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Estimating senesced biomass of desert steppe in Inner Mongolia using field spectrometric data

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ABSTRACT

The amount of senesced biomass in vegetation plays an important role in estimation of carbon storage and plant stress. In this paper, the spectral predictors for estimating senesced biomass were evaluated based on field spectral and corresponding biophysical parameter measurements during the growing seasons of 2009 and 2010 in the desert steppe of Inner Mongolia. Results showed the cellulose absorption index (CAI) was the best one among senesced vegetation coverage indices and band depth indices. The model involving CAI yielded the highest coefficient of determination (R^2 = 0.67) and the lowest root mean square error of leave-one-out cross validation (RMSECV = 17.9 g m^{-2}) compared with normalized difference index (NDI) (R^2 = 0.21, RMSECV = 27.6 g m^{-2}), soil-adjusted corn residue index (SACRI) (R^2 = 0.29, RMSECV = 26.2 g m^{-2}), modified soil-adjusted crop residue index (MSACRI) (R^2 = 0.1, RMSECV = 29.5 g m^{-2}), dead fuel index (DFI) (R^2 = 0.28, RMSECV = 26.3 g m^{-2}), lignocellulose absorption depth (LCD) (R^2 = 0.56, RMSECV = 20.5 g m^{-2}) and lignocellulose absorption area (LCA) (R^2 = 0.54, RMSECV = 21.1 g m^{-2}). The results of this study suggest that CAI has good potential to estimate senesced biomass in desert steppe areas.

1. Introduction

Estimating carbon storage of terrestrial ecosystems has been a central focus of research over the past two decades because of its importance to terrestrial carbon cycles and ecosystem processes. As one of the most widespread ecosystem types, accurate assessment of grass biomass is increasingly needed to reduce uncertainty for this terrestrial carbon sink (Fava et al., 2010). From a functional perspective, vegetation can be classified as senesced vegetation (standing dead plant and litter) and green vegetation (Guerschman et al., 2009). The amount of senesced biomass (standing dead biomass and litter biomass) in vegetation plays an important role in estimating carbon storage of grassland ecosystem (Numata et al., 2008). Many efforts to estimate senesced vegetation coverage have been made based on remotely sensed data during the past decades (Aase and Tanaka, 1991; McNairn and Protz, 1993; Biard et al., 1995; Daughtry et al., 1996, 2004, 2005, 2006; Asner and Lobell, 2000; Smith et al., 2000; Daughtry, 2001; Chevrier et al., 2002; Nagler et al., 2003). However, very few studies have been conducted to estimate senesced biomass based on remotely sensed data.

In contrast to step-function spectral reflectance curve of green vegetation, the reflectance spectra of both senesced vegetation and soils lack unique spectral feature in visible-near infrared (400–1100 nm) wavelength region (Aase and Tanaka, 1991; Daughtry et al., 1996). Senesced vegetation and soils are often spectrally similar and differ only in amplitude at a given wavelength (Baird and Baret, 1997), which makes discrimination between soils and senesced vegetation difficult or nearly impossible in visible-near infrared region. In short wavelength infrared region, a lignocellulose absorption pit near 2100 nm in the reflectance spectra of senesced vegetation has been observed and might have been caused by cellulose, hemicellulose, lignin, and other structural compounds (Elvidge, 1990; Roberts et al., 1993). The absorption feature near 2100 nm is not evident in the spectra of soils and green vegetation (Nagler et al., 2000; Daughtry, 2001; Streck et al., 2002). Based on this absorption feature, Daughtry et al. (1996) proposed a hyperspectral index, cellulose absorption index (CAI), to estimate crop residue and plant litter coverage. McNairn and Protz (1993) found that corn residue coverage was related to an NDVI-like TM band 4 and 5 normalized reflectance and then proposed normalized difference index (NDI). Further variations of this index are the soil-adjusted corn residue index (SACRI) (Biard et al., 1995) and the modified soil-adjusted crop residue index (MSACRI) (Bannari et al.,

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2000). Nevertheless, the TM-based indices were created based on only two components (senesced vegetation and soils) excluding green vegetation. Cao et al. (2010) therefore proposed a MODIS-based index, dead fuel index (DFI), to estimate senesced vegetation coverage based on three-component mixture. These indices were found effective for senesced vegetation coverage estimation under natural conditions and/or controlled conditions in the laboratory (McNairn and Protz, 1993; Biard et al., 1995; Bannari et al., 2000; Nagler et al., 2003; Daughtry et al., 2004, 2006; Cao et al., 2010). However, the potential of these indices for estimating senesced biomass has not to our knowledge been addressed by researchers and still remains to be examined.

Hyperspectral sensors provide a contiguous spectrum defined by a large number of spectral bands, typically measured across the optical wavelengths (350–2500 nm). Improved spectral dimensionality enhances quantification of physical attributes of vegetation and allows for the development of highly spectral indices (Numata et al., 2008). For example, band depth indices (i.e., absorption depth and area) calculated from continuum removal spectra have been used successfully to estimate biochemical parameters (Kokaly and Clark, 1999; Curran et al., 2001; Mutanga et al., 2004a) and biophysical parameters (Mutanga and Skidmore, 2004b; Chen et al., 2009). As discussed above, a lignocellulose absorption pit near 2100 nm in reflectance spectra of senesced vegetation has been observed. More importantly, there is deepening of the lignocellulose absorption pit with an increase in senesced vegetation coverage and biomass (Streck et al., 2002; Nagler et al., 2003). Therefore, an investigation of band depths in the lignocellulose absorption portion might provide more information on senesced biomass. To the best of our knowledge, very few studies have been conducted to explore the potential of this methodology to estimate senesced biomass.

Thus, this research objective was to ascertain the utilities of spectral indices (senesced vegetation coverage indices and band depth indices) for estimating senesced biomass. To achieve the objective, senesced biomass and hyperspectral data were collected in the desert steppe of Inner Mongolia during the growing seasons of 2009 and 2010.

2. Materials and methods

2.1. Study site

The experiment was conducted at Sonid Zuoqi temperate desert steppe ecosystem research station (44°05′19″N, 113°34′20″E, 972 m above sea level), Inner Mongolia, China. Long-term mean annual temperature is 3.1 °C with monthly mean temperature ranging from −18.7 °C in January to 22 °C in July. Long-term mean annual precipitation is approximately 185 mm with 85% distributed in the growing season (from May to September). According to the Chinese Soil Classification System, the soil at the study site is classified as brown calcic soil, which is equivalent to orthid and argid in the United State Soil Taxonomy (Gong et al., 1999). The desert steppe vegetation is dominated by *Stipa klemenzii* Roshev., and the main species are *Agropyron desertorum(Fisch.)* Schult., *Cleistogenes squarrosa(Trin.)* Keng, *Artemisia frigida* Willd.Sp.Pl., and *Caragana microphylia* Lam. The study site has been fenced since November 1997 and never under any management scheme.

2.2. Data collection

The campaigns were carried out during the growing seasons of 2009 and 2010. A simple random sampling method was adopted in the study. For the campaigns in 2009, the observed dates were 13–17 May, 6–11 June, 11–17 July, 6–13 August, and 16–20 September. In every campaign, 24 vegetation canopy plots and 1 bare soil plot of 0.5 m × 0.5 m were selected. For the campaign in 2010, the exact dates were between 23 and 30 August, 38 vegetation canopy plots of 0.5 m × 0.5 m were selected. All plots were located using a GPS system to avoid the same area of previous field campaigns.

All the canopy spectral measurements were taken on a clear day with no visible cloud cover between 11:30 and 14:00 (local time) using an Analytical Spectral Device (ASD) spectroradiometer, FieldSpec3 Pro FR (Analytical Spectral Device, Inc., Boulder, Colorado, USA). The spectroradiometer covers the range from 350 nm to 2500 nm, the sampling interval over 350–1050 nm range is 1.4 nm with a spectral resolution of 3 nm. Over 1050–2500 nm range, the sampling interval is 2 nm and the spectral resolution is between 10 nm and 12 nm. The results are interpolated by the ASD software to produce readings at every 1 nm. The sensor, with a field of view of 25°, was mounted on a tripod and positioned 1.2 m above vegetation canopies at nadir position, which allowed coverage of a circular area with a diameter of about 0.5 m. Thirty replicates were taken for each canopy spectral measurement, and the averaged reflectance was used for the analyses. Prior to each measurement, the radiance of a white standard panel coated with $BaSO_4$ was recorded for normalization of the target measurements.

The senesced biomass (standing dead biomass and litter biomass) was collected using tradition agronomic methods, and then was dried at 65 °C for 48 h. During the process, three grass samples were damaged and in total 155 grass samples were remained for the analysis. To avoid mismatch between the field of view and 0.5 m × 0.5 m quadrat of biomass measurements, a reference stack was placed at each measurement plot for collecting biomass after ASD measures. Senesced biomass was determined by dividing the weight of the dried senesced biomass by the surface area of the plot ($g\,m^{-2}$).

2.3. Methods

2.3.1. Data analysis

Two main approaches were adopted in this study: (i) senesced vegetation coverage indices (CAI, NDI, SACRI, MSACRI, and DFI) and (ii) band depth indices (lignocellulose absorption depth and lignocellulose absorption area). No saturation problem was found in the relationships between the various spectral predictors and ground-collected senesced biomass, so linear regression analyses were performed to verify which predictor is the most appropriate for monitoring senesced biomass of desert steppe. The performance of the various spectral predictors was compared using the explained variance (coefficient of determination, R^2) and the prediction error (the root mean square error of leave-one-out cross-validation, RMSECV).

In leave-one-out cross-validation, each sample is excluded in turn and the regression model is calculated with all the remnants samples and used to predict that sample. Benefits of the leave-one-out cross-validation are its aptitude to detect outliers and its capability of providing nearly unbiased estimations of the prediction error (Efron and Gong, 1983; Schlerf et al., 2005).

2.3.2. Senesced vegetation coverage indices

In this study, CAI, NDI, SACRI, MSACRI, and DFI were selected to evaluate their performance in senesced biomass estimation.

CAI is determined via the following equation (Daughtry et al., 1996):

$$\mathrm{CAI} = [0.5 \times (R_{2.0} + R_{2.2}) - R_{2.1}] \times 100 \quad (1)$$

where, $R_{2.0}$, $R_{2.1}$, and $R_{2.2}$ are mean reflectance at 2000–2050 nm, 2080–2130 nm, and 2190–2240 nm, respectively. To enhance the discrepancies, the CAI values were multiplied by 100.