European Journal of Remote Sensing

ISSN: (Print) 2279-7254 (Online) Journal homepage: https://www.tandfonline.com/loi/tejr20

Determination of green aboveground biomass in desert steppe using litter-soil-adjusted vegetation index

Hongrui Ren & Guangsheng Zhou

To cite this article: Hongrui Ren & Guangsheng Zhou (2014) Determination of green aboveground biomass in desert steppe using litter-soil-adjusted vegetation index, European Journal of Remote Sensing, 47:1, 611-625, DOI: 10.5721/EuJRS20144734

To link to this article: https://doi.org/10.5721/EuJRS20144734

Published online: 17 Feb 2017.

European Journal of Remote Sensing - 2014, 47: 611-625

doi: 10.5721/EuJRS20144734

Received 31/10/2013, accepted 18/07/2014

European Journal of Remote Sensing

An official journal of the Italian Society of Remote Sensing

www.aitjournal.com

Determination of green aboveground biomass in desert steppe using litter-soil-adjusted vegetation index

Hongrui Ren[1] and Guangsheng Zhou[2,3]*

[1]Department of Science and Technology of Surveying and Mapping,
College of Mining Engineering, Taiyuan University of Technology, No. 79, West Yingze Street,
Wanbailin District, 030024, Taiyuan, Shanxi, China
[2]Chinese Academy of Meteorological Sciences, No. 46, Zhongguancun South Street,
Haidian District, 100081, Beijing, China
[3]State Key Laboratory of Vegetation and Environmental Change, Institute of Botany,
Chinese Academy of Sciences, No. 20 Nanxincun Xiangshan, Haidian District, 100093, Beijing, China
*Corresponding author, e-mail address: gszhou@ibcas.ac.cn

Abstract

Accurate estimation of green aboveground biomass in arid and semiarid grassland is essential for a variety of studies, such as sustainable grassland management, fire risk assessment, climate change, and environmental degradation. A great need exists for the establishment of robust method for estimating green aboveground biomass in arid and semiarid grassland due to the influences of soil background and litter. In the study, a new index (litter-soil-adjusted vegetation index, L-SAVI) was proposed to estimate green aboveground biomass in arid and semiarid grassland. The L-SAVI was also evaluated based on biomass and spectra *in situ* measurements in the desert steppe of Inner Mongolia. Results showed that, the performance of the new index was better than that of NDVI (normalized difference vegetation index), SAVI (soil-adjusted vegetation index), MSAVI (modified soil-adjusted vegetation index), OSAVI (optimised soil-adjusted vegetation index), TSAVI (transformed soil-adjusted vegetation index), ATSAVI (adjusted transformed soil-adjusted vegetation index), PVI (perpendicular vegetation index), GSAVI (green-adjusted vegetation index), and L-ATSAVI (litter-corrected ATSAVI) in our study site. The logic behind the L-SAVI was to enable the SAVI to be less sensitive to litter by incorporating the CAI (cellulose absorption index) in the SAVI. In conclusion, the L-SAVI is a suitable predictor for complementing existing vegetation indices on green aboveground biomass estimation in arid and semiarid grassland.

Keywords: Green aboveground biomass, desert steppe, field spectrometry, litter-soil-adjusted vegetation indices, cellulose absorption index.

Introduction

Grassland is one of the most widespread ecosystem types, and accurate estimation of grassland green aboveground biomass is increasingly needed to reduce uncertainty of this terrestrial carbon sink [Scurlock and Hall, 1998; Scurlock et al., 2002], especially in arid and semiarid areas [Cui et al., 2011; Fang et al., 2010; Eisfelder et al., 2012]. Green aboveground biomass is also a key ecological variable in arid and semiarid grassland [Eisfelder et al., 2012], and influences important environmental processes, such as soil erosion, environmental degradation, and desertification [Verstraete, 1986; Eswaran et al., 2001; Hirata et al., 2001; Moleele et al., 2001; Mulligan, 2009]. Therefore, a great need exists for the establishment of robust and transferable methods for green aboveground biomass estimation in arid and semiarid grassland. Traditional methods of aboveground green biomass estimation based on destructive sampling are expensive, time-consuming, and feasible only to small-scale biomass survey.

Remote sensing techniques offer an effective solution for accurately estimating green aboveground biomass in grassland [Schino et al., 2003; Liu et al., 2004; Elsfelder et al., 2012]. Vegetation indices calculated from red and near-infrared (NIR) bands are good indicators of vegetation photosynthetic activity [Myneni and Los, 1995; Myneni et al., 1995; Liu et al., 2013; Marino and Alvino, 2014], and are well correlated to green aboveground biomass in grassland [Schino et al., 2003; Ren et al., 2011]. The well-known vegetation index, now widely used for green aboveground biomass estimation in grassland [Wessels et al., 2006; An et al., 2013; Gao et al., 2013; Jin et al., 2014; Xia et al., 2014], is normalized difference vegetation index (NDVI) [Rouse et al., 1974]. However, the index loses its utility for estimating green aboveground biomass in sparse vegetation canopy situation because of prominent contribution of soil background [Boschetti et al., 2007]. Based on the algorithm of NDVI, Huete [1988] therefore proposed soil-adjusted vegetation index (SAVI) to minimize soil background influence by incorporating a correcting factor. Further evolutions of the SAVI are the modified soil-adjusted vegetation index (MSAVI) [Qi et al., 1994], optimised soil-adjusted vegetation index (OSAVI) [Rondeaux et al., 1996], transformed soil-adjusted vegetation index (TSAVI) [Baret et al., 1989], adjusted transformed soil-adjusted vegetation index (ATSAVI) [Baret and Guyot, 1991], perpendicular vegetation index (PVI) [Richardson and Wiegand, 1977], and green-adjusted vegetation index (GSAVI) [Tian et al., 2005]. Among these soil-adjusted vegetation indices, the TSAVI, ATSAVI, and PVI were developed to minimize soil background influence by incorporating the slope and intercept of the soil line, which was established by linear regression of soil reflectance in red-NIR spectral portions. Compared with the soil-adjusted SAVI, MSAVI, OSAVI, and GSAVI, the algorithms of TSAVI, ATSAVI, and PVI containing the soil line parameters greatly limit their applications due to the difficulty of obtaining the real soil line [Baret et al., 1993; Fox et al., 2004; Liu et al., 2008].

The contribution of the litter is another prominent barrier to the determination of green aboveground biomass in arid and semiarid grassland, where the litter is a large vegetation component [Van Leeuwen and Huete, 1996; Asner et al., 1998; Guo, 2002; He et al., 2006; Ren and Zhou, 2012]. He et al. [2006] therefore proposed the litter-corrected ATSAVI (L-ATSAVI) to minimize litter influence by incorporating cellulose absorption index (CAI) in the ATSAVI. The CAI was developed by Daughtry et al. [1996] to estimate crop residue coverage based on lignocellulose absorption feature near 2100 nm [Daughtry et al., 2004, 2005, 2006], and was also found effective for estimating litter coverage and litter mass in grassland [Cao et al. 2010; Ren and Zhou, 2012]. Results of He et al. [2006] showed that, the L-ATSAVI improved leaf area index estimation accuracy in a mixed grassland ecosystem by about 10%. As with the ATSAVI, the algorithm of the L-ATSAVI contains the slope and intercept of the soil line, which may limit its applications.

Thus, the objectives of our study were to: (1) propose a practical vegetation index (litter-corrected SAVI, L-SAVI), which does not contain the soil line parameters, for estimating green aboveground biomass in arid and semiarid grassland, and (2) compare the performance of L-SAVI with that of litter-soil-adjusted L-ATSAVI, soil-unadjusted NDVI, and soil-adjusted SAVI, MSAVI, OSAVI, TSAVI, ATSAVI, PVI, and GSAVI. To achieve these objectives, green aboveground biomass and spectra measurements were conducted in an desert steppe of Inner Mongolia.

Materials and methods

Study area

Green aboveground biomass and spectra measurements were carried out in the late August 2010 at the Sonid Zuoqi desert steppe ecosystem research station (latitude: 44°05’19”N, longitude: 113°34’20”E, altitude: 972 m) (Fig. 1). The study site, which has been fenced to prevent grazing and to protect the plant communities from other disturbances, has flat topography and uniform vegetation distribution, and covers a total area of about 50 hectares. The site has arid and semiarid temperate continental climate. According to long-term climate data (1960-2000) from a nearest meteorological station (latitude: 43°52’01”N, longitude: 113°37’59”E, altitude: 1037 m) in Sonid Zuoqi, mean annual temperature is 3.1°C, and mean annual precipitation is 185 mm, 60-80% of which occurs during growing season (from May to September). As a typical temperate desert steppe ecosystem on the Mongolia Plateau, the vegetation is dominated by *Stipa klemenzii* Roshev. The main species are *Caragana microphylia* Lam., *Agropyron desertorum (Fisch.)* Schult., *Artemisia frigida* Willd.Sp.Pl., and *Cleistogenes squarrosa(Trin.)* Keng. According to United States Department of Agriculture Soil Taxonomy [USDA, 1999], the soil in our study site is classified as argids (suborder) of aridisols (order).

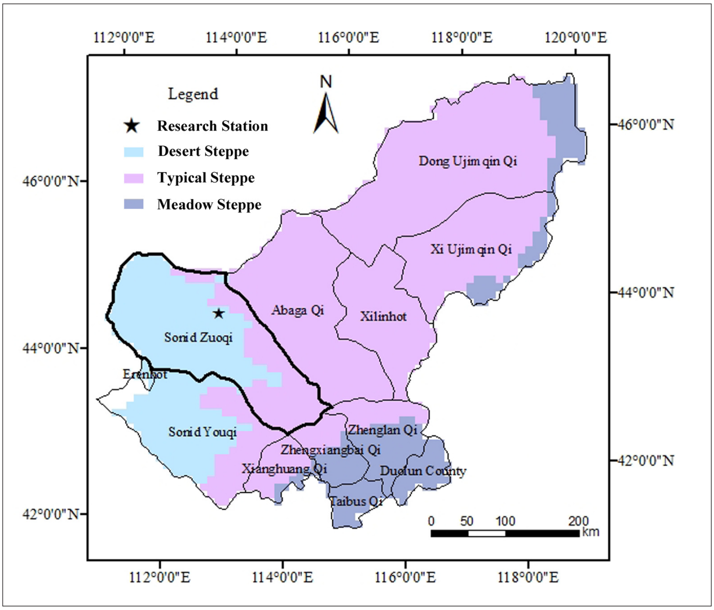

Figure 1 - Location of Sonid Zuoqi desert steppe ecosystem research station (The distributions of desert steppe, typical steppe, and meadow steppe are derived from “Vegetation Regionalization Map of China” (1:1 million) compiled by the Editorial Board of Vegetation Map of China [Zhang, 2007]).

Data collection

A total of 38 plots (0.5 m × 0.5 m) were randomly selected for green aboveground biomass and spectra investigation in the study site. The distance between the plots was about tens of meters to a few hundred meters. The plots could represent the study site well in green aboveground biomass due to the spatial homogeneity of the desert steppe ecosystem. Canopy hyperspectral investigations were conducted using an ASD portable spectroradiometer (Analytical Spectral Device, Inc., Boulder, Colorado, USA) and a white standard panel under clear and sunny environments between 11:30 and 14:00 h local time. The spectroradiometer can provide 2151 bands spectral reflectance with a spectral resolution of 1 nm wavelength between 350 nm and 2500 nm. In our study, the spectroradiometer was located at about 1.2 m above ground surface at nadir position with a field of view (FOV) of 25°. Canopy spectrum of each plot was calculated as the average of all thirty replicates. The replicates were done by one after another. The white standard panel was used to normalize the target investigations. After canopy spectra measurements, all living vascular plant and litter within each plot were collected at the ground level using traditional agronomic methods, and then was dried at 65°C for 48 hours. Green aboveground biomass (g m^{-2}) and litter mass (g m^{-2}) of each plot were calculated by dividing the dry weight of the living vascular plant and litter by the area of the plot.

Vegetation indices

In the present study, similar to the L-ATSAVI, we proposed a litter-adjusted SAVI (L-SAVI) to estimate green aboveground biomass in arid and semiarid grassland by incorporating CAI as a adjustment factor in the SAVI. The logic behind the SAVI was to enable NDVI to be less sensitive to soil background influence. The logic behind the L-SAVI was to enable SAVI to be less sensitive to litter influence. We also compared the performance of L-SAVI with that of soil-unadjusted NDVI, soil-adjusted SAVI, MSAVI, OSAVI, TSAVI, ATSAVI, PVI, and GSAVI, and litter-soil-adjusted L-ATSAVI. These vegetation indices were calculated by the following equation.

$$L-SAVI=\frac{1.5\times(1+L\times CAI)\times(R_{NIR}-R_{red})}{R_{NIR}+R_{red}+0.5+L\times CAI} \qquad [1]$$

$$CAI=100\times(\frac{R_{2000}+R_{2200}}{2}-R_{2100}) \qquad [2]$$

$$NDVI=\frac{R_{NIR}-R_{red}}{R_{NIR}+R_{red}} \qquad [3]$$

$$SAVI=1.5\times\frac{R_{NIR}-R_{red}}{R_{NIR}+R_{red}+0.5} \qquad [4]$$

$$MSAVI = 0.5 \times ((2 \times R_{NIR} + 1) - \sqrt{(2 \times R_{NIR} + 1)^2 - 8 \times (R_{NIR} - R_{red}))} \quad [5]$$

$$OSAVI = 1.16 \times \frac{R_{NIR} - R_{red}}{R_{NIR} + R_{red} + 0.16} \quad [6]$$

$$TSAVI = \frac{a \times (R_{NIR} - a \times R_{red} - b)}{a \times R_{NIR} + R_{red} + a \times b} \quad [7]$$

$$ATSAVI = \frac{a \times (R_{NIR} - a \times R_{red} - b)}{a \times R_{NIR} + R_{red} - a \times b + 0.08 \times (1 + a^2)} \quad [8]$$

$$PVI = \frac{R_{NIR} - a \times R_{red} - b}{\sqrt{1 + a^2}} \quad [9]$$

$$GSAVI = 1.5 \times \frac{R_{NIR} - R_{green}}{R_{NIR} + R_{green} + 0.5} \quad [10]$$

$$L - ATSAVI = \frac{a \times (R_{NIR} - a \times R_{red} - b)}{a \times R_{NIR} + R_{red} - a \times b + 0.08 \times (1 + a^2) + 10 \times (\frac{R_{2000} + R_{2200}}{2} - R_{2100})} \quad [11]$$

where R_{NIR} is mean reflectance at 760-900 nm, R_{red} is mean reflectance at 630-690 nm, R_{green} is mean reflectance at 520-600 nm, R_{2000} is mean reflectance at 2000-2050 nm, R_{2100} is mean reflectance at 2080-2130 nm, R_{2200} is mean reflectance at 2190-2240 nm, L is the adjustment factor, *a* is the slope of soil line, and *b* is the intercept of soil line. In our study site, *a* = 1.0448 and *b* = 0.0475. In the L-SAVI, we multiplied CAI L times to adjust litter effects. The value of L is different with various proportion of litter, green plant, and soil.

Data analysis

All L-SAVIs were computed with different values of L from -0.5 to 0.5 at an interval of 0.05 to explore the relationships between green aboveground biomass and L-SAVIs in our study site. The optimal L-SAVI was determined by coefficient of determination (R^2) from linear regression. In our study, no saturation problem arose in the relationships between vegetation indices and green aboveground biomass due to sparse green vegetation cover. Thus, linear regression analyses were employed to examine the performance of these vegetation indices for green aboveground biomass estimation. The efficiency of models was assessed by R^2, root mean squared error (RMSE), and relative error (RE). All the analyses were carried out in R statistical language [R Development Core Team, 2012].

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - y_i')^2} \qquad [12]$$

$$\mathrm{RE} = \frac{\mathrm{RMSE}}{y} \times 100\% \qquad [13]$$

where y_i is measured green aboveground biomass of plot i, y_i' is predicted green aboveground biomass of plot i, n is the number of plots, and y is mean value of green aboveground biomass of all plots.

Results

Statistics of measured biomass and spectral reflectance

As a precursor to the results, the statistics of measured green aboveground biomass and litter mass were performed (Tab. 1). As expected, green aboveground biomass and litter mass showed wider variation among the sampled plots. Green aboveground biomass ranged from 25.2 g m^{-2} to 110.4 g m^{-2} with an average of 59.1 g m^{-2}, while litter mass varied from 21.2 g m^{-2} to 154 g m^{-2} with an average of 75.8 g m^{-2}. The wider variation was planned to make the relationships between green aboveground biomass and vegetation indices as universal and realistic as possible.

Table 1 - Descriptive statistics of measured green aboveground biomass and litter mass (n = 38) in the desert steppe of Inner Mongolia.

	Green aboveground biomass	Litter mass
Mean (g m^{-2})	59.1	75.8
Standard deviation (g m^{-2})	20.0	32.4
Minimum (g m^{-2})	25.2	21.2
Maximum (g m^{-2})	110.4	154.0

As shown in Figure 2, the reflectance spectra collected in our study site did not have the typical pattern of green plant spectrum, namely lower values in the red wavelengths due to chlorophyll absorption and higher values in the NIR wavelengths, attributable to mesophyll scattering. Although the reflectance spectra showed water absorption pits in the shortwave-infrared (SWIR) wavelengths, the absorption strength was not as strong as that of green plant spectrum. In addition, the differences in reflectance values in the NIR and SWIR wavelengths was much larger than that in the visible wavelengths.

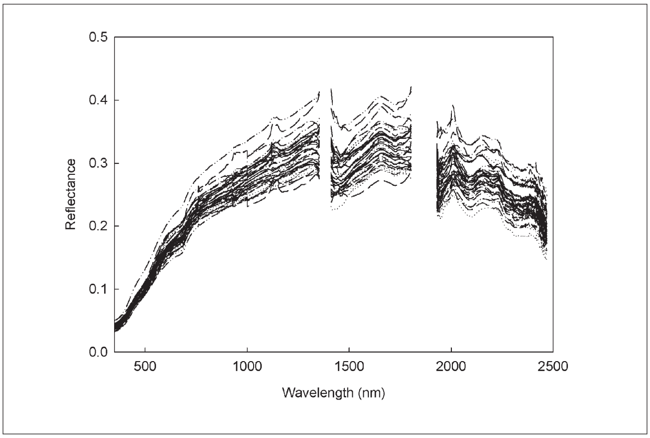

Figure 2 - Canopy reflectance of 38 plots in the desert steppe of Inner Mongolia. The reflectance at atmosphere window (1361-1395 nm, 1811-1925 nm, and 2475-2500 nm) was excluded in the figure.

Optimal L-SAVI determination

All values of L-SAVIs were calculated with different values of L from -0.5 to 0.5 at an interval of 0.05. The R^2 obtained from linear regressions between green aboveground biomass and all L-SAVIs are presented in Figure 3. Results showed that, the values of R^2 severely decreased with decreasing values of L when the values of L were less than -0.25, and the values of R^2 slowly decreased with increasing values of L when the values of L were more than -0.25. The maximum of R^2 (0.56) was achieved when a value of L = -0.25 was employed in the L-SAVI. The performance of optimal L-SAVI for estimating green aboveground biomass in our study site is presented in Figure 4. The regression relation was statistically significant at $P < 0.001$. The R^2, RMSE, and RE of regression model based on optimal L-SAVI were 0.56, 13.39 g m^{-2}, and 22.7%, respectively.

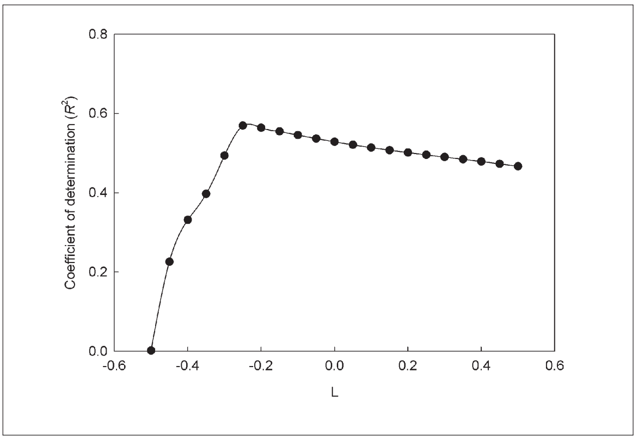

Figure 3 - Coefficients of determination (R^2) of linear regressions between green aboveground biomass and all L-SAVIs based on different values of L.

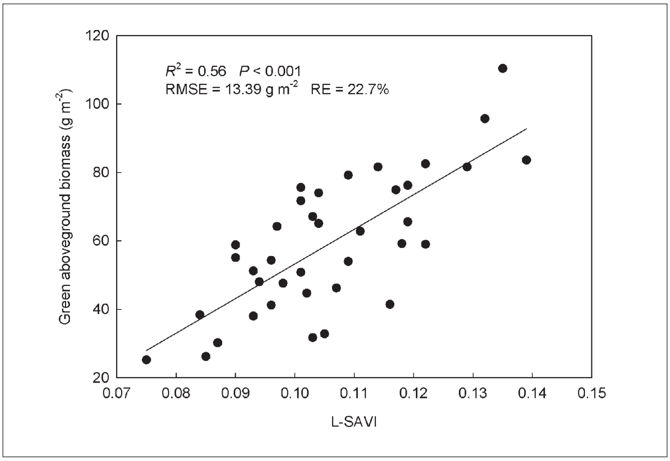

Figure 4 - Linear regression between green aboveground biomass and optimal L-SAVI.

Comparison of optimal L-SAVI with other vegetation indices

A comparative analysis of the performance of these soil-unadjusted, soil-adjusted and litter-soil-adjusted vegetation indices is presented in Table 2. The regression models were all statistically significant at $P < 0.001$. Among these vegetation indices, the soil-adjusted GSAVI yielded the lowest estimation accuracy (R^2 = 0.32, RMSE = 16.42 g m^{-2}, RE = 27.2%) (Fig. 5h), and did not make any improvements over soil-unadjusted NDVI (R^2 = 0.46, RMSE = 14.66 g m^{-2}, RE = 24.8%) (Fig. 5a). Among seven soil-adjusted vegetation indices, the SAVI (Fig. 5b) and OSAVI (Fig. 5d) produced the highest accuracy (R^2 = 0.52, RMSE = 13.9 g m^{-2}, RE = 23.5%) in our study site. The litter-soil-adjusted L-ATSAVI (Fig. 5i) showed better performance for estimating green aboveground biomass, and yielded higher R^2 (0.54), lower RMSE (13.74 g m^{-2}), and lower RE (23.2%) than these soil-unadjusted and soil-adjusted vegetation indices.

Table 2 - Linear regression analyses between green aboveground biomass and vegetation indices. Y represents green aboveground biomass, and x represents vegetation index.

Vegetation indices	Regression model	R^2	RMSE (g m^{-2})	RE (%)	P
NDVI	y = 896.2x – 75.5	0.46	14.66	24.8	<0.001
SAVI	y = 1256.3x – 68.8	0.52	13.89	23.5	<0.001
MSAVI	y = 1303.2x – 57.5	0.49	14.23	24.1	<0.001
OSAVI	y = 1109.1x – 80.0	0.52	13.88	23.5	<0.001
TSAVI	y = 606.0x + 48.5	0.48	14.47	24.5	<0.001
ATSAVI	y = 893.4x + 48.0	0.48	14.48	24.5	<0.001
PVI	y = 2455.8x + 47.6	0.47	14.54	24.6	<0.001
GSAVI	y = 649.9x – 54.1	0.32	16.42	27.7	<0.001
L-ATSAVI	y = 683.5x + 47.7	0.54	13.74	23.2	<0.001
L-SAVI	y = 1017.9x – 48.6	0.56	13.39	22.7	<0.001

As shown in Table 2, the L-SAVI appeared the best predictor of green aboveground biomass in our study site. Compared with these published vegetation indices (Fig. 5), the litter-soil-adjusted L-SAVI, established in the present study, effectively improved estimation accuracy of green aboveground biomass (Fig. 4). The L-SAVI could account for 56% of green aboveground biomass variation, and improved estimation capability by about 2-24% compared with other vegetation indices.

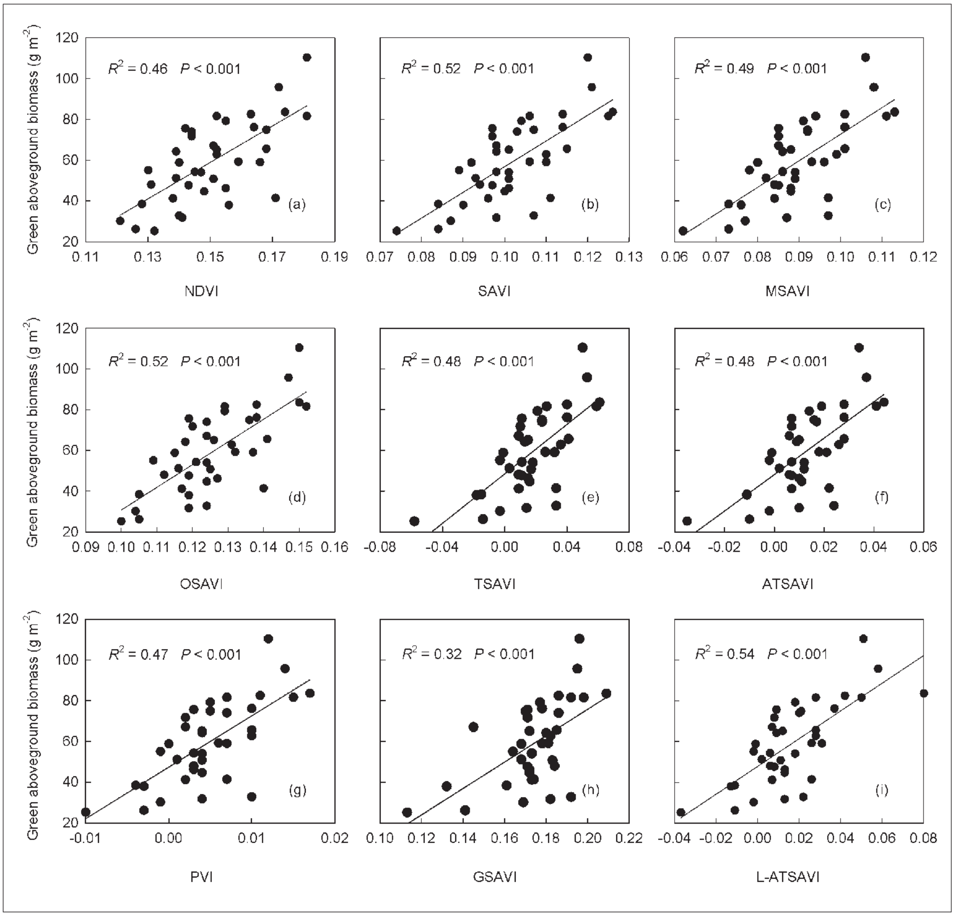

Figure 5 - Linear regressions between green aboveground biomass and (a) NDVI, (b) SAVI, (c) MSAVI, (d) OSAVI, (e) TSAVI, (f) ATSAVI, (g) PVI, (h) GSAVI, and (i) L-ATSAVI.

Discussion

As shown in many studies, accurate estimation of green aboveground biomass using remotely sensed data remains a challenge in arid and semiarid grassland due to sparse green vegetation cover and litter [Svoray and Shoshany, 2003; He et al., 2006; Wessels et al., 2006; Beeri et al., 2007]. Based on our field observations, green vegetation cover in our study site was less than 30%, and mean value of litter mass in all sampling plots was 75.8 g m^{-2}, while mean value of green aboveground biomass was 59.1 g m^{-2}. Our sampling results are essentially consistent with the results of Feng et al. (unpublished data), in which litter mass ranged from 13.6 g m^{-2} to 147.9 g m^{-2} with an average of 69.7 g m^{-2}, while green aboveground biomass varied from 19.4 g m^{-2} to 125.5 g m^{-2} with an average of 55.8 g m^{-2} in a large-scale field campaign in the desert steppe of Sonid Zuoqi and Sonid Youqi. As showed in other studies [Guo, 2002], the effect of litter often controlled the total fraction of aboveground biomass in a semiarid mixed grassland.

Surely, the spectral response used for green vegetation characterization in arid and semiarid grassland is strongly influenced by litter and soil background. As shown in Figure 2, the red absorption portion, NIR reflectance portion, and water absorption portions observed in our study site were not as strong as those of typical green plants [Zhao, 2003]. We attributed this mostly to that, the spectral signals from green vegetation were much weaker than those from litter and soil background. Therefore, the spectral signals of litter and soil background and their variations must be emphatically considered for green aboveground biomass estimation using remotely sensed data in arid and semiarid grassland [Elvidge and Lyon, 1985; Huete et al., 1985; Qi and Wallace, 2002; Montandon and Small, 2008].

To reduce or remove soil background influence in sparse green vegetation cover situation, substantial studies have been conducted to improve soil-unadjusted vegetation indices and to develop soil-adjusted vegetation indices [Richardson and Wiegand, 1977; Huete, 1988; Baret et al., 1989; Baret and Guyot, 1991; Qi et al., 1994; Rondeaux et al., 1996]. As shown in Table 2, these soil-adjusted vegetation indices, except the GSAVI, yielded better performance than the soil-unadjusted NDVI for green aboveground biomass estimation in our study site. The poor performance of GSAVI probably due to much higher reflectance in green reflectance portion (Fig. 2) and much lower reflectance in NIR reflectance portion in our study site compared with that of green plant [Zhao, 2003].

In comparison, the combined influences of soil background and litter, which may result in poor estimation of green aboveground biomass in arid and semiarid grassland, have received relatively little attention. Only very few studies have been conducted to reduce or remove the influences. For example, He et al. [2006] developed the L-ATSAVI to minimize soil background and litter influences in a semiarid mixed grassland. As expected, the L-ATSAVI had better estimation than other soil-unadjusted and soil-adjusted vegetation indices (Tab. 2 and Fig. 5). Nevertheless, the algorithm of L-ATSAVI contains the soil line parameters, which may limit its popularization and application.

Therefore, in this present study, a practical litter-soil-adjusted L-SAVI, which does not contain the soil line parameters, was proposed to estimate green aboveground biomass in arid and semiarid grassland. As shown in Table 2, Figure 4, and Figure 5, the L-SAVI provided some improvements over these soil-unadjusted and soil-adjusted vegetation indices for green aboveground biomass estimation in the desert steppe of Inner Mongolia. This was what we expected because of low green vegetation cover and a large amount of litter mass in our study site. Compared with the L-ATSAVI, the L-SAVI gave slightly better estimation of green aboveground biomass. Nevertheless, the L-SAVI is not build upon the slope and intercept of the soil line and valuable for application and generalization.

Conclusions

In this present study, a new litter-soil-adjusted vegetation index (L-SAVI) was proposed to estimate green aboveground biomass in arid and semiarid grassland, where the accurate estimation of green aboveground biomass is still a challenge due to the influences of soil background and litter. The L-SAVI was computed by incorporating CAI as a litter adjustment factor in the SAVI. The new method is a practical predictor for complementing existing soil-unadjusted/-adjusted and litter-soil-adjusted vegetation indices on estimation of aboveground green biomass in arid and semiarid grassland. Moreover, the algorithm of L-SAVI does not contain the soil line parameters, which may greatly provide an easy option for its applications.

Compared with the pixel size of airborne hyperspectral data (for example, Hyperion with a pixel size of 30 m × 30 m; AVIRIS with a pixel size of 20 m × 20 m), the measured area of field hyperspectral data was much small in our study. The spectral resolutions (for example, Hyperion and AVIRIS with a spectral resolution of 10 nm) and atmospheric conditions of the airborne hyperspectral data were also different from the plot-scale, field hyperspectral measurement in our study. Therefore, further studies need to be carried out to examine the efficacy of the L-SAVI using airborne hyperspectral remotely sensed data.

Green aboveground biomass estimation in our study might be time- or site-specific, and the L-SAVI needs to be further examined with additional green aboveground biomass measurements from other regions/sites and radiative transfer models. In addition, the efficacy of this new index for estimating other green plant parameters such as chlorophyll content and leaf area index in arid and semiarid grassland also needs to be established, which is important work we will do.

Acknowledgements

We are grateful to two anonymous reviewers for their constructive comments and suggestions. This research was jointly supported by the National Natural Science Foundation of China (41301053) and Natural Science Foundation of Shanxi (2013021030-1).

References

An N., Price K.P., Blair J.M. (2013) - *Estimating above-ground net primary productivity of the tallgrass prairie ecosystem of the Central Great Plains using AVHRR NDVI.* International Journal of Remote Sensing, 34: 3717-3735. doi: http://dx.doi.org/10.1080/01431161.2012.757376.

Asner G.P., Wessman C.A., Schimel D.S., Archer S. (1998) - *Variability in leaf and litter optical properties: implications for canopy BRDF model inversions using AVHRR, MODIS, and MISR.* Remote Sensing of Environment, 63: 200-215. doi: http://dx.doi.org/10.1016/S0034-4257(97)00138-7.

Baret F., Guyot G., Major D.J. (1989) - *TSAVI: a vegetation index which minimizes soil brightness effects on LAI and APAR estimation.* In IGARSS'89, Proceedings of the IEEE International Geoscience and Remote Sensing Symposium and 12th Canadian Symposium on Remote Sensing, 10-14 July 1989, Vancouver B.C. IEEE, Piscataway N.J. 3, pp. 1355-1358.

Baret F., Guyot G. (1991) - *Potentials and limits of vegetation indices for LAI and APAR assessment.* Remote Sensing of Environment, 35: 161-173. doi: http://dx.doi.org/10.1016/0034-4257(91)90009-U.

Baret F., Jacquemoud S., Hanocq J.F. (1993) - *About the soil line concept in remote sensing.* Advances in Space Research, 13: 281-284. doi: http://dx.doi.org/10.1016/0273-

1177(93)90560-X.
Beeri O., Phillips R., Hendrickson J., Frank A.B., Kronberg S. (2007) - *Estimating forage quantify and quality using aerial hyperspectral imagery for northern mixed-grass prairie.* Remote Sensing of Environment, 110: 216-225. doi: http://dx.doi.org/10.1016/j.rse.2007.02.027.
Boschetti M., Bocchi S., Brivio P.A. (2007) - *Assessment of pasture production in the Italian Alps using spectrometric and remote sensing information.* Agriculture, Ecosystems and Environment, 118: 267-272. doi: http://dx.doi.org/10.1016/j.agee.2006.05.024.
Cao J., Chen J., Matsushita B., Imura H. (2010) - *Developing a MODIS-based index to discriminate dead fuel from photosynthetic vegetation and soil background in the Asian steppe area.* International Journal of Remote Sensing, 31: 1589-1604. doi: http://dx.doi.org/10.1080/01431160903475274.
Cui D., Li Y.L., Wang X.Y., Zhao X.Y., Zhang T.H. (2011) - *Spatial distribution of aboveground biomass of grassland in desert and desertified regions in Northern China.* Journal of Desert Research, 31 (4): 868-872.
Daughtry C.S.T., McMurtrey III J.E., Nagler P.L., Kim M.S., Chappelle E.W. (1996) - *Spectral reflectance of soils and crop residues.* In: Davies, A.M.C., William, P. (Eds.), Near Infrared Spectroscopy: The Future Waves. NIR Publications, Chichester, UK, pp. 505-510.
Daughtry C.S.T., Hunt Jr E.R., McMurtrey III J.E. (2004) - *Assessing crop residue cover using shortwave infrared reflectance.* Remote Sensing of Environment, 90: 126-134. doi: http://dx.doi.org/10.1016/j.rse.2003.10.023.
Daughtry C.S.T., Hunt Jr E.R., Doraiswamy P.C., McMurtrey III J.E. (2005) - *Remote sensing the spatial distribution of crop residue.* Agronomy Journal, 97: 864-874. doi: http://dx.doi.org/10.2134/agronj2003.0291.
Daughtry C.S.T., Doraiswamy P.C., Hunt Jr E.R., Stern A.J., McMurtrey III J.E., Prueger J.H. (2006) - *Remote sensing of crop residue cover and soil tillage intensity.* Soil & Tillage Research, 91: 101-108. doi: http://dx.doi.org/10.1016 /j.still.2005.11.013.
Eisfelder C., Kuenzer C., Dech S. (2012) - *Derivation of biomass information for semi-arid areas using remote-sensing data.* International Journal of Remote Sensing, 33: 2937-2984. doi: http://dx.doi.org/10.1080/01431161.2011.620034.
Elvidge C.D., Lyon R.J.P. (1985) - *Influence of rock-soil spectral variation on the assessment of green biomass.* Remote Sensing of Environment, 17: 265-279. doi: http://dx.doi.org/10.1016/0034-4257(85)90099-9.
Eswaran H., Lai R., Reich P.F. (2001) - *Land degradation: an overview. In Responses to Land Degradation.* Proceedings of the 2nd International Conference on Land Degradation and Desertification, 2001, Bridges E.M., Hannam I.D., Oldeman L.R., Pening de Vries F.W.T., Scher S.J., Sompatpanit S. (Eds.), Khon Kaen, Thailand, pp. 20-35.
Fang J.Y., Yang Y.H., Ma W.H., Annwar M.M.T., Shen H.H. (2010) - *Ecosystem carbon stocks and their changes in China's grasslands.* Science China Life Science, 53 (7): 757-765. doi: http://dx.doi.org/10.1007/s11427-010-4029-x.
Fox G.A., Sabbagh G.J., Searcy S.W., Yang C. (2004) - *An automated soil line identification routine for remotely sensed images.* Soil Science Society of America Journal, 68:1326-1331. doi: http://dx.doi.org/10.2136/sssaj2004.1326.
Gao T., Xu B., Yang X.C., Jin Y.X., Ma H.L., Li J.Y., Yu H.D. (2013) - *Using MODIS time*

series data to estimate aboveground biomass and its spatio-temporal variation in Inner Mongolia's grassland between 2001 and 2011. International Journal of Remote Sensing, 34: 7796-7810. doi: http://dx.doi.org/10.1080/01431161.2013.823000.

Guo X. (2002) - *Discrimination of Saskatchewan prairie ecoregions using multitemporal 10-day composite NDVI data.* Prairie Perspectives, 5: 174-186.

He Y.H., Guo X.L., Wilmshurst J. (2006) - *Studying mixed grassland ecosystems I: suitable hyperspectral vegetation indices.* Canadian Journal of Remote Sensing, 32: 98-107. doi: http://dx.doi.org/10.5589/m06-009.

Hirata M., Kogab N., Shinjo H., Fujita H., Gintzburger G., Miyazaki A. (2001) - *Vegetation classification by satellite image processing in a dry area of northeastern Syria.* International Journal of Remote Sensing, 23: 507-516. doi: http://dx.doi.org/10.1080/01431160050505829.

Huete A.R., Jackson R.D., Post D.F. (1985) - *Spectral response of a plant canopy with different soil backgrounds.* Remote Sensing of Environment, 17: 37-53. doi: http://dx.doi.org/10.1016/0034-4257(85)90111-7.

Huete A.R. (1988) - *A soil-adjusted vegetation index (SAVI).* Remote Sensing of Environment, 25: 295-309. doi: http://dx.doi.org/10.1016/0034-4257(88)90106-X.

Jin Y.X., Yang X.C., Qiu J.J., Li J.Y., Gao T., Wu Q., Zhao F., Ma H.L., Yu H.D., Xu B. (2014) - *Remote sensing-based biomass estimation and its spatio-temporal variations in temperate grassland northern China.* Remote Sensing, 6: 1496-1513. doi: http://dx.doi.org/10.3390/rs6021496.

Liu Y., Zha Y., Gao J., Ni S. (2004) - *Assessment of grassland degradation near Lake Qinhai, West China, using Landsat TM and in situ reflectance spectra data.* International Journal of Remote Sensing, 25: 4177-4189. doi: http://dx.doi.org/10.1080/01431160410001680419.

Liu H.J., Zhang B., Song K.S., Wang Z.M., Duan H.T., Yang F., Zhang X.L. (2008) - *Soil line influence factors analysis based on laboratory soil hyperspectral reflectance.* Journal of Remote Sensing, 12: 119-127.

Liu L.Y., Zhao J.J., Guan L.L. (2013) - *Tracking photosynthetic injury of Paraquat-treated crop using chlorophyll fluorescence from hyperspectral data.* European Journal of Remote Sensing, 46: 459-473. doi: http://dx.doi.org/10.5721/EuJRS20134627.

Marino S., Alvino A. (2014) - *Proximal sensing and vegetation indices for site-specific evaluation on an irrigated crop tomato.* European Journal of Remote Sensing, 47: 271-283. doi: http://dx.doi.org/10.5721/EuJRS20144717.

Moleele N., Ringrose S., Arnberg W., Lunden B., Vanderpost C. (2001) - *Assessment of vegetation indexes useful for browse (forage) prediction in semi-arid rangeland.* International Journal of Remote Sensing, 22: 741-756. doi: http://dx.doi.org/10.1080/01431160051060147.

Montandon L.M., Small E.E. (2008) - *The impact of soil reflectance on the quantification of the green vegetation fraction from NDVI.* Remote Sensing of Environment, 112: 1835-1845. doi: http://dx.doi.org/10.1016/j.rse.2007.09.007.

Mulligan M. (2009) - *Integrated environmental modelling to characterize processes of land degradation and desertification for policy support.* In: Recent Advances in Remote Sensing and Geoinformation Processing for Land Degradation Assessment, Roder A., Hill J. (Eds), pp. 45-72. doi: http://dx.doi.org/10.1201/9780203875445.ch3.

Myneni R.B., Los S.O. (1995) - *Potential gross primary productivity of terrestrial vegetation from 1982-1990.* Geophysical Research Letters, 22: 2617-2620. doi: http://dx.doi.org/10.1029/95GL02562.

Myneni R.B., Maggion S., Laquinta J., Privette J.L., Gobron N., Pinty B., Kimes D.S., Verstraete M.M., Williams D.L. (1995) - *Optical remote sensing of vegetation: modeling, caveats, and algorithms.* Remote Sensing of Environment, 51: 169-188. doi: http://dx.doi.org/10.1016/0034-4257(94)00073-V.

Qi J., Chehbouni A., Huete A.R., Kerr Y.H., Sorooshia S. (1994) - *A modified soil adjusted vegetation index.* Remote Sensing of Environment, 48: 119-126. doi: http://dx.doi.org/10.1016/0034-4257(94)90134-1.

Qi J., Wallace O. (2002) - *Biophysical attributes estimation from satellite images in arid regions.* In: Proceeding of the International Geoscience and Remote Sensing Symposium 2002, IGARSS, 24-28 June 2002, Toronto, Canada, 4: 2000-2002.

R Development Core Team. (2012) - *R: A Language and Environment for Statistical Computing.* R Foundation for Statistical Computing, Vienna.

Ren H.R., Zhou G.S., Zhang X.S. (2011) - *Estimation of green aboveground biomass of desert steppe in Inner Mongolia based on red edge reflectance curve area method*. Biosystems Engineering, 109: 385-395. doi: http://dx.doi.org/10.1016/j.biosystemseng.2011.05.004.

Ren H.R., Zhou G.S. (2012) - *Estimating senesced biomass of desert steppe in Inner Mongolia using field spectrometric data.* Agricultural and Forest Meteorology, 161: 66-71. doi: http://dx.doi.org/10.1016/j.agrformet.2012.03.010.

Richardson A.J., Wiegand C.L. (1977) - *Distinguishing vegetation from soil background information.* Photogrammetric Engineering & Remote Sensing, 43 (2): 1541-1552.

Rondeaux G., Steven M., Baret F. (1996) - *Optimization of soil-adjusted vegetation indices.* Remote Sensing of Environment, 55: 95-107. doi: http://dx.doi.org/10.1016/0034-4257(95)00186-7.

Rouse J.W., Haas R.H., Schell J.A., Deering D.W. (1974) - *Monitoring vegetation systems in the Great Plains with ERTS, third ERTS symposium.* NASA SP-351, 1: 309-351.

Schino G., Borfecchia F., Dececco L., Dibari C., Iannetta M., Maritini S., Pedrotti F. (2003) - *Satellite estimate of grass biomass in a mountainous range in central Italy.* Agroforestry Systems, 59: 157-162. doi: http://dx.doi.org/10.1023/A:1026308928874.

Scurlock J.M.O., Hall D.O. (1998) - *The global carbon sink: a grassland perspective.* Global Change Biology, 4: 229-233. doi: http://dx.doi.org/10.1046/j.1365-2486.1998.00151.x.

Scurlock J.M.O., Johnson K., Olson R.J. (2002) - *Estimating net primary productivity from grassland biomass dynamics measurements.* Global Change Biology, 8: 736-753. doi: http://dx.doi.org/10.1046/j.1365-2486.2002.00512.x.

Svoray T., Shoshany M. (2003) - *Herbaceous biomass retrieval in habitats of complex composition: a model merging SAR images with unmixed Landsat TM data.* IEEE Transactions on Geoscience and Remote Sensing, 41: 1592-1602. doi: http://dx.doi.org/10.1109/TGRS.2003.813351.

Tian Y.C., Zhu Y., Cao W.X. (2005) - *Monitoring soluble sugar, total nitrogen & its ratio in wheat leaves with canopy spectral reflectance.* Acta Agronomica sinica, 31: 355-360.

United States Department of Agriculture (1999) - *Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys.* Available online at: ftp: //ftp-

fc.sc.egov.usda.gov/NSSC/Soil_Taxonomy/tax.pdf.
Verstraete M.M. (1986) - *Defining desertification: a review.* Climate Change, 9: 5-18. doi: http://dx.doi.org/10.1007/BF00140520.
Van Leeuwen W.J.D., Huete A.R. (1996) - *Effects of standing litter on the biophysical interpretation of plant canopies with spectral indices.* Remote Sensing of Environment, 55: 123-134. doi: http://dx.doi.org/10.1016/0034-4257(95)00198-0.
Wessels S.D., Prince S.D., Zambatis N., Macfadyen S., Frost P.E., Van Zyl D. (2006) - *Relationship between herbaceous biomass and 1-km2 Advanced Very High Resolution Radiometer (AVHRR) NDVI in Kruger National Park, South Africa.* International Journal of Remote Sensing, 27: 951-973. doi: http://dx.doi.org/10.1080/01431160500169098.
Xia J.Z., Liu S.G., Liang S.L., Chen Y., Xu W.F., Yuan W.P. (2014) - *Spatio-temporal patterns and climate variables controlling of biomass carbon stock of global grassland ecosystems from 1982 to 2006.* Remote Sensing, 6: 1783-1802. doi: http://dx.doi.org/10.3390/rs6031783.
Zhao Y.S. (2003) - *The Principle and Method of Analysis of Remote Sensing Application*. Beijing: Science Press.
Zhang X. (2007) - *Vegetation Map and Vegetation Regionalization Map of China* (1:1 million). Beijing: China Land Press.