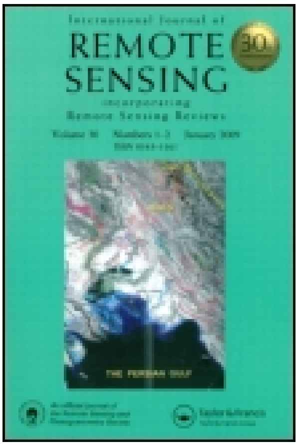

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Do vegetation indices provide a reliable indication of vegetation degradation? A case study in the Mongolian pastures

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Space and ground observations were applied to explore the ability of remote sensing techniques to assess the effect of grazing on vegetation degradation. The steppe biome of Mongolia was used as the study area, in which several pairs of sites were investigated – each pair comprised an ungrazed (fenced-off) area and a heavily grazed area. For each pair, the enhanced vegetation index (EVI), computed from Landsat-7 Enhanced Thematic Mapper Plus (ETM+) data, along with field-observed biophysical variables (e.g. plant density, species composite, above-ground biomass (AGB), and percentage cover) and plant spectral reflectance data were collected. As expected, plant density, AGB, and percentage cover values were significantly higher in the ungrazed areas than in the adjacent grazed ones. However, unexpectedly, the grazed areas had significantly higher EVI values than the ungrazed areas. It was found that unpalatable species had invaded into the grazed areas, substituting the native grasses. These invasive species, mostly characterized by denser leaf structure, induced higher spectral responses in the near infrared (NIR) region of the electromagnetic spectrum. EVI is the preferred vegetation index to use for detecting this phenomenon, since it is more sensitive to variations in leaf cellular structural as expressed in the NIR (rather than the red) portion of the spectrum. The current study contradicts the general assumption that the higher the vegetation index value, the better the grazing conditions.

1. Introduction

Grazing by domestic animals is among land-use practices with strong impacts on native vegetation in rangelands throughout the world. According to the Food and Agriculture Organization, FAO (FAOSTAT data 2006), permanent grasslands extend over 3.4×10^9 ha worldwide, representing approximately 26% of the Earth's land surface. Therefore, range management and monitoring using traditional field surveys, especially over vast and remote areas, might be problematic since these are expensive, manpower-demanding, and time-consuming processes. Satellite remote sensing, with its large surface cover and frequent routine observation, has been intensively used for a large number of vegetation applications in rangelands. Examples for such applications include: assessing biomass (Schino et al.

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2003) and leaf area index (Friedl et al. 1994); monitoring vegetation temporal dynamics and phenological changes (Reed et al. 1994; de Beurs and Henebry 2004); classifying plant communities (Clark, Seyfried, and Harris 2001); calculating fractional vegetation cover (Dymond et al. 1992); estimating grass quality for herbivores (Girard et al. 1990; Griffith et al. 2002); monitoring primary production (Prince 1991) and CO_2 (Vourlitis et al. 2003; Wylie et al. 2003); distinguishing grassland from non-grassland (Fuller et al. 1989); evaluating grassland management status (Henebry 1993; Mino, Saito, and Ogawa 1998); quantifying grazing intensities (Kawamura et al. 2005); and many more. These applications have mostly been implemented using various vegetation indices (e.g. Todd, Hoffer, and Milchunas 1998; Schino et al. 2003) and, among these, the normalized difference vegetation index (NDVI) (Tucker 1979) is by far the most commonly used:

$$\mathrm{NDVI} = \frac{\rho_{\mathrm{NIR}} - \rho_R}{\rho_{\mathrm{NIR}} + \rho_R}, \tag{1}$$

where ρ are reflectance values in the respective spectral bands. NDVI is based on the difference between the maximum absorption of radiation in the red (R) spectral region (due to chlorophyll pigments) and the maximum reflection of radiation in the near infrared (NIR) region (due to leaf cellular structure), and the fact that soil spectra, lacking these mechanisms, typically do not show such a dramatic spectral difference. Despite its wide range of applications, NDVI has several disadvantages that have led to the development of other vegetation indices – the soil adjusted vegetation index (SAVI), which is supposed to be less sensitive to soil background (Huete 1988), and the atmospheric resistant vegetation index (ARVI), aimed at reducing the atmospheric effect (Kaufman and Tanré 1992). More recently, the enhanced vegetation index (EVI) was developed in order to optimize the vegetation signal, with improved sensitivity in high-biomass regions while correcting for canopy background signals, thereby reducing atmosphere influences (Liu and Huete 1995; Huete et al. 1997). EVI is based on the NDVI, SAVI, and ARVI indices, and uses functionalities from each in order to overcome soil and atmospheric interferences. EVI is formulated as

$$\mathrm{EVI} = G \times \frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{red}}}{\rho_{\mathrm{NIR}} + C1 \times \rho_{\mathrm{red}} - C2 \times \rho_{\mathrm{Blue}} + L}, \tag{2}$$

where ρ are atmospherically corrected or partially corrected (Rayleigh and ozone absorption) surface reflectances in the respective spectral bands, L is the canopy background adjustment term, $C1$ and $C2$ are the coefficients of the aerosol resistance term that uses the blue band to correct for aerosol influences in the red band, and G is the gain factor. The coefficients adopted in the EVI algorithm are $L = 1$, $C1 = 6$, $C2 = 7.5$, and $G = 2.5$. It should be noted that whereas NDVI is chlorophyll sensitive and responds mostly to ρ_{red} variations, EVI is more ρ_{NIR} sensitive and responsive to canopy structural variations, including LAI, canopy type, and architecture (Pettorelli et al. 2005).

Overgrazing is considered to be the key cause of *rangeland degradation* (Thomas and Middleton 1994), which is in turn almost entirely manifested as *vegetation degradation* (Dregne and Chou 1992). The latter is directly related to reduction in biomass and/or decrease in plant species diversity (Eswaran, Beinroth, and Virmani 2000). However, since it is usually easier to measure vegetation degradation qualitatively rather than quantitatively, predicting a tendency towards rangeland degradation is not always straightforward. For instance, vegetation degradation may be manifested not by biomass loss, but by invasion by or increase in undesirable species that may actually increase biomass production on degraded rangelands/ecosystems, or by loss of palatable pasture grasses and their replacement with unpalatable species (Dregne and Chou 1992; Brown and Archer 1999). From the remote sensing point of view, the above-mentioned vegetation applications, which are related to quantitative variables, are widely implemented in rangelands. Bastin, Pickup, and Pearce (1995), who examined the potential of spaceborne systems for rangeland degradation mapping around Australian watering points, noted that it is impossible to distinguish between different plants or changes in species composition. However, more recently, taking advantage of hyperspectral image spectroscopy technology, a few studies have been aimed at mapping the distribution of certain biological invaders (Lass et al. 2002, 2005; Underwood, Ustin, and DiPietro 2003; Bradley and Mustard 2005, 2006; He et al. 2011) and evaluating changes in canopy chemistry and other canopy characteristics caused by invasion (Asner and Vitousek 2005).

In Mongolia, from historic times, animal husbandry has been the main plank of the economy, with natural pastures comprising more than 78% of its territory. Native grassland is distributed over an area of some 125.8 million ha and, from preliminary studies, it is estimated that there are about 2270 grass species and 600 of other fodder plants. During the last 70 years, population density in the Mongolian drylands has increased more than threefold and total domestic livestock numbers have increased over 2.3-fold. In 2009, there were about 44 million animals including 0.3 million camels, 2.1 million horses, 2.5 million cattle, 17.9 million sheep, and 19.5 million goats. Due to market demands, the number of goats – which are a major source of cashmere and a major cause of pasture degradation – rose by about 400–500% more than the level recommended for ecological balance (Regdel and Dugarjav 2010).

Consequently, detrimental anthropogenic activities such as overgrazing have accelerated, causing vegetation degradation to become the main type of rangeland degradation (Adyasuren 1998; Batjargal 1999; Fujita et al. 2009). A few case studies, at plot-scale level, have drawn attention to a severe decrease in vegetation cover due to overgrazing near settlements and water sources. Yonghong and Jargalsaihan (1993) noted that plant community abundance (composition and richness) decreased as grazing pressure increased, and the native vegetation was replaced by exotic species in the northeast pastureland of the country. They found that succession series along the grazing gradient were *Stipa grandis* and *Leymus chinensis* in the lightly grazed sites, *Stipa krylovii*, *Artemisia frigida*, and low grasses in the moderately grazed sites, and *Carex duriuscula*, *Artemisia scoparia*, and annuals in the heavily grazed sites. Fernandez-Gimenez and Allen-Diaz (1999) found, based on ground observations over 2 years, that the vegetation pattern (in terms of species composition, biomass, etc.) changed along grazing gradients beginning at the watering points, in response to increased grazing pressure in the Mountain Steppe and Steppe zones of Mongolia, while no consistent changes due to grazing were observed in the desert steppe. Also, it was noted that vegetation changes over degraded and eroded areas were significant, and unpalatable plants or weeds fully occupied these areas. However, no shrub encroachment was found to be associated with degradation in Mongolia's grassland (Tserenbaljid 2002; Fernandez-Gimenez and Allen-Diaz 1999).

In the current study, advantage was taken of a unique phenomenon in Mongolia. The Trans-Mongolian Railway, established in the 1950s, traverses the country from the northern border with Russia to the southern border with China, a distance of over 1000 km (Figure 1). The northern segment of this line, connecting Ulan-Ude, Soviet Union, with Ulaanbaatar (the capital city of Mongolia), became operational in 1950 while the southern segment, linking the capital and the Chinese border, was completed in 1955. Since then, its entire length has been protected by fences to avoid animals crossing. Therefore, no grazing is allowed within the fences while intensive grazing characterizes the surrounding

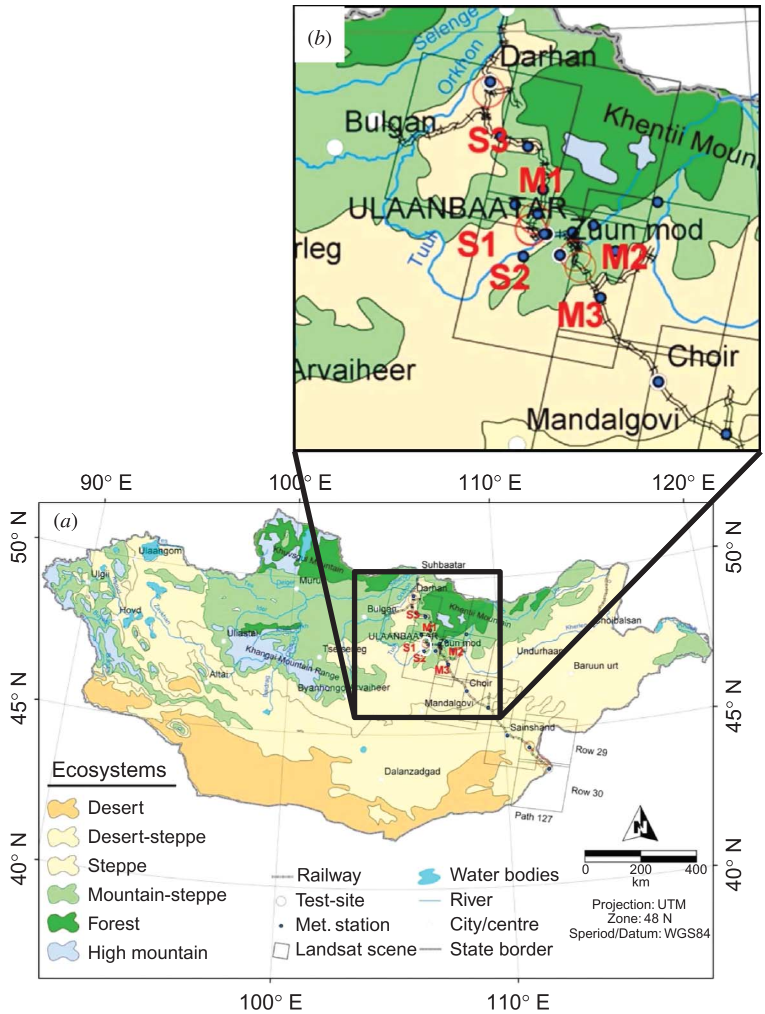

Figure 1. (*a*) Geo-botanical map of Mongolia and the railway that traverses the country from the northern border with Russia to the southern border with China. Locations of the Landsat images are presented; (*b*) study sites along the route of the railway.

area. Vegetation degradation has been amplified in the vicinity of the railway, since the train is the major means of transporting herds and goods to the markets in Ulaanbaatar. Since the railway passes through grasslands with different grazing pressures within and outside the enclosures, it enables the investigation of different plant communities and hence human-induced rangeland degradation. The old railway was constructed according to the topography and thus followed the contour lines, while the fences were stretched along shorter routes. Consequently, when the track curves the distance between flanking fences can be as wide as several kilometres, enabling remote sensing research using high-resolution imagery (Figure 2). The current article attempts at exploring the ability of the remote sensing technique to assess vegetation degradation in the Mongolian steppes. It is hypothesized that intensive grazing reduces plant density, above-ground net primary production, and fractional vegetation cover compared with the adjacent ungrazed sites, and that this situation leads to significantly lower EVI values outside the fence than within.

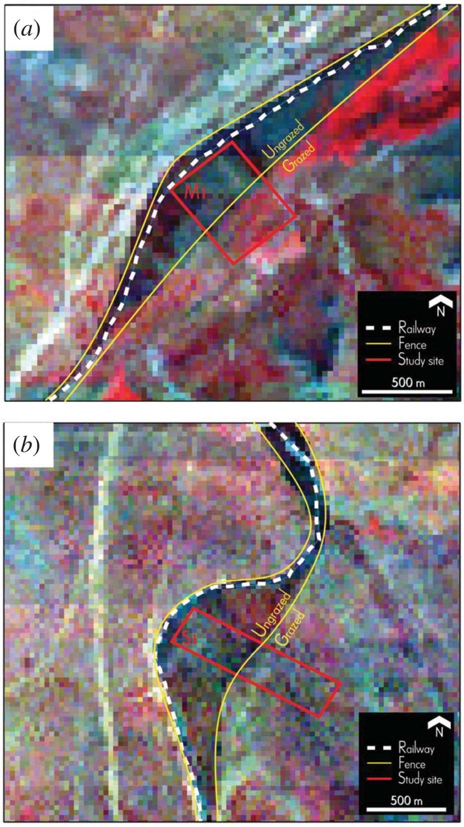

Figure 2. Example of a Landsat ETM+ image (RGB = 4,3,2) showing (*a*) study site M1 and (*b*) study site S1. The area between the fence and the railway is the ungrazed area, while intensive grazing characterizes the surrounding area. Note the reddish colour in the grazed area indicating relatively high NIR reflectance.

2. Study area

Mongolia has a continental climate, characterized by cold, dry winters and warm, wet (rainy) summers. The current research is focused on the Mongolian steppe biome (excluding the desert steppe) (Figure 1), which occupies approximately 4.5×10^8 ha. Mean annual precipitation ranges from less than 75 mm in the south to more than 350 mm in the north, and mean annual temperature gradually decreases from 7°C in the south to –7°C in the north. The aridity index (ratio of precipitation to potential evapotranspiration) ranges from 0.2 to 0.5; Budyko (1974) classified the study area as a semi-arid environment. The northern part of the study area, called the Mountain Steppe, is characterized by a relative steep topography with perennial bunchgrasses in the southern slopes of the mountains, while the northern slopes are covered by coniferous forests over the steppe and meadow types of vegetation. The main plant species in this region are *Festuca sibirica* Hack. ex Boiss., *Stipa krylovii* Roshev., *Stipa grandis* P. Smirn., *Stipa baicalensis* Roshev., *Agrostis mongholica* Roshev., *Galium verum* L., *Poa attenuata* Trin., *Agropyron cristatum* (L.) Beauv., *Leymus chinensis* (Trin.) Tzvel., *Koeleria cristata* (L.) Pers., *Artemisia frigida* Willd., *A. dracunculus* L., *Allium senescens* L., and *Allium ramosum* L. The Steppe zone in the southern part of the study area is characterized by flat plains and rolling hills covered in feather grass and shrubs. Here the main plant species are *Stipa krylovii* Roshev., *Leymus chinensis* (Trin.) Tzvel., *Bupleurum scorzonerifolium* Willd., *Cleistogenes squarrosa* (Trin.) Keng., *Carex duriuscula* C.A. Mey., *Agropyron cristatum* (L.), *Festuca lenensis* Drob., *Artemisia frigida* Willd., *Artemisia adamsii* Bess., *Potentilla acaulis* L., *Allium senescens* L., *Ephedra sinica* Stapf., *Caragana microphylla* Lam., and *Caragana pygmaea* (L.) DC. In more humid ecotopes along valley bottoms and inter-mountain troughs, plant communities are formed by *Agrostis mongholica* Roshev., *Leymus chinensis* (Trin.) Tzvel., *Carex duriuscula* C.A. Mey., *Thermopsis lanceolata* R. Br., *Artemisia laciniata* Willd., *Halerpestes salsuginosa* (Pall. Ex Georgi) Greene., *Glaux maritima* L., *Iris bungei* Maxim., and *Potentilla anserina* L.

3. Methodology

The research was conducted in six study sites selected along the route of the railway (Figure 1). Three are located within the Mountain Steppe zone (denoted hereafter as sites M1, M2, and M3) and the other three are in the Steppe zone (S1, S2, and S3). Each site consists of pairs of study polygons – ungrazed (fenced-off area) and heavily grazed (outside the fences). All sites are large enough in terms of the spatial resolution of Landsat images (30×30 m) and are characterized by flat topography.

Four Landsat-7 Enhanced Thematic Mapper Plus (ETM+) images acquired in the early 2000s were used (20 September 2000, 31 August 2001, 13 September 2000, and 26 July 2002 for path 132 – row 26, 131–27, 131–26, and 130–27, respectively). In order to reduce scene-to-scene variation related to sun angle, differences in atmospheric condition, and vegetation phenology, all images were selected during the vegetation growing season, when the ability to discriminate between vegetation and soil cover is optimal. In addition, cloud cover is minimal in all images. Digital number values were converted to radiance, and ground-leaving reflectances were created from radiances using the 6S algorithm (Vermote et al. 1997). Later, the four images were merged to create a continuous scene, and EVI (Equation (2)) was computed from reflectance values. This index was selected in order to reduce the uncertainty related to soil background and atmospheric effects throughout the entire study area. Approximately, the same number of pixels was sampled in the grazed and adjacent ungrazed polygons.

Ground-truth activities were conducted during two field campaigns in the summers of 2002 and 2003, within the framework of the Joint Russian–Mongolian Complex Biological Expedition, a joint venture by the A.N. Severtsov Institute of Ecology and Evolution RAS, Russia, the Remote Sensing Laboratory (Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Israel), the Institute of Botany (Mongolian Academy of Science), and the National Remote Sensing Centre (Ministry for Nature and Environment of Mongolia). In each of the six study sites a detailed geo-botanical survey of biophysical variables of dominant and co-dominant plant species was conducted using the method described by Shennikov (1964) to determine species composition, plant density, and canopy cover. Relative abundance of species was evaluated by the Drude method (Shennikov 1964), nomenclature followed that of Gubanov (1996), and the above-ground biomass (AGB) of plants was sampled by the method of Larin (1956). Samples were air dried and weighed in the laboratory using an electronic balance of scale 0.1 g. The study polygons were precisely located by the global positioning system (GPS).

In conjunction with the above, spectral reflectance measurements were implemented during the ground surveys using the FieldSpec-HandHeld Spectroradiometer, manufactured by Analytical Spectral Devices (ASD 2000) at wavelength range

325–1075 nm with a spectral resolution of 2 nm. A high intensity contact probe device with a fibre optic was attached to the spectroradiometer. This device has an independent light source (about twofold higher than solar intensity) that makes measurement feasible under all-weather conditions. The contact probe was attached to clipped plants and soil samples. Measurements of a white reference panel (Spectralon plate, Labsphere Inc., North Sutton, NH, USA) were taken immediately before each spectral reading. Reflectance measurements were used to calculate NDVI (Equation (1)) and EVI (Equation (2)).

In order to further explore and compare the performance of these indices for assessing grazing conditions, relative sensitivity (S_r) analysis was carried out as suggested by Gitelson (2004). The general expression for comparing the performance of two spectral indices (X and Y) with respect to any variable is

$$S_r = \left(\frac{\mathrm{d}X}{\mathrm{d}Y}\right)\left(\frac{\Delta Y}{\Delta X}\right), \tag{3}$$

where dX and dY are first derivatives of the compared indices under study, that is, the slope of the regression line that holds the independent variable and the index as the dependent variable; ΔY and ΔX are the ranges of the indices; $S_r > 1$ means that index X is more sensitive (i.e. varies more with respect to the independent variable), $S_r = 1$ means that sensitivities are equal, and $S_r < 1$ means that index Y is more sensitive to the independent variable (Ji and Peters 2007). When $S_r > 1$, the larger the value (either positive or negative), the more sensitive is index X to the variable under study. When $S_r < 1$, the closer the value to zero (either positive or negative), the more sensitive is index Y to the variable under study.

4. Results and discussion

The vegetation communities in each of the six study sites, both within and outside the fencing, were observed during the field campaigns and are presented in Table 1. Table 2 summarizes the results for biophysical variables, their descriptive statistics, and significance. These variables include plant density (plants per unit area), AGB (g m^{-2}), and

Table 1. Vegetation communities in the study sites.

Zone	Site	Polygon	Community
Mountain steppe	M1	Fenced	*Halerpestes salsuginosa* + *Agrostis mongholica* + *Iris bungei*
Mountain steppe	M1	Grazed	*Glaux* maritima + *Agrostis mongholica*
Mountain steppe	M2	Fenced	*Agropyron* cristatum + *Stipa* krylovii + *Leymus chinensis*
Mountain steppe	M2	Grazed	*Leymus chinensis*
Mountain steppe	M3	Fenced	*Galium verum* + *Stipa* krylovii + *Poa* attenuata + *Leymus chinensis*
Mountain steppe	M3	Grazed	*Gallium verum* + *Potentilla* acaulis + *Artemisia frigida*
Steppe	S1	Fenced	*Stipa krylovii* + *Bupleurum* scorzonerifolium + *Cleistogenes squarrosa*,
Steppe	S1	Grazed	*Carex* duriuscula + *Artemisia adamsii*
Steppe	S2	Fenced	*Agropyron* cristatum + *Festuca* lenensis + *Stipa krylovii*
Steppe	S2	Grazed	*Artemisia* frigida + *Potentilla acaulis*
Steppe	S3	Fenced	*Allium senescens* + *A.* ramosum + *Stipa grandis*
Steppe	S3	Grazed	*Carex* duriuscula + *Artemisia frigida*

Table 2. Biophysical variables in the grazed and ungrazed polygons at the study sites, descriptive statistics, and significance.

Polygon	Plant density (plants per unit area)		Above-ground biomass (g m^{-2})		Cover (%)		EVI	
	Ungrazed	Grazed	Ungrazed	Grazed	Ungrazed	Grazed	Ungrazed	Grazed
M1	23	12	216.7	32.2	99.9	59.0	0.21	0.28
M2	29	25	126.4	81.2	58.5	52.0	0.26	0.30
M3	34	25	188.6	43.7	62.6	48.5	0.20	0.28
S1	30	12	53.6	19.2	73.0	50.0	0.25	0.27
S2	20	14	66.1	61.4	55.0	56.0	0.21	0.27
S3	25	20	122.8	114.6	48.0	45.5	0.22	0.27
Average	26.83	18.00	129.03	58.72	66.17	51.83	0.22	0.28
SD	5.12	6.16	64.70	35.00	18.50	4.97	0.02	0.01
t-Test significance	0.004		0.036		0.037		0.001	

percentage of vegetation cover. Values of the Landsat-derived EVI are also presented. Between 23 and 34 plants per square metre were counted within the fencing, while 12–25 plants were found outside (Figure 3(*a*)). Thus, a higher plant density characterizes ungrazed polygons in comparison with the adjacent grazed ones. Similarly, as shown in Figure 3(*b*), within the fencing the average AGB is double that outside. This ratio is higher in the Mountain Steppe polygons than in the Steppe ones. The same trend can also be observed for plant cover, where higher plant cover was observed in the ungrazed polygons in comparison with the grazed ones (Figure 3(*c*)). However, a different trend was revealed by analysis of the image data (Figure 3(*d*)). EVI values derived from Landsat-ETM+ were significantly higher outside the enclosures than within. Additional statistical analyses (*t*-tests) were performed for plant density, AGB, percentage cover, and EVI values, confirming significant differences for each of these variables between grazed and ungrazed areas (Figure 3, Table 2).

This phenomenon (i.e. higher reflectance in grazed areas) was found consistently in each of the study sites, as illustrated in Figure 4. This unexpected finding – negative relations between biophysical variables and vegetation index – requires further discussion regarding plant composition, phenology, and the palatability characteristics of plants. Consequently, detailed examination of the entire species inventory, including individual species name, family, growth form, leaf structure, palatability, and nutrient value, is listed in Table 3. The list is ordered with respect to spectroradiometer-derived NIR reflectance values, which reveal that most of the unpalatable species have high NIR reflectance due to their leaf/cell structure – either thick, hairy, or with high water content (e.g. succulent species).

4.1. Mountain Steppe zone

Different perennial grasses dominate the ungrazed areas, while mostly forbs with little contribution from grasses dominate the grazed areas. The perennial grasses have a good palatable value for animals during the summer, and some, such as *Stipa krylovii* and *Agropyron cristatum*, are especially highly nutritious and are very digestible plants for all livestock throughout the year (Jigjidsuren and Johnson 2003). They bloom in early August and develop mature seeds in September. Also, communities such as *Poa attenuata*, *Leymus chinensis*, and *Agrostis mongholica* have very high palatability for all livestock, especially

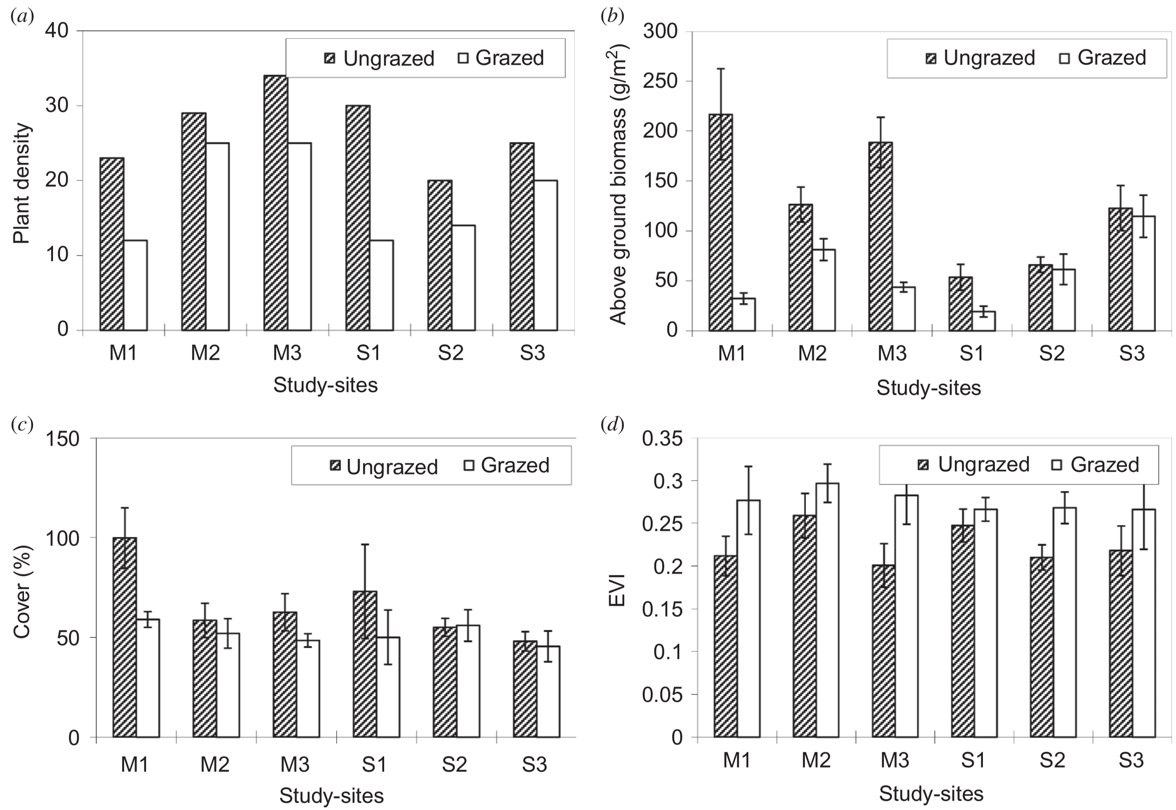

Figure 3. Results of biophysical variables and vegetation index values in the six study sites (Mountain Steppe: M1, M2, M3 and Steppe: S1, S2, S3), in grazed and ungrazed (fenced-off) areas. Variables include: (*a*) plant density (plants per unit area); (*b*) above-ground biomass (g m^{-2}); (*c*) percentage of vegetation cover; and (*d*) Landsat-derived enhanced vegetation index (EVI) values. Note that at all sites, biophysical variable values are higher in the ungrazed areas than in the grazed, while EVI values show the opposite relations. Vertical bars denote ±1 standard deviation of the mean and show a significant difference between grazed and ungrazed areas. Detailed results are listed in Table 2.

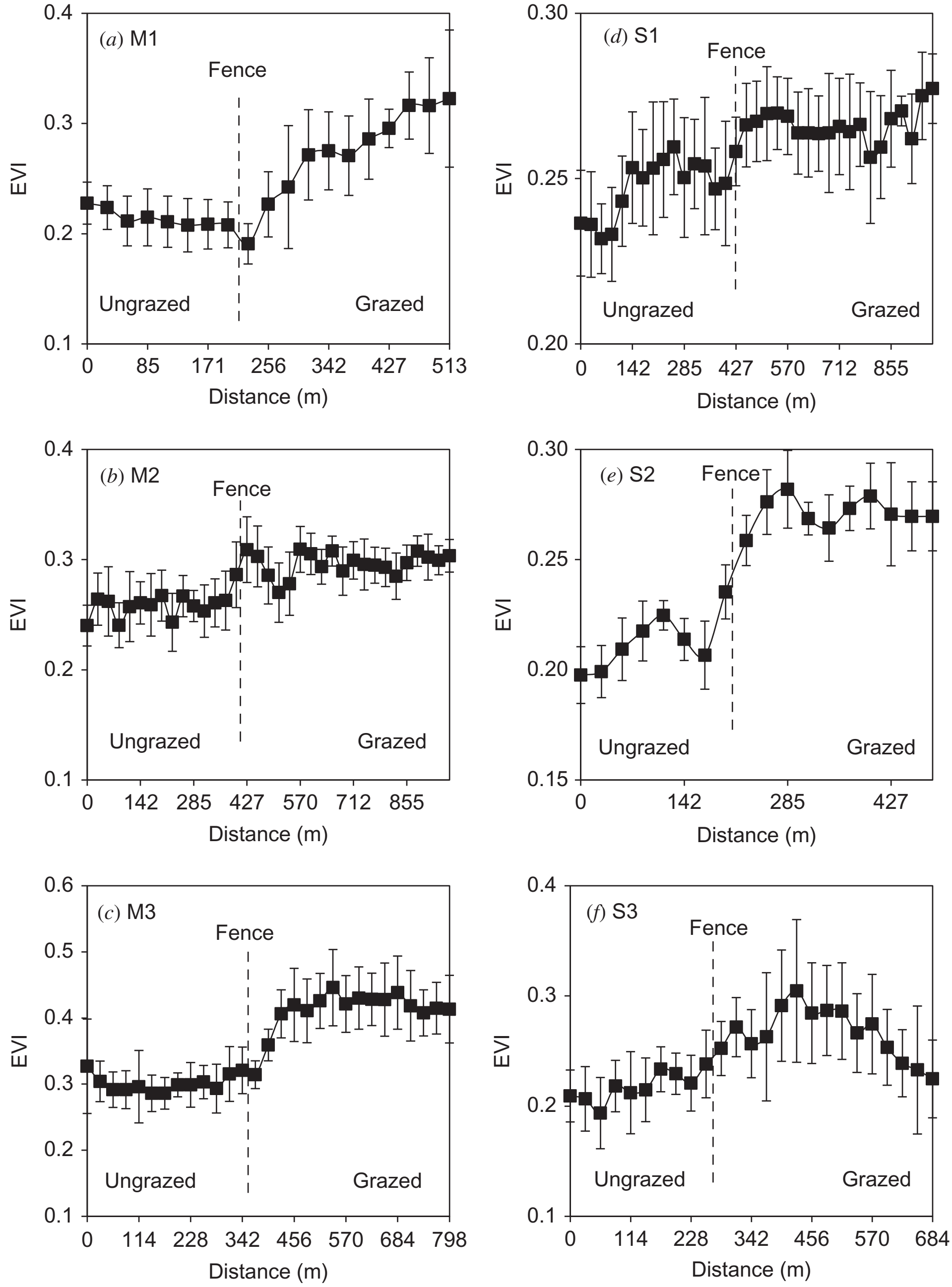

Figure 4. Landsat-derived enhanced vegetation index (EVI) values across the study sites (Mountain Steppe: M1, M2, M3 and Steppe: S1, S2, S3) perpendicular to the fence. Note that EVI values are lower in the ungrazed areas than in the grazed. Vertical bars denote ±1 standard deviation of the mean and show a significant difference between grazed and ungrazed areas.

Table 3. List of individual species, families, growth forms, leaf structure, palatability, and nutrient value. The list is ordered with respect to NIR reflectance values. Note that most of the unpalatable species have high NIR reflectance due to their leaf structure – either thick, hairy, or with high water content (succulent) (from Gubanov 1996).

Site	Plant species	Family	Growth form	Leaf structure	Palatability or nutrient value	NIR
M1	*Glaux maritima* L.	*Primulaceae* Vent.	Perennial, forb	Succulent	Unpalatable	0.79
S3	*Thermopsis lanceolata* R. Br.	*Leguminosae* Juss.	Perennial, forb	Thin	Unpalatable	0.73
S2	*Ephedra sinica* Stapf.	*Ephedraceae* Dum.	Dwarf shrub	Scalelike, thick	Unpalatable, evergreen, poisonous plant	0.73
S1, S2, S3	*Cleistogenes squarrosa* (Trin.) Keng.	*Poaceae* Barnhart	Perennial, grass	Thin	Highly palatable	0.73
S2	*Festuca lenensis* Drob.	*Poaceae* Barnhart	Perennial, grass	Thick	Highly palatable	0.72
M1	*Potentilla anserina* L.	*Rosaceae* Juss.	Perennial, forb	Thin, with hairy	Unpalatable	0.70
M3	*Artemisia laciniata* Willd.	*Asteraceae* Dumort.	Perennial, sage	Thin	Unpalatable	0.70
M1	*Halerpestes salsuginosa* (Pall.ex Georgi) Greene	*Ranunculaceae* Juss.	Perennial, forb	Thin	Highly palatable	0.70
M3, S2, S3	*Potentilla acaulis* L.	*Rosaceae* Juss.	Perennial, forb	Thick, with hairy	Unpalatable	0.69
M1	*Iris bungei* Maxim.	*Iridaceae* Lindl.	Perennial, forb	Succulent	Unpalatable, not grazed when green	0.67
S3	*Allium ramosum* L.	*Liliaceae* Juss.	Perennial, forb	Succulent	Highly palatable	0.62
M2, M3, S1, S2, S3	*Agropyron cristatum* (L.) Beauv.	*Poaceae* Barnhart	Perennial, grass	Thick, flat, hairy on upper surface	Highly palatable	0.59
S3	*Kochia prostrata* (L.) Schrad.	*Chenopodiaceae* Vent.	Semi-shrub	Succulent	Highly palatable	0.59
M2, M3	*Artemisia dracunculus* L.	*Asteraceae* Dumort.	Semi-shrub	Thin	Unpalatable	0.58
M1, M3	*Allium bidentatum* Fisch.ex Prokh.	*Liliaceae* Juss.	Perennial, forb	Succulent	Highly palatable	0.56
S3	*Allium senescens* L.	*Liliaceae* Juss.	Perennial, forb	Succulent	Highly palatable	0.55

(*Continued*)

Table 3. (*Continued*).

Site	Plant species	Family	Growth form	Leaf structure	Palatability or nutrient value	NIR
S2, S3, M2, M3	*Artemisia frigida* Willd.	*Asteraceae* Dumort.	Semi-shrub	Thick, silvery with silky hair on both sides	Highly palatable	0.55
M1, M2, M3, S1, S2	*Stipa krylovii* Roshev.	*Poaceae* Barnhart	Perennial, grass	Thick	Highly palatable	0.55
M1, M2, M3, S2	*Leymus chinensis* (Trin.) Tzvel.	*Poaceae* Barnhart	Perennial, grass	Thick	Highly palatable	0.53
S3	*Stipa grandis* P. Smirn.	*Poaceae* Barnhart	Perennial, grass	Thick	Highly palatable	0.52
S1, S3, M3	*Carex duriuscula* C.A. Mey.	*Cyperaceae* Juss.	Perennial sedge	Thick	Highly palatable	0.52
S2	*Festuca* sp.	*Gramineae* Juss.	Perennial grass	Thick	Highly palatable	0.52
M1	*Bupleurum scorzonerifolium* Willd.	*Umbelliferae* Juss.	Perennial forb	Thin	Highly palatable	0.52
M3	*Caragana pygmaea* (L.) DC.	*Leguminosae* Juss.	Shrub	Thick	Highly palatable	0.51
M2, M3	*Poa attenuata* Trin.	*Poaceae* Barnhart	Perennial grass	Thin	Highly palatable	0.51
M2	*Ptilotrichum tenuifolium* (Steph.) C.A. Mey.	*Brassicaceae* Burnett.	Semi-shrub	Thick	Unpalatable	0.48
S3	*Chenopodium* sp.	*Cnenopodiaceae* Vent.	Annual plant	Thick	Unpalatable	0.47
M3	*Galium verum* L.	*Rubiaceae* Juss.	Perennial forb	Thick	Highly palatable	0.47
S1	*Heteropappus hispidus* (Thunb.) Less.	*Asteraceae* Dumort.	Biennial plant	Thick	Unpalatable	0.44
S1	*Artemisia adamsii* Bess.	*Asteraceae* Dumort.	Perennial sage	Thick, with hairy	Unpalatable	0.41
M1	*Agrostis mongholica* Roshev.	*Poaceae* Barnhart	Perennial grass	Thin	Highly palatable	0.41
M2, M3, S2	*Koeleria cristata* (L.) Pers.	*Poaceae* Barnhart	Perennial grass	Thick	Highly palatable	0.40
S3	*Caragana microphylla* Lam.	*Leguminosae* Juss.	Shrub	Thin	Highly palatable	0.36

small animals (i.e. sheep and goats) over the whole season, and constitute the main plant contributors to Mongolia's pastureland (Tserenbaljid 2002) in addition to the other native *Poaceae* grasses. During the blooming period in August, the dominant perennial grasses, which reach a height of 30–70 cm, have bright grey and brown-grey flowers (1–1.5 cm wide) situated at the tip of their spikes. Since these needle grasses grow relatively uniformly and cover about 20–30% of the fenced-off areas in each study site, the surface looks relatively brighter to the human eye (Figure 5(*a*)). In the false-colour composite of the Landsat image the ungrazed areas looks dark, and no indication for photosynthetic activity is observed (Figure 2). In the grazed areas, perennial forbs, short grasses, and semi-shrubs dominate (detailed in Table 1). Livestock, especially sheep, can barely graze on these plants in summer, while goats moderately graze them in the autumn. Therefore,

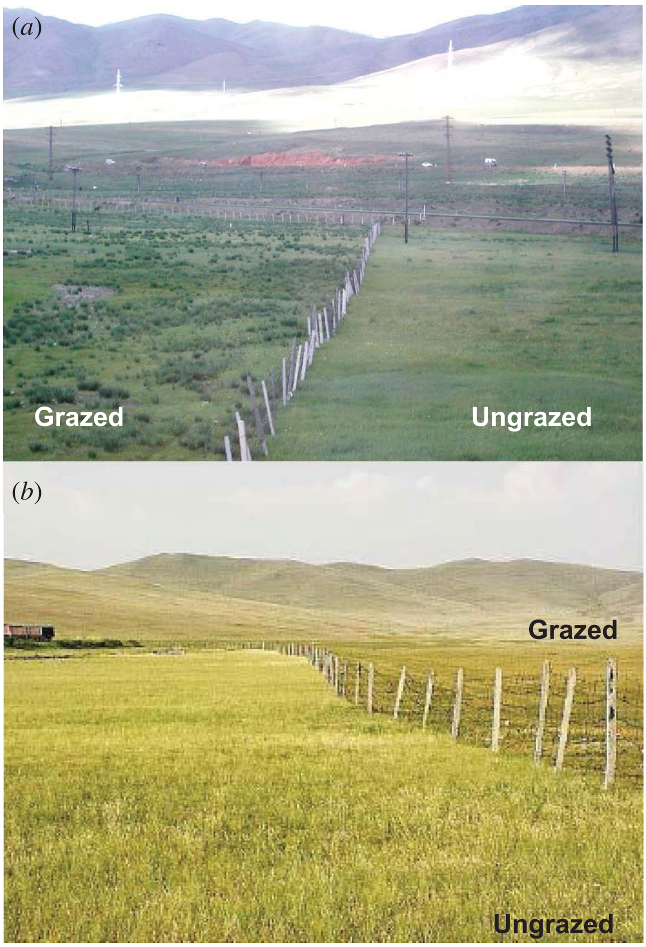

Figure 5. General view of the research sites: (*a*) Mountain Steppe site (M1): the ungrazed area is dominated by *Halerpestes salsuginosa* and *Agrostis mongolica*, and the grazed area by *Glaux maritime* and *A. mongholica*. Note that the darker tones in the grazed area are due to the widespread presence of *Iris bungei*. (*b*) Steppe site (S1): dominating the ungrazed area are *Stipa krylovii*, *Bupleurum scorzonerifolium*, and *Cleistogenes squarrosa*, and the grazed area is dominated by *Carex duriuscula* and *Artemisia adamsii*. Note the brighter tones in the fenced-off area due to the presence of *S. krylovii*.

areas dominated by these plants are seen as relatively green (Figure 5(*a*)). Nevertheless, these dense bunch-forming semi-shrubs are very nutritious for livestock in early summer and late autumn when toxic values might be low. Gunin et al. (1999) noted that several species such as *Artemisia* (*A. scoparia*, *A. frigida*, *A. adamsii*, *Iris bungei*) and *Leymus chinensis*, both abundant in the grazed areas of the present study, are indicators for rangeland degradation and human-induced desertification processes.

4.2. Steppe zone

In the three study sites selected in the Steppe zone, communities of perennial grasses and forbs (see Table 1 for details) dominate the ungrazed areas. All these plants have a very high nutritional value, so they are invaluable forage plants (Jigjidsuren and Johnson 2003). By contrast, perennial shrubs dominated in the grazed areas. As noted by Fernandez-Gimenez and Allen-Diaz (1999), these latter species have undergone different levels of degradation in the Steppe zone of Mongolia. Visually, ungrazed areas in the Steppe are seen as brighter than the grazed areas due to abundance of the perennial grass *Stipa krylovii* (Figure 5(*b*)).

Figure 6 illustrates the spectral reflectance curves of all species in all study sites, grouped into palatable and unpalatable species. Generally, it will be seen that the NIR range of the spectrum (800–900 nm) for the dominant species in the fenced-off area, mostly highly palatable plants (e.g. *Caragana microphylla*, *Koeleria cristata*, *Agrostis mongholica*, and *Galium verum*) have lower reflectance levels, while many of the unpalatable species that occupy the grazed areas (e.g. *Glaux maritima*, *Thermopsis lanceolata*, *Ephedra sinica*, *Potentilla anserina*, *P. acaulis*, *Artemisia laciniata*, *Iris bungei*, and more) have higher reflectance levels (see details in Table 3). General discriminant analysis (GDA) (Baudat and Anouar 2000) was applied in order to verify the significance of differences between the two groups. It was found that in 81.3% of species, the NIR spectra of palatable can be classified as palatable at a very high level of significance ($p << 0.01$), and in 81.8% of species the NIR spectra of unpalatable species can be classified as unpalatable at a level

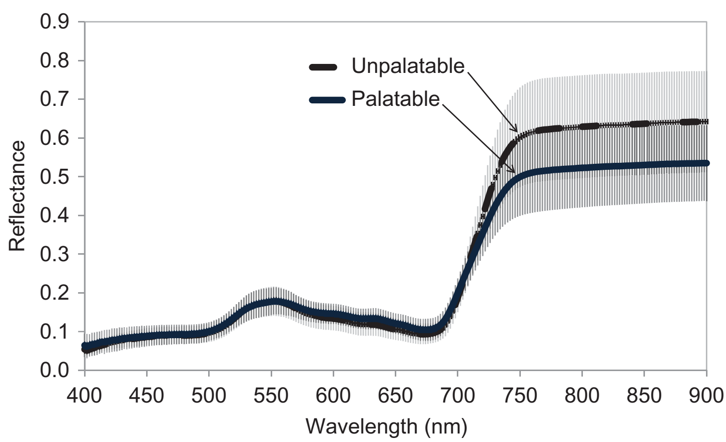

Figure 6. Spectral reflectance curves of all species in all study sites grouped into palatable and unpalatable species. It will be seen that many of the dominant species in the fenced-off area, mostly highly palatable plants, have lower reflectance levels in the NIR part of the electromagnetic spectrum. In contrast, most of the unpalatable species that occupy the grazing areas have higher reflectance levels in the NIR.

Figure 7. Dominant species in the Mountain Steppe zone. (*a*) *Iris bungei*, representative of grazed areas, is a succulent plant characterized by a high refractive index that produces high NIR reflectance values; (*b*) *Stipa krylovii*, representative of protected areas, is a highly palatable grass. During mid-summer it turns yellow, its cells lose water, and its refractive index decreases, and hence its NIR reflectance decreases.

of significance of $p = 0.01$. Figure 7 demonstrates these differences using two representatives from the Mountain Steppe site (M1) (see Figure 5(*a*)). *Stipa krylovii* is a highly palatable grass that represents the protected area. In mid-summer this grass turns yellow, and so its cells lose water, the refractive index decreases, and hence reflectance in the NIR decreases. *Iris bungei* represents the grazed area. This is a succulent plant and is therefore characterized by a high refractive index that produces high reflectance values in the NIR region.

As indicated by Pettorelli et al. (2005), whereas NDVI is chlorophyll sensitive and responds mostly to variation in the red band, EVI is more NIR sensitive and responsive to canopy structural variations, including LAI, canopy type, and architecture. This theory was further examined in the current project. Figure 8(*a*) confirms that there is higher correlation

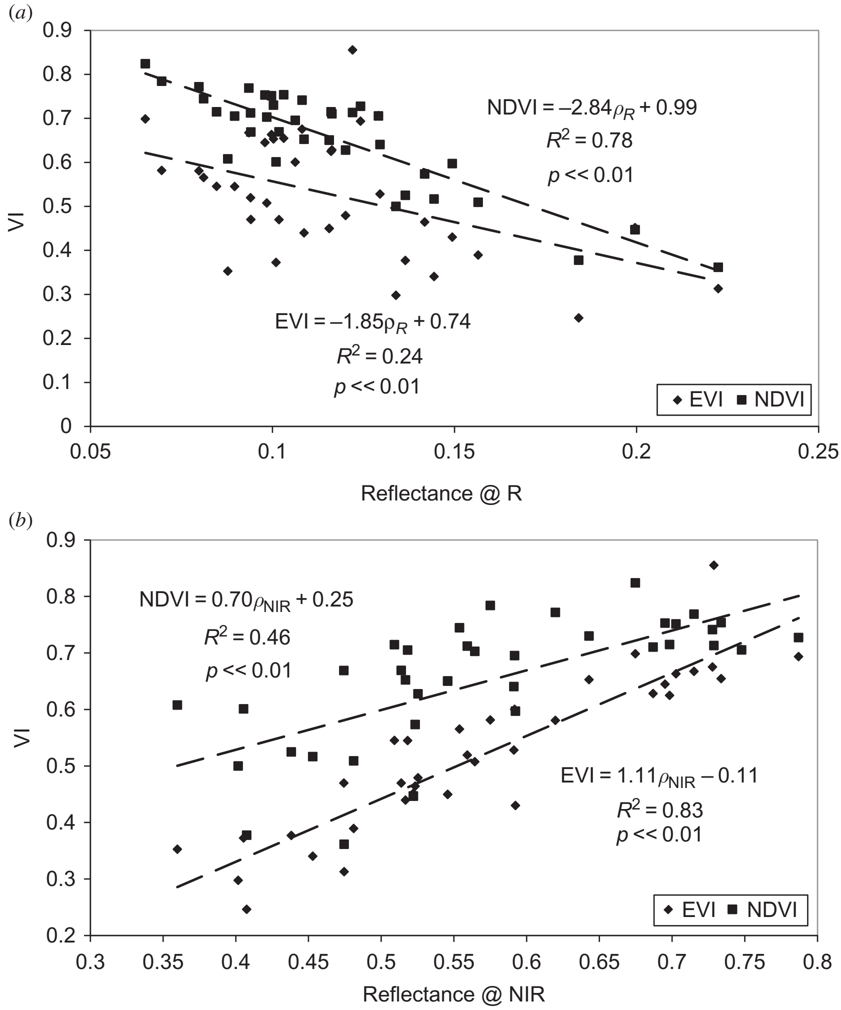

Figure 8. Enhanced vegetation index (EVI) values as a function of reflectance values in the NIR. Strong and significant correlation shows that the index is primarily dependent on leaf structure.

between NDVI and reflectance in the red band than EVI ($r^2 = 0.78$ vs $r^2 = 0.24$, respectively). However, since the grazed areas are primarily characterized by plants with higher reflectance levels in the NIR, due to their leaf cellular structure, higher correlation was found between EVI and reflectance levels in the NIR band than for NDVI ($r^2 = 0.83$ vs $r^2 = 0.46$, respectively), as illustrated in Figure 8(*b*). This conclusion can be also shown from the correlation matrix presented in Table 4, which summarizes the relationships between NDVI, EVI, and reflectance values in the red and NIR bands in terms of correlation coefficient (r). One will notice that the correlation coefficient between the red and NIR bands is only –0.27, though still significant. It should be noted that the present reflectance measurements are related to the leaf level rather that the canopy level. The relative sensitivity of the two indices to the red and NIR bands was examined by applying Equation (3). Results of this analysis confirm that NDVI is more sensitive to reflectance in the red band than EVI, while EVI is more sensitive than NDVI in the NIR. Relative sensitivity (S_r) values are presented in Table 5.

Table 4. Relationships between NDVI, EVI, and reflectance values in the red and NIR bands in terms of Pearson's correlation coefficient (r). Values in italics indicate significant level >99%.

	Red	NIR	NDVI
NIR	−0.27		
NDVI	*−0.88*	*0.68*	
EVI	*−0.49*	*0.91*	*0.81*

Table 5. Relative sensitivity values. $S_r > 1$ means that index X is more sensitive, $S_r = 1$ means sensitivities are equal, and $S_r < 1$ means that index Y is more sensitive to the independent variable. NDVI is more sensitive to reflectance in the red band than EVI, while EVI is more sensitive than NDVI in the NIR.

	$X = \text{EVI}$	
$Y = \text{NDVI}$	0.86	For red
$Y = \text{NDVI}$	2.09	For NIR

5. Conclusions

Ground observations along the route of the Mongolian Railway confirm previous range condition models of vegetation dynamics (e.g. Dyksterhuis 1949). These models predict that as herbivore numbers increase, AGB and cover decline and species composition shifts from dominance by perennial grasses and forbs ('climax' species) towards dominance by unpalatable forbs and weedy annuals. When grazing is decreased or stopped, AGB and cover are predicted to increase again and species composition is shifted back towards late-successional stages. Plant invasion due to grazing in semi-arid and arid systems is a familiar phenomenon in several sites worldwide. For example, in the southwest USA the most conspicuous vegetation change is the growth of creosotebush shrubs, mesquite trees, cholla, and prickly pear cactus, which have transformed the grasslands into a mesquite–grass savanna (e.g. Grover and Musick, 1990; McClaran 2003). Similar to the results of the current study, observations over the last 100 years have revealed a gradual increase in the cover and density of these plants. Although the standard remote sensing-based vegetation index models assume higher index values as AGB and cover increase, the results of the current study show the opposite. The reason is the difference in leaf cellular structure and phenological stage between palatable species within the fenced-off area and unpalatable species outside. Palatable species include mainly grasses that turn yellow in mid-summer, while invading species can be succulent plants characterized by high refractive index that produce high reflectance values. EVI is the correct vegetation index to select for detecting this phenomenon, since it is more sensitive to variations in leaf cell structure as this is expressed in the NIR rather than in the red portion of the spectrum. Although no similar spectral measurements are known from other sites, it is assumed, with high confidence, that similar results would be obtained.

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