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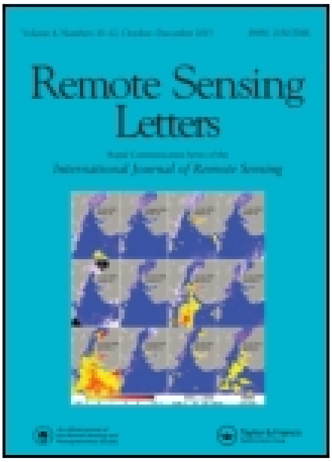

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Response of spectral vegetation indices to a stocking rate experiment in Inner Mongolia, China

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Response of spectral vegetation indices to a stocking rate experiment in Inner Mongolia, China

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Techniques for mapping and monitoring vegetation status under human disturbance (e.g., grazing livestock) can contribute to sustainable development of grasslands. The main objective of this paper is to investigate whether the effects of differences in grazing intensity (measured by stocking rate (SR)) could be discriminated using in situ spectral data. The experiment was conducted with controlled SRs on the Sino-German experimental farm in the Xilingol grassland, Inner Mongolia, P.R. China. Canopy spectral measurements were made on experimental paddocks that varied by SRs, terrain and management type. Eight vegetation indices (VIs) were calculated from ASD field spectrometer data for each paddock. We modelled the variability within and between paddocks using a linear mixed model to isolate the effect of grazing intensity on VI response. All VIs showed significant negative relationships to grazing intensity that were ameliorated on paddocks with haying compared to traditional direct grazing. The best VIs for detecting differences in paddocks due to the levels of SR were photochemical reflectance index (PRI), broadband normalized difference vegetation index (bNDVI) and narrowband NDVI (nNDVI1). The responses of VIs to vegetation conditions as affected by different SRs offer promise for the use of airborne and satellite remote sensing to map vegetation status and to evaluate the effects of grazing intensities at regional scales.

1. Introduction

Natural grasslands and savannas cover more than 40% of the terrestrial globe and provide important resources to modern societies (Moore 1996; Chapin, Sala, and Huber-Sannwald 2001). Monitoring and assessment of grassland resources are increasingly important in aiding their conservation and, in some cases, their restoration (He et al. 2005; De Luis, Raventós, and González-Hidalgo 2006). With increasing population and intensified human activities such as over-grazing, grassland degradation has been observed in many parts of the world. In the northern part of China, where grasslands are the dominant ecological systems, livestock is the main source of income for people; at the same time, the increasing population and policies aimed at sedentarization have led to heavy grazing intensity, which has imposed negative effects on vegetation health (He et al. 2005). Appropriate management of grazing should balance requirements for both feasible livestock production and biodiversity conservation of grasslands (Kleinebecker, Weber, and Hölzel 2011). Previous work done in northern China showed that grazing intensities had complex effects on above-ground biomass (AGB) (Fang et al. 2012). A long-term (20-year) exclosure experiment resulted in significantly increased AGB and belowground biomass, species richness, cover and height for vegetation communities

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*Corresponding author. Email: zongyaosha@whu.edu.cn in typical steppe communities in northern China (Cheng et al. 2011). Still, another study conducted in the meadow steppe in the Xilin river basin, northern China, found that light grazing could increase plant biomass production at both individual and community levels, though overgrazing significantly decreased average plant morphological traits (Ren, Zheng, and Bai 2009). Better information about the response of grasslands to grazing and about the broadscale environmental implications of grazing is needed.

Data on grazing levels have been collected through direct field survey and indirect modelling approaches (Kawamura et al. 2005). The direct approach uses fixed-point field surveys to provide the most accurate method for observing grazing intensity, but is time-consuming and costly; for example, the grid cell method was used to track livestock numbers within units of defined grid areas for a particular period (Kawamura et al. 2005). Remote sensing techniques are known to be useful for quantifying various grassland properties remotely (Gao 2006; Al-Bakri and Taylor 2003). Satellite platforms in particular offer an effective means of collecting contemporary data from vast areas and in short periods of time (Moreau et al. 2003; Nordberg and Evertson 2003). Remote sensing is a useful tool for retrieving information about AGB and therefore may provide an indirect approach to evaluating grazing intensity (Pickup and Chewings 1994; Washington-Allen et al. 2010; Ahamed et al. 2011). Comprehensive work applying remote sensing methods for biomass feedstock production is discussed in literature (Ahamed et al. 2011). Particularly, the relationships between spectral vegetation indices (VIs) and AGB have been used to assess the spatial and temporal variation of biomass (Gao 2006). The VI-based methods estimate AGB by establishing empirical relationships between recorded biomass and the transformations of two or more remotely sensed spectral wavelengths (He et al. 2005; Tueller 1989); notable among these indexes is the normalized difference vegetation index (NDVI) (Al-Bakri and Taylor 2003). Other VIs have also been widely tested, including the enhanced vegetation index (EVI), considering greenness saturation, soil-adjusted vegetation index (SAVI), which considers soil background effect, and easy-to-apply simple ratio (SimpR) index (Tucker 1979; Jiang et al. 2007; Huete 1997; Gilabert et al. 2002). Most VIs show positive correlations with AGB (Huete 1997; Edirisinghe, Clark, and Waugh 2012). Tests are needed to evaluate whether spectral indices are sensitive to differences in grassland condition that stem from differences in grazing intensity (Kawamura et al. 2005; Duan et al. 2012).

We investigated whether field spectrometry data could be used to discriminate grassland conditions under experimentally manipulated stocking rates (SRs). As a preliminary step in evaluating the possibility of mapping the effects of grazing intensity with satellite-based imagery, we explored the potential of eight spectral indices to discriminate the vegetation differences found in paddocks with different SRs, and tested their interactions with terrain types (sloping or flat) and livestock management approaches. The haying approach, which takes feed to animals without direct grazing on vegetation, was recently adopted in the study region as a campaign to counteract the severe threat of overgrazing on the grassland (Schönbach et al. 2009). While VIs cannot be used to directly determine the causes of observed differences in vegetation condition, the experimental design permits evaluation of the vegetation and subsequent spectral effects of one important factor in grassland degradation. To the best of our knowledge, experimental tests of the ability of spectral indices to discriminate the changes to grassland condition brought on by differences in SRs have not been reported to date.

2. Methodology

2.1. Study area and grazing experiment

The research was conducted on the Sino-German experimental farm in the Xilingol grassland, Inner Mongolia, P.R. China (Schönbach et al. 2009), 15 km south of the Inner Mongolia

Grassland Ecosystem Research Station (IMGERS, Chinese Academy of Sciences, 43.38°N, 116.42°E, 1270 m.a.s.l.). The Xilingol grassland is part of the Central Asian steppe ecosystem, with a dry and cold mid-latitude climate where the mean annual temperature is 0.7°C and the mean annual precipitation is around 350 mm (Kawamura et al. 2005). The dominant species are *Leymus chinensis* and *Stipa grandis*. The increasing grazing intensity in the past decades has had negative consequences for vegetation health (Tong et al. 2004).

SRs were manipulated in experimental paddocks extending over a total area of 160 ha and started in 2005, within the framework of the Sino-German experiment (Schönbach et al. 2009). Experimental paddocks were fenced areas of 2 ha (100 m × 200 m rectangle), mainly covered by *Stipa grandis*. Seven different levels of SR were implemented on random paddocks: 0 sheep/ha (no grazing, SR 0 hereafter), 1.5 sheep/ha (SR 1.5), 3 sheep/ha (SR 3.0), 4.5 sheep/ha (SR 4.5), 6 sheep/ha (SR 6.0), 7.5 sheep/ha (SR 7.5) and 9 sheep/ha (SR 9.0). Before the study was conducted, the background of the paddocks was evaluated (through vegetation cover and soil) to minimize the background difference. The sheep selected for grazing were 15-month-old, 35-kg live weight females and the grazing treatment began in 2005 with the grazing season running from mid-June to mid-September (about 95 days) each year.

Paddocks were also selected to vary in terms of topography and livestock management strategies. Paddocks were classified as either flat or sloped (with slope angle around 15°). Additionally, paddocks underwent two types of livestock management strategies: traditional direct grazing and the newly introduced haying approach. The traditional direct grazing approach allowed livestock free access to graze (grazing, hereafter), while haying approach took the feed to animals without direct grazing (haying, hereafter). Grazing and haying were implemented for the same length of time. For each combination of SR (seven levels), terrain type (two levels) and livestock management (two levels), a single paddock was established without replication.

2.2. Spectrometric measurements and statistical analysis

The ASD FieldSpec 3 Pro spectroradiometer (ASD, Analytical Spectral Devices, Inc., 2005) was used to collect field spectra in each experimental paddock, with wavelength ranging from 350 to 2500 nm. Considering spatial variations of vegetation cover, a large quadrat with an area of 60 m × 60 m was located using a random starting location and N-S/E-W orientation within each paddock. Spectral measurements were made at 16 locations within each quadrat, starting at a corner and then transecting diagonally to the opposite corner while stopping every 10 m for a measurement, and repeating for the perpendicular cross-transect. A tripod was used to mount the tip of the fibre optic cable with a 25° field-of-view optic aligned plumb to gravity at 1.3 m above the surface, resulting in a ground field-of-view of about 1 m in diameter, large enough to cover a representative sample of vegetation. We collected 10 spectral readings at each location, with each reading comprised of 30 spectra averaged together in order to improve the signal-to-noise ratio of the measurement. The 10 readings for each of the 16 points in each quadrat were averaged first, producing 16 spectral data samples for each quadrat. All the measurements were collected on 28 and 29 July 2010 (approximately at the stage of maximum vegetation growth) between 10:00 am and 02:00 pm under sunny and cloudless conditions. A white reference Spectralon calibration panel was used every 5–10 measurements to recalibrate to any change in atmospheric conditions and sun irradiance. To avoid possible bias caused by bidirectional reflectance distribution function (BRDF) effect among different treatments, the sequential order of the plots during spectra collection was randomly decided.

Eight VIs (Table 1) were tested as indicators to differentiate the treatments (SR, terrain types and land use), including four broadband indices commonly used with satellite instruments (i.e., Landsat and the moderate resolution imaging spectroradiometer (MODIS)) to monitor grassland condition, and four narrowband indices hypothesized to take advantage of the finer spectral resolution of the radiometer and of hyperspectral sensors. Broadband indices included broadband NDVI (bNDVI), SimpR, EVI, and generalized soil-adjusted vegetation index (GESAVI). These VIs have known sensitivity to a wide range of ecological properties and processes, for example, vegetation cover and productivity (Tucker 1979; Huete 1997). Narrowband indices included narrowband NDVI 1 (nNDVI1, with near-infrared or NIR band set as 775 nm and red band set as 662 nm), narrowband NDVI 2 (nNDVI2, with NIR band as 750 nm and red band as 705 nm), green NDVI (GNDVI) and photochemical reflectance index (PRI). These latter two indices are targeted for sensitivity to leaf pigment content and photosynthetic efficiency (Gitelson, Kaufman, and Merzlyak 1996; Drolet et al. 2005).

We analysed the data using a descriptive (univariate) analysis to identify the variability of VI values by SR livestock management and terrain. We were interested, in particular, in the linearity of the response of VI values to SR, in supporting our subsequent statistical modelling decisions. Next, we developed a separate linear mixed model for the relationship between SR

Table 1. Eight vegetation indices (VIs) used as indicators for vegetation status.

Name	Explanation	Calculation formula*	Reference
nNDVI1	Narrowband NDVI1	$\frac{R_{775\ \mathrm{nm}} - R_{662\ \mathrm{nm}}}{R_{775\ \mathrm{nm}} + R_{662\ \mathrm{nm}}}$	Kawamura et al. (2008); Campbell et al. (2007)
nNDVI2	Narrowband NDVI2	$\frac{R_{750\ \mathrm{nm}} - R_{705\ \mathrm{nm}}}{R_{750\ \mathrm{nm}} + R_{705\ \mathrm{nm}}}$	Sims and Gamon (2002)
bNDVI	Broadband NDVI	$\frac{R_{775\ \mathrm{nm}-900\ \mathrm{nm}} - R_{630\ \mathrm{nm}-690\ \mathrm{nm}}}{R_{775\ \mathrm{nm}-900\ \mathrm{nm}} + R_{630\ \mathrm{nm}-690\ \mathrm{nm}}}$	Tucker (1979)
SimpR	Simple ratio VI	$\frac{R_{775\ \mathrm{nm}-900\ \mathrm{nm}}}{R_{630\ \mathrm{nm}-690\ \mathrm{nm}} \times 10}$	Tucker (1979)
EVI	Enhanced VI	$\frac{R_{775\ \mathrm{nm}-900\ \mathrm{nm}} - R_{630\ \mathrm{nm}-690\ \mathrm{nm}}}{0.4 \times (R_{775\ \mathrm{nm}-900\ \mathrm{nm}} + f)}$, where $f = 6 \times R_{630\ \mathrm{nm}-690\ \mathrm{nm}} - 7.5 \times R_{450\ \mathrm{nm}-520\ \mathrm{nm}} + 1$	Huete (1997)
GESAVI	Generalized soil-adjusted VI	$\frac{R_{775\ \mathrm{nm}-900\ \mathrm{nm}} - 1.17 \times R_{630\ \mathrm{nm}-690\ \mathrm{nm}} - 0.01}{R_{630\ \mathrm{nm}-690\ \mathrm{nm}} + 0.35}$	Gilabert et al. (2002)
GNDVI	Green NDVI	$\frac{R_{750\ \mathrm{nm}} - R_{550\ \mathrm{nm}}}{R_{750\ \mathrm{nm}} + R_{550\ \mathrm{nm}}}$	Gitelson, Kaufman, and Merzlyak (1996)
PRI	Photochemical reflectance index	$\frac{R_{531\ \mathrm{nm}} - R_{570\ \mathrm{nm}}}{R_{531\ \mathrm{nm}} + R_{570\ \mathrm{nm}}}$	Gamon, Peñuelas, and Field (1992)

Note: *Combination of spectral reflectance (R) at different wavelengths. The number after letter R indicates wavelength or the range of wavelengths. SimpR was originally defined as $R_{775\ \mathrm{nm}-900\ \mathrm{nm}}/R_{630\ \mathrm{nm}-690\ \mathrm{nm}}$ (Tucker 1979); here a factor of 10 is used to scale the value so that it is easier to present along with other VIs.

and each of the eight VIs. Properly constructed, linear mixed models can be used to account for spatial clustering and lack of independence of the sort that characterizes our spectral measurements (Bolker et al. 2009). In order to make use of all of our measurements (16 locations within each quadrat), we accounted for the quadrat-level variation using a random effect variable that identified the paddocks. Next, we estimated coefficients for the fixed effects SR, livestock management, terrain and their interactions, while accounting for the quadrat-level random effect. The coefficients were estimated using the restricted maximum likelihood approach in the lme4 package (Bates 2010) with R v3.0.2.

Confidence intervals for coefficient significance testing are estimated using a profiling approach (Bates 2010). To measure the relative contribution of the SR variable to the model for each VI, we used analysis of variance (ANOVA) and a chi-square test that compares a model that omits SR (i.e., includes only the quadrat random effect, livestock management and terrain) and was fitted with a maximum likelihood (ML) method, with a full ML model. We compare the chi-square values (χ^2) from this test across the VI models to evaluate relative sensitivity of each VI to the differences in vegetation conditions as affected by SR.

3. Results

3.1. Descriptive results

The selected VIs responded differently to the three treatment variables, though the direction of the effect was nearly always the same (Figures 1 and 2). Overall, because of similarities in responsiveness of their red and near-infrared wavelength bands, nNDVI1 and bNDVI had similar values for a given treatment.

When the SR increased, all the VI values tended to decrease, reflecting the negative impact of grazing on vegetation growth and the generally positive correlations between VIs and vegetation biomass (Figure 1). All VIs show steepest decreases from SR 4.5 to SR 6.0, indicating that VIs are very sensitive to grazing intensities in that range. On the other hand, the VIs seemed to level out or even slightly increase in the range from SR 6.0 to SR 9.0, possibly because differences in biomass above this level are small, and the influence of background

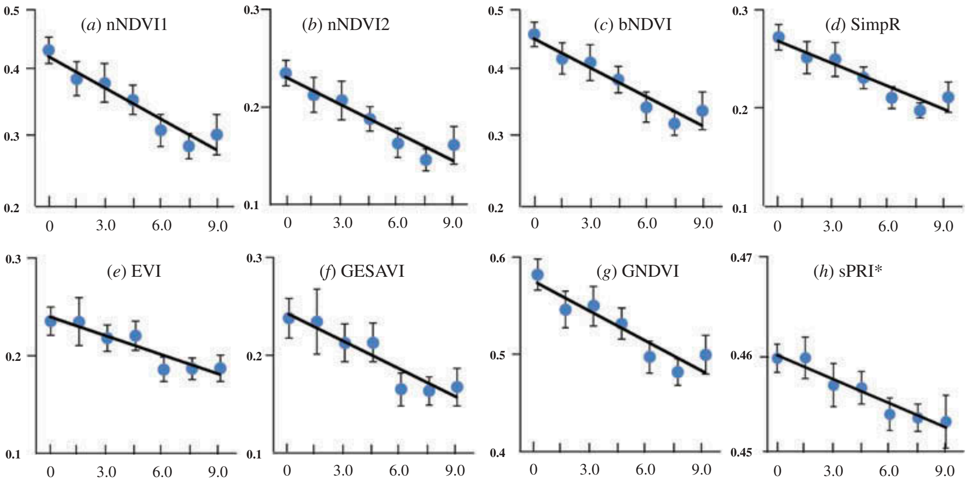

Figure 1. Mean and standard deviation of VI values under different stocking rates, with best fit line. *sPRI in (h) is scaled PRI using function sPRI = (PRI + 1)/2 (Rahman et al. 2004) for better illustration.

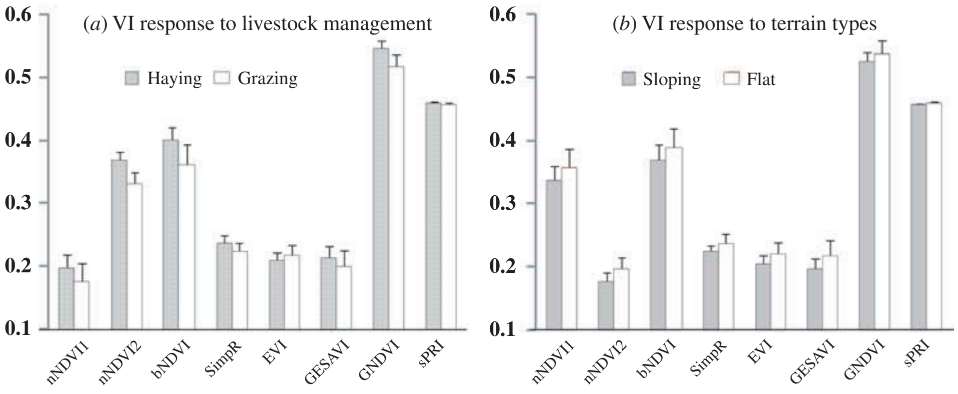

Figure 2. Mean and standard deviation of VI values relative to (*a*) livestock management and (*b*) terrain types.

*sPRI in *x*-axis is scaled PRI using function sPRI = (PRI + 1)/2 (Rahman et al. 2004) for better illustration.

reflectance from soil is so large that their differences are not detectable spectrally. Despite these slight deviations, the overall trend across all levels of SR is reasonably well approximated by a linear function. For this reason, and for the sake of parsimony in model estimation, we estimate SR with a linear function in the statistical models.

Except for EVI, hayed paddocks had slightly higher VI values than grazed paddocks (Figure 2(*a*)). We hypothesize that the newly adopted livestock management strategy was better in sustaining grassland productivity compared to the traditional way. In terms of terrain types, flat paddocks always had slightly higher VI values than the sloped ones (Figure 2(*b*)).

3.2. Statistical results from linear mixed model

The random effect in the linear mixed model indicates that there was a significant ($p < 0.01$) level of inter-quadrat variability for all VIs (Table 2). Accounting for this random effect is appropriate given the use of repeated measurements within each quadrat and reduces inferential risks associated with pseudoreplication. Of the three treatment variables, entered as fixed effects in the model, SR was the only variable that was consistently and significantly related to VI on its own ($p < 0.01$; Table 2). In all cases, the estimated effect was linear and negative, confirming that, when traditional grazing is used, increases in SRs had the significant effect of consistently reducing values for all VIs, through its effects on vegetation properties, for example, biomass. Only in the cases of EVI and GESAVI did livestock management show a significant effect on VI values ($p < 0.05$). In both cases, the negative coefficient suggests that, where no stocking was present, haying plots had lower VI values once other factors were taken into account. This is somewhat meaningless in the context of this model, as haying is only meaningful when SR > 0. Livestock management had a much more meaningful effect through its interaction with SR, and this effect was consistent across all VIs ($p < 0.05$). The introduction of haying had the effect of reducing the slope of the relationship between SR and the VIs, suggesting that it ameliorated the degrading effects of increased SR.

The χ^2 tests for the ANOVA results revealed that SR contributed significantly to the fit of the models. Further, it revealed that the best three VIs for detecting differences in the levels of SR were PRI, bNDVI and nNDVI1, based on the fact that their χ^2 values were the highest. The EVI and GESAVI appeared to be the least sensitive indices to SR.

Table 2. Linear mixed model results. Numeric values in the first eight rows are estimated coefficient values for the random effect, fixed effects for the three treatment variables and their interactions. Significance levels are based on a profiling test (Bates 2010). The last row is the result of an ANOVA test comparing estimated models with and without SR.

Items	nNDVI1	nNDVI2	bNDVI	SimpR	EVI	GESAVI	GNDVI	PRI
[Quadrat effects]	0.433†	0.241†	0.458†	2.747†	0.281†	0.301†	0.590†	−0.0734†
Stocking rate (1)	−0.025†	−0.016†	−0.024†	−0.127†	−0.013†	−0.019†	−0.016†	−0.0029†
[a]LM (2)	−0.006	−0.003	−0.005	−0.034	−0.063*	−0.083*	−0.011	−0.0005
Terrain (3)	0.012	−0.003	0.009	0.007	−0.026	−0.035	0.006	−0.0013
(1) × (2)	0.018†	0.011*	0.018†	0.088*	0.014†	0.019†	0.012*	0.0021†
(1) × (3)	0.002	0.002	0.002	0.014	0.003	0.005	0.001	0.0004
(2) × (3)	−0.093*	−0.056	−0.085	−0.494	0.009	0.006	−0.061	−0.0067
(1) × (2) × (3)	0.002	0.001	0.001	0.012	−0.004	−0.006	0.001	−0.0004
χ^2 (2,3) vs. (1,2,3)	28.705†	26.372†	29.141†	24.256†	16.358†	17.516†	24.858†	29.713†

Note: [a]LM: Livestock management; *significant at $p < 0.05$; †significant at $p < 0.01$.

4. Discussion and conclusions

The responses of VIs to variations in vegetation characteristics due to experimentally controlled SRs were investigated in a typical grassland in Inner Mongolia, P.R. China, using in situ spectral data. While it is known that SR is a critical factor affecting the grassland vegetation growth in that area (Tong et al. 2004), and that spectral VIs are responsive to vegetation biomass and vegetation growing status, the potential for VIs in assessing vegetation conditions specifically resulting from differences in SRs has not been previously investigated. We explored how eight different VIs performed as indicators of the vegetation conditions that reflect grazing intensities. While accounting for the interactions with slope and livestock management approach, and for the grouping of measurements associated with the experimental design, our results confirm that, when grazing is employed, increased SRs affected vegetation biomass and other properties in a way that resulted in significant linear decreases in all eight VIs.

The inclusion of interaction terms in our model showed confounding or interacting influences of terrain and livestock management on the vegetation (and consequently spectral) responses to grazing intensities. The experimental plots were specifically selected and designed to be as similar as possible on other ecosystem characteristics (e.g., soil texture and vegetation communities). Though we tried to minimize the background effect in our experiment, other factors that were not included in the experimental design may also be important modifiers of the relationships between spectral indices and SR, including differences in background soil type and differences in soil water availability variables (Pacheco-Labrador and Martin 2014; Zhang and Dong 2009). Although we saw slightly higher VI values on flat versus sloping terrain, the statistical results indicated that topography (flat terrain and sloping terrain) had no significant impact on grassland vegetation as reflected by the VIs, once we accounted for the effects of SRs and livestock management. Because the Inner Mongolia grassland, China, has complex topography, greater detail in the different levels of terrain may have revealed a stronger effect, but we were unable to detect an effect with these two levels.

The interaction effects with the livestock management variable suggest that feeding livestock after haying vegetation improves grassland condition compared to the traditional direct grazing on vegetation. This is revealed in both the fact that VI values on the hayed plots were higher than those under traditional grazing (Figure 2(*a*)) and the statistical results, which show an amelioration of the effects of SR on VI when haying is introduced.

The positive coefficient for the interaction term between SR and livestock management approach suggests that use of haying increases VI values to a degree that is proportional to the SR, meaning that increases in SR do not degrade the grassland as much. This is consistent with the goal of this new management strategy, but it also suggests that direct detection of SR via VI-based indicators will certainly require some information about the livestock management strategies used.

4.1. Extension of remote sensing imagery to regional scales study

The results of this study help to bridge field surveys using field spectroradiometer measurements and remote sensors, possibly on airborne or satellite platforms, for mapping vegetation conditions that are indicative of differential SRs based on our finding that the SRs are significantly correlated to VI values. Eight VIs (narrowband VIs including nNDVI1, nNDVI2, GNDVI and PRI, and broadband VIs including bNDVI, SR, EVI and GESAVI) were examined for their sensitivity to different SRs. Of those VIs, we found that the best ones for detecting differences in the levels of SR were PRI, broadband NDVI (bNDVI) and narrowband NDVI with the red band at 662 nm (nNDVI1). The difference in the sensitivity likely arises from different spectral responses at the wavelengths adopted. The focus of PRI on photosynthetic light-use efficiency appears to be advantageous for detecting relevant vegetation differences in this grassland system.

The narrowband VIs (nNDVI1, nNDVI2, GNDVI and PRI) could discriminate the SRs well, but nNDVI1 and PRI were more sensitive to vegetation differences due to SRs, other variables being equal. When extending to airborne or satellite remote sensing platforms, such narrowband indices usually require hyperspectral sensors (e.g., Hyperion and HyMap). The broadband VIs (bNDVI, SimpR, EVI and GESAVI) can be built from the spectral bands corresponding to the commonly used multi-spectral remotely sensed imagery, such as Landsat series (medium spatial resolution) and MODIS (coarse spatial resolution) imagery, and thus may have wider applicability because they can be mapped easily from those satellite images. Of these broadband VIs, EVI and GESAVI were least sensitive to SRs, and bNDVI and SimpR showed highest capability in detecting differences in vegetation characteristics due to variable SRs. This relative level of sensitivity suggests that saturation and a high degree of background contamination, problems for which EVI and GESAVI were developed to address, are not significant issues in this typical grassland. Therefore, broadband VIs bNDVI and SimpR derived from medium and coarse spatial resolution imagery provides potential for mapping regional grazing levels, provided the region is under consistent grazing, as opposed to haying, management. One concern is that, when coarse resolution sensors such as MODIS are used or when complex terrain in the study area is present, the VIs derived from the spectral reflectance can be affected due to atmospheric path scattering and BRDF effect; it is often recommended to have VIs improved through BRDF models (Gao et al. 2002). The interaction of the responsiveness of VIs to SR with livestock management suggests that a monitoring programme would need to be considered, among others, information about the approaches livestock managers are taking in order to achieve the best success using a remote sensing approach. Overall, results of this study offer the possibility of extending field (plot) measurements at canopy level to airborne and satellite multi-spectral sensor data for discriminating grazing intensity in grasslands.

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