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

Hongrui Ren\textsuperscript{a},\textsuperscript{b}, Guangsheng Zhou\textsuperscript{c},\textsuperscript{a,\textasteriskcentered}

\textsuperscript{a} State Key Laboratory of Vegetation and Environmental Change, Institute of Botany, The Chinese Academy of Sciences, Beijing 100093, China
\textsuperscript{b} Graduate School of the Chinese Academy of Sciences, Beijing 100049, China
\textsuperscript{c} Chinese Academy of Meteorological Sciences, Beijing 100081, China

\textbf{A R T I C L E   I N F O}

Article history:
Received 15 September 2011
Received in revised form 24 February 2012
Accepted 18 March 2012

Keywords:
Senesced biomass
Desert steppe
Remote sensing
CAI
Continuum removal

\textbf{A B S T R A C T}

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.

\textsuperscript{\textasteriskcentered} Corresponding author at: State Key Laboratory of Vegetation and Environmental Change, Institute of Botany, The Chinese Academy of Sciences, Nanxincun Xiangshan, Haidian District, Beijing 100093, China. Tel.: +86 10 62836268; fax: +86 10 82595862.
\textit{E-mail address:} gzhou@ibcas.ac.cn (G. Zhou).

© 2012 Elsevier B.V. All rights reserved.

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; Daugtry et al., 1996, 2004, 2005, 2006; Asner and Lobell, 2000; Smith et al., 2000; Daugtry, 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; Daugtry 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; Daugtry, 2001; Streck et al., 2002). Based on this absorption feature, Daugtry 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.,...
2.1. Caragana et in objective, is distributed (McNairn 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 Zuqi 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 squarrosoa* (Trin.) Keng, *Artemisia frigida* Willd.Sp.Pl., and *Caragana microphylla* 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 BaSO4 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, R²) 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 remaining 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; Schleifer 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):

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

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.
NDI, SACRI, and MSACRI are determined via the following equations (McNairn and Prozt, 1993; Biard et al., 1995; Bannari et al., 2000):

\[
\text{NDI} = \frac{R_4 - R_5}{R_4 + R_5} \quad (2)
\]

\[
\text{SACRI} = \frac{\alpha(R_4 - R_5 - \beta)}{\alpha R_4 + R_5 - \alpha \beta} \quad (3)
\]

\[
\text{MSACRI} = C \times \frac{\alpha(R_5 - \alpha R_7 - \beta)}{\alpha R_5 + R_7 - \alpha \beta} \quad (4)
\]

where, \(R_4\), \(R_5\), and \(R_7\) are reflectance at TM bands 4, 5, and 7, respectively; \(\alpha\) and \(\beta\) are the slope and intercept of the soil line equation, respectively; \(C\) is multiplicative constant which is equal to 5. Spectral resampling from ASD FieldSpec channels to TM sensor was performed using the spectral resampling routine available on ENVI 4.3 software (Research Systems, Inc.). Sensor-specific spectral response functions were set for TM channels. To calculate SACRI and MSACRI, soil line was obtained using five soil specimens collected in 2009 based on the simulated TM bands 3 and 4.

DFI is determined via the following equation (Cao et al., 2010):

\[
\text{DFI} = 100 \left(1 - \frac{R_7}{R_6}\right) \left(\frac{R_1}{R_2}\right) \quad (5)
\]

where, \(R_1\), \(R_2\), \(R_6\), and \(R_7\) are the reflectance in MODIS bands 1, 2, 6, and 7, respectively. Spectral resampling from the ASD FieldSpec channels to MODIS sensor was performed using the spectral resampling routine available on ENVI 4.3 software (Research Systems, Inc.). Sensor-specific spectral response functions were set for MODIS channels.

2.3.3. Band depth indices

Band depth analysis was done on continuum removed spectrum between 2015 nm and 2155 nm in our study (Fig. 1). The selected region is mainly influenced by lignocellulose absorption. Continuum removal was applied in the lignocellulose absorption pit in order to isolate that absorption feature and enhance differences in absorption. The continuum is a convex hull fitted over the top of a spectrum utilizing straight-line segments that connect local spectral maxima (Mutanga and Skidmore, 2004b).

The continuum removed spectrum \(R'\) was obtained by dividing the reflectance value \(R\) for each point in the absorption pit by the reflectance level of the continuum line \(R_c\) at the corresponding wavelength. The output curves had values between zero and one, in which the absorption pits were enhanced and the absolute variance removed (Schmidt and Skidmore, 2003).

Fig. 2 shows the band depth (BD) that was calculated from the continuum removed spectrum using the following equation:

\[
\text{BD} = 1 - R' = 1 - \frac{R}{R_c} \quad (6)
\]

where, BD is band depth; \(R'\) is continuum removed spectrum; \(R\) is original reflectance value in the absorption pit; \(R_c\) is reflectance value of continuum line at the corresponding wavelength.

In this study, the lignocellulose absorption depth (LCD) and lignocellulose absorption area (LCA) were selected to evaluate their performance for estimating senesced biomass (Numata et al., 2008). They were determined via the following equations:

\[
\text{LCD} = \max(\text{BD}_2015\text{–}2155) \quad (7)
\]

\[
\text{LCA} = \sum_{i=2015}^{2155} \text{BD}_i \quad (8)
\]

where, \(\text{BD}_i\) is band depth at band \(i\).

![Fig. 1. Lignocellulose absorption feature illustrated on the mean reflectance spectrum (n = 155). The continuum is located between 2015 nm and 2155 nm.](image)

![Fig. 2. Mean band depth profile for lignocellulose absorption feature (n = 155).](image)

![Fig. 3. Linear regression between senesced biomass and cellulose absorption index (CAI).](image)
3. Results

3.1. Senesced vegetation coverage indices

The performance of five senesced vegetation coverage indices for monitoring senesced biomass of desert steppe is presented in Figs. 3 and 4 and Table 1. All the relationships were statistically significant at P<0.01. The CAI produces higher coefficient of determination ($R^2 = 0.67$) and lower root mean square error of leave-one-out cross validation (RMSECV = 17.9 g m$^{-2}$) compared with other indices which yielded $R^2$ and RMSECV values of less than 0.3 and more than 26 g m$^{-2}$, respectively. Among the five indices, the MSACRI showed the lowest $R^2$ (0.1) and the highest RMSECV (29.5 g m$^{-2}$).

The CAI could explain 67% of senesced biomass and improved the senesced biomass estimation capability in our study area by about 45% compared with other senesced vegetation coverage indices. The results indicate that the CAI, widely used for monitoring senesced vegetation coverage, is equally effective for monitoring senesced biomass of desert steppe, and other indices (NDI, SACRI, MSACRI, and DFI) have limitations in estimation senesced biomass in our study area.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Performance of senesced vegetation coverage indices for senesced biomass estimation (n=155).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Senesced vegetation coverage indices</td>
<td>$R^2$</td>
</tr>
<tr>
<td>CAI</td>
<td>0.67</td>
</tr>
<tr>
<td>NDI</td>
<td>0.21</td>
</tr>
<tr>
<td>SACRI</td>
<td>0.29</td>
</tr>
<tr>
<td>MSACRI</td>
<td>0.10</td>
</tr>
<tr>
<td>DFI</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Fig. 4. Linear regression between senesced biomass and four senesced vegetation coverage indices.
Table 2

<table>
<thead>
<tr>
<th>Band depth indices</th>
<th>$R^2$</th>
<th>$P$</th>
<th>RMSECV (g.m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCD</td>
<td>0.56</td>
<td>&lt;0.01</td>
<td>20.5</td>
</tr>
<tr>
<td>LCA</td>
<td>0.54</td>
<td>&lt;0.01</td>
<td>21.1</td>
</tr>
</tbody>
</table>

3.2. Band depth indices

A comparative analysis of the performance of LCD and LCA for monitoring senesced biomass of desert steppe is presented in Fig. 5 and Table 2. The relationships between senesced biomass and band depth indices (LCD and LCA) were statistically significant at $P < 0.01$. The LCD showed a slightly better performance than LCA for monitoring senesced biomass of desert steppe. The regression model involving LCD produced a higher $R^2$ (0.56) and a lower RMSECV (20.5 g.m$^{-2}$) compared with LCA which yielded $R^2$ and RMSECV values of 0.54 and 21.1 g.m$^{-2}$, respectively.

Compared with senesced vegetation coverage indices, although the performance of LCD and LCA for senesced biomass estimation was better than that of NDI, SACRI, MSACRI, and DFI, the performance was not better than that of CAI. Thus, the CAI appeared to be the best indicator at estimating senesced biomass of desert steppe in our study area.

4. Discussion

The present study demonstrates the utilities of different spectral indices for monitoring senesced biomass of the desert steppe in Inner Mongolia. The performance of CAI was better than that of four multispectral senesced vegetation coverage indices (NDI, SACRI, MSACRI, and DFI) and two band depth indices (LCD and LCA).

A comprehensive evaluation by Daughtry et al. (2005) found that CAI was easily affected by green vegetation. Because water is the primary absorber in short wavelength infrared region, the high moisture content of green vegetation significantly attenuated the reflectance signal from the absorption features near 2100 nm (Gao and Goetz, 1994; Murphy, 1995). Daughtry et al. (2004) also found that, small fractions of green vegetation (<30%) in the scene have little effect on the overall estimation accuracy, but as the fraction of green vegetation (>30%) in the scene increased, the errors for estimating senesced vegetation coverage using CAI increased. In our study, green vegetation coverage within each sampling plot was less than 30%. Therefore, it is necessary to explore the utility of CAI for monitoring senesced biomass of grassland with a high fraction of green vegetation, which is work we will do in the future.

The TM-based senesced vegetation coverage indices (NDI, SACRI, and MSACRI) were not reliable predictors for senesced biomass in our study area (Fig. 4 and Table 1). The results were consistent with those of Cao et al. (2010) who reported that NDI, SACRI, and MSACRI were unsuitable to discriminate senesced vegetation from green vegetation and soils in a study of senesced vegetation coverage estimation. The main reason was that, these indices were created based on only two components (senesced vegetation and soils) excluding green vegetation, which limits their application in three-component mixture of senesced vegetation, green vegetation and soils.

Theoretically, the MODIS-based DFI should be a good tool for estimating senesced biomass in our study area because the index was created based on three-component mixture of green vegetation, senesced vegetation and soils. The index was also proven to have good potential to estimate senesced vegetation coverage in steppe areas (Cao et al., 2010). Unfortunately, DFI was not reliable predictor for senesced biomass in our study area (Fig. 4 and Table 1). The possible explanation was that, DFI was developed using numerical simulation under controlled environmental conditions, and has not been validated under natural conditions so far.

The coefficients of determination ($R^2$) calculated from linear regressions between senesced biomass and LCD and LCA were 0.56 and 0.54, respectively, in our study area. The results were better than those of Numata et al. (2008) who reported lower correlations (0.28 and 0.29, respectively) for pasture senesced biomass in the Brazilian Amazon. Furthermore, Numata et al. (2008) found that, there was a trend of saturation of LCD above 200 g.m$^{-2}$ of senesced biomass observed in B. brizantha, and the relationship can be better expressed by non-linear trend. In this study, no trend of saturation was found in the relationships between LCD and LCA and senesced biomass. The values of senesced biomass sampled on the ground

![Fig. 5. Linear regression between senesced biomass and two band depth indices.](image-url)
were less than 200 g m⁻² in our study. However, is there a trend of saturation of LCD and LCA if the values of senesced biomass in our study area are more than 200 g m⁻²? This is also work we will do in the future.

5. Conclusions

This study applied five senesced vegetation coverage indices and two band depth indices to estimate senesced biomass in the desert steppe of Inner Mongolia. The hyperspectral index, CAI, performed better than any other method tested in this study. The TM-based NDI, SACRI, and MSACRI and MODIS-based DFI were not reliable predictors for senesced biomass in our study area. Continuum removal is a useful normalization tool that enhances band depth differences, thereby providing some improvements over TM-based NDI, SACRI, and MSACRI and MODIS-based DFI. It should be noted that such estimation based on an empirical model might be site- or time-specific and unsuitable for application to different spatial and temporal scales.

Further research is necessary to assess the performance of CAI for estimating senesced biomass of grassland with a high green vegetation coverage (>30%). Compared with the pixel size of satellite/airborne remotely sensed data, the sampling area in our study is small. Moreover, the atmospheric conditions and spectral resolutions are also different. Therefore, based on remotely sensed images with high spectral resolution, additional research on estimating senesced biomass is still needed to validate the CAI. In addition, the efficacy of CAI for predicting senesced biomass of other vegetation covers such as crop and shrub also needs to be established.

Acknowledgments

This research was jointly supported by State Key Development Program of Basic Research (2010CB951303) and National Natural Science Foundation of China (90711001, 40971123).

References


