained by the dimensionality of the satellite imagery (Theseira et al., 2002). It is important to balance the total number of endmembers and the overall optimization of the LSMM model. More endmembers can enable the model to explain more spectral heterogeneity and accordingly improve its applicability. However, too many endmembers will make the model too sensitive to endmember selection and overfit the data, producing an unstable solution (Li et al., 2015; Meng et al., 2017).

In this paper, taking the Zoige alpine peat wetland in China as a case area, the objective is to develop a practical method to quantify the explicit FVC details with both a high spatial and temporal resolution. The method is expected to routinely produce reliable and spatio-temporally continuous FVC data from HJ-1A/B images with a spatial resolution of 30 m and a sub-monthly temporal resolution. To achieve this objective, we first composited the Chinese HJ-1A/B constellation images at a 30 m spatial resolution with a 2 day revisiting time at a 16-day interval to improve the spatio-temporal continuity. An adaptive endmember selection linear spectral mixture model (ASLSMM) was then proposed to improve the unmixing accuracy by considering the spectral and temporal variability for each pixel. Reference FVC data generated from both super-high resolution Unmanned Aerial Vehicle (UAV) images and multi-temporal *in situ* field measurements, which were acquired from the Zoige integrated multi-scale remote sensing experiment (Li et al., 2016), were used to evaluate the accuracy and applicability of the proposed model, as well as the spatio-temporal consistency of the estimated FVC.

2. Study area and data

2.1. Study area

The study area is the Zoige wetland, located at the eastern edge of the Qinghai-Tibet Plateau (Fig. 1(a)). The Zoige wetland is regarded as one of the largest alpine peat wetlands in the world, containing approximately 40% of the total peat stocks in China (Wang et al., 2016). This ecosystem is a crucial area for water conservation along the upper reaches of Yangtze River and Yellow River, providing significant habitat for wetland biodiversity conservation and acting as a huge carbon sink (Bai et al., 2013). However, human activities (*e.g.*, overgrazing, wetland drainage, *etc.*) and climate change have resulted in substantial changes in wetland distribution and vegetation structure in recent decades (Bian et al., 2010a; Li et al., 2012a; Li et al., 2016). It is thus crucial to monitor details in FVC variation for studying the wetland carbon cycle in wetlands and climate change.

The study area is distinguished by relatively flat topography with an average altitude of 3500 m (Wang et al., 2016). The climate is cold and wet, with an annual mean temperature of 0.7–3.3 °C. The mean annual