Remote Sensing of Environment 213 (2018) 34–48

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Grassland canopy cover and aboveground biomass in Mongolia and Inner Mongolia: Spatiotemporal estimates and controlling factors

Ranjeet John[a,*], Jiquan Chen[a], Vincenzo Giannico[a,b], Hogeun Park[a], Jingfeng Xiao[c], Gabriela Shirkey[a], Zutao Ouyang[a], Changliang Shao[d], Raffaele Lafortezza[a,b], Jiaguo Qi[a]

[a] Center for Global Change and Earth Observations, Michigan State University, MI 48823, USA
[b] The Department of Agricultural and Environmental Science, The University of Bari Aldo Moro, Via Amendola 165/A, 70126 Bari, Italy
[c] Earth Systems Research Center, Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, NH 03824, USA
[d] Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, China

A R T I C L E I N F O

Keywords:
Grasslands
Semiarid
MODIS
Cubist
Livestock density
Mongolian Plateau

A B S T R A C T

Temperate and semiarid grasslands comprise 80% of the land area on the Mongolian Plateau and environs, which includes Mongolia (MG), and the province of Inner Mongolia (IM), China. Substantial land cover/use change in the last few decades, driven by a combination of post-liberalization socioeconomic changes and extreme climatic events, has degraded these water-limited grassland's structure and function. Hence, a precise estimation of canopy cover (CC, %) and aboveground biomass (AGB, g m^{-2}) is needed. In this study, we analyzed > 1000 field observations with sampling during June, July and August (JJA) in 2006, 2007, 2010 and 2016 in IM and 2010–2012 and 2014–2016 in MG. The field sampling was stratified by the dominant vegetation types on the plateau, including the meadow steppe, the typical steppe, and the desert steppe. Here we used Moderate Resolution Imaging Spectroradiometer (MODIS) derived surface reflectance and vegetation indices optimized for low cover conditions to develop and test predictive models of CC and AGB using observed samples as training and validation data through rule-based regression tree models. We then used the predictive models to estimate spatially-explicit CC and AGB for the plateau over the last decade (2000–2016). Our study demonstrated the effectiveness of our predictive models in up-scaling ground observations to the regional scale across steppe types. Our results showed that model R^2 and RMSE for CC and AGB were 0.74 (13.1%) and 0.62 (85.9 g m^{-2}), respectively. The validation R^2 and RMSE for CC and AGB were 0.67 (14.4%) and 0.68 (76.9 g m^{-2}), respectively. The mean ± SD for CC and AGB were 24.9 ± 23.4% and 155.2 ± 115.2 g m^{-2}, respectively. We also found that our scaled up estimates were significantly related to inter-annual climatic variability and anthropogenic drivers especially distance to urban/built-up areas and livestock density. In addition to their direct use in quantifying the spatiotemporal changes in the terrestrial carbon budget, results from these predictive models can help decision makers and rangeland managers plan sustainable livestock practices in the future.

1. Introduction

Semiarid ecosystems cover 41% of the terrestrial surface and support 38% of the global population, of which a greater proportion includes most developing countries (Reynolds et al., 2007). While tropical forest biomes dominate the terrestrial carbon sink, its inter-annual variability is controlled by semiarid ecosystems which are strongly associated with circulation-driven variations in precipitation and temperature (Ahlström et al., 2015). Higher carbon turnover rates in semiarid ecosystems were found to be important drivers of inter-annual variability of the global carbon cycle with projections suggesting that tropical forest ecosystems might become less relevant drivers (Poulter et al., 2014). The canopy cover (CC) and above ground biomass (AGB) of these semiarid ecosystems are relatively low, but given their large extent, climate driven dynamics coupled with anthropogenic modification can significantly impact their vegetation structure and function as well as regional and global carbon budgets (Ahlström et al., 2015).

The Eurasian steppe constitutes a major portion of global temperate grasslands and forms a contiguous belt across the continent from the Mediterranean basin to eastern China (Wesche et al., 2016; Qi et al., 2017). The Mongolian steppe represents a significant proportion of the

* Corresponding author.
E-mail address: ranjeetj@msu.edu (R. John).

https://doi.org/10.1016/j.rse.2018.05.002
Received 14 July 2017; Received in revised form 28 April 2018; Accepted 1 May 2018

Eurasian steppe that is largely intact with high biodiversity (John et al., 2008; Khishigbayar et al., 2015). However, these grasslands and the pastoralists that they support face an uncertain future owing to interactions among a warming trend over the past 50 years, an increasing frequency in extreme climate events, rapid changes in land cover/use (e.g., increasing grazing density and mining) and changes in governance and policies (Fernández-Giménez et al., 2012; Reid et al., 2014; Chen et al., 2015b; Khishigbayar et al., 2015; John et al., 2016; Fernández-Giménez et al., 2017). Precipitation, the major limiting factor in these semiarid ecosystems, has high temporal and spatial variability, while a combination of droughts and *dzuds* (i.e., severe winter associated with high livestock mortality) is known to explain the inter-annual dynamics in AGB (Bai et al., 2004; John et al., 2013b).

Livestock sustainability in Mongolia and other semiarid ecosystems depends on dry season forage which has high spatiotemporal variability (Jacques et al., 2014). The timely monitoring of CC and AGB through synoptic-scale remote sensing is thus essential for forage estimation and in turn, determination of carrying capacity of livestock population enabling regulation of stocking rates for sustainable use of grassland resources (Rasmussen et al., 1999; Marsett et al., 2006). The impact of both climate and anthropogenic drivers on ecosystem structure and function as represented by CC and AGB is of significance to our understanding of carbon stocks of the Mongolian Plateau (MP)'s grassland ecosystems (Xie et al., 2009; Zhang et al., 2014).

Scientific investigations on estimating CC and AGB in semiarid environments over large extents (e.g. the Sahel and the MP) recommend sampling data over a range of vegetation types, biomes and vegetation zones over the growing season in order to obtain robust calibration models (Guan et al., 2012; Jacques et al., 2014; Ferner et al., 2015). Most grassland scale-up studies are limited in terms of measurements (Ma et al., 2010) or sampling extent along relatively short environmental gradients. Furthermore, very few studies cover different phenological stages of the growing season (Jacques et al., 2014; Ferner et al., 2015). Such surveys are both expensive and time-consuming and, therefore, satellite-based remote sensing using wide-swath sensors like the MODerate-resolution Imaging Spectroradiometer (*MODIS*) are especially valuable in remote areas of large areal extent like the MP for rapid acquisition of vegetation seasonal dynamics at the landscape and regional scales. Satellite-derived vegetation indices (VI) are considered as proxies of primary productivity and linearly related to several biophysical variables such as canopy cover (i.e., the proportion of surface unit area obscured by vegetation matter when viewed from above), leaf area, and chlorophyll (Tucker and Sellers, 1986). VIs from Landsat TM or MODIS obtained during the same month and year (Xie et al., 2009; Zhao et al., 2014) have been used to scale-up CC and AGB from the landscape to the regional scale through statistical models (Halperin et al., 2016; Zhang et al., 2016). However, these empirical models have serious drawbacks owing to uncertainties in their model coefficients which are site-specific and differ by ecosystem type and season. In addition, most CC and AGB scale-up models are based on the normalized difference vegetation index (NDVI), which is sensitive to the soil background signature and therefore not optimal for semiarid ecosystems with < 50% canopy cover (Huete et al., 2002; Chopping et al., 2008; Jacques et al., 2014). There have been few studies which focused on large area estimation of dry forage and canopy cover using dry vegetation VIs optimized for low cover conditions (e.g., enhanced vegetation index (EVI), normalized difference senescence vegetation index (NDSVI) (Marsett et al., 2006; Chopping et al., 2008; Jacques et al., 2014; Guerschman et al., 2015). The ability of MODIS-derived dry forage indices to estimate dry season biomass has also been limited due to the lack of representative, in situ data to serve as training data.

Non-parametric, data-mining/machine learning methods (e.g., Random Forest and Cubist) have been used in the recent past to scale-up net ecosystem production (NEP) and gross primary production (GPP) from eddy covariance towers (Xiao et al., 2010; Wylie et al., 2016). However, few studies have used RF or Cubist to scale-up from extensive, in situ samples of CC (Lehnert et al., 2015; Halperin et al., 2016) and fewer still for AGB scale-up (Blackard et al., 2008) to the national scale. Regression tree algorithms, and Cubist in particular are uniquely suited for dealing with nonlinear relationships, utilizing continuous and categorical variables, and modeling complex interactions (Xiao et al., 2010; Wylie et al., 2016). They also provide an alternative to precipitation driven, process based models which are limited by the spatial variability of rainfall and by the sparseness of meteorological stations in remote areas such as the Eurasian Steppe (Wylie et al., 2016). While regression trees are prone to overfitting, this drawback can be attenuated through cross validation and combining several rule-based models into committee models which are averaged for a final prediction (Xiao et al., 2008; Wylie et al., 2016).

Most scale-up studies on the MP are limited by extent as it is difficult to obtain in situ measurements while maintaining an adequate number for stratified random sampling (Feng et al., 2005; Gao et al., 2012; Zhao et al., 2014). A notable exception is a study where net ecosystem production was scaled up from eddy covariance flux towers and MODIS VIs in Inner Mongolia and surrounding provinces to obtain regional coverage using Cubist rule-based models (Zhang et al., 2014). There have been far fewer scaling up studies in Mongolia, which are limited temporally and in spatial extent (Angerer, 2012). Thus, there exists a knowledge gap regarding CC and AGB estimates that can be addressed by developing remote sensing products customized for the MP.

Here we investigate the relationships between extensive in situ measurements across the MP and VIs derived from the MODIS *Nadir BRDF Adjusted Reflectance* (*NBAR*) product using regression tree rule-based models. Our objectives were to: 1) develop non-parametric predictive models to scale-up CC and AGB using MODIS 500 m data along with ancillary variables across the entire MP; 2) model uncertainties and quantify inter-annual variability of peak season CC and AGB; and 3) explain the spatiotemporal heterogeneity of CC and AGB by examining the impact of anthropogenic drivers and inter-annual climatic variability.

2. Materials and methods

2.1. Study area

The MP covers approximately 2.7×10^6 km, bounded by 35°N -55°N latitude and 90°E-130°E longitude. The elevation of the MP varies greatly with an average elevation of over 1285 m and a relief of 4198 m. Mean annual temperature ranges from −4.5 °C to 8.6 °C (Yu et al., 2003; Nandintsetseg et al., 2007; Bai et al., 2008), while the mean annual precipitation (MAP) varies from 368 mm in the meadow steppe to 166 mm in the desert steppe, with up to 75% of annual rainfall occurring during the summer (JJA) (Rao et al., 2015). The plateau includes three steppe types, the meadow-mountain steppe, the typical steppe, and the desert steppe (25.1, 26.1 and 27.2% of the entire area, respectively) (Hilker et al., 2014; Wesche et al., 2016), with their distribution determined mostly by the precipitation gradient (Fig. 1). The typical steppe corresponds to the cold, semi-arid climate type (BSk) of the Köppen classification with a MAP of 300 mm. The typical steppe is predominantly herbaceous in nature with a vegetation cover of 25–100% that is characterized by *Stipa krylovii, Stipa grandis*, *Carex duriusula, Cleistogenes spp.*, *Leymus Chinenis*, and *Artemisia frigida* (in overgrazed areas). The meadow-mountain Steppe corresponds to the subarctic climate in the northeast with cool summers and severe dry winters (Dwc) in the Khangaii Mountains of Mongolia and the Greater Khingan Mountains in Inner Mongolia with a MAP of 400 mm. The meadow steppe consists of moist grasslands with high canopy cover of 60–90% (Liu et al., 2013), and herbaceous species that are less tolerant to drought, including species such as *Poa attenuata*, *Festucca lenensis*, *Stipa baicalensis*, *Filifolium sibiricum*, *Leymus Chinenis*, *Carex pediformis* and *Artemisia frigida* (Fernández-Giménez and Allen-Diaz, 1999; Khishigbayar et al., 2015). The desert steppe corresponds to the cold