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Rangeland cover component quantification using broad (TM) and narrow-band (1.4 NM) spectrometry

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Abstract

Calibrated predictive relationships obtained from simple and multiple regression of thematic mapper or broad-band (BB) and 1.4 nm interval or narrow-band (NB) spectral data were evaluated for quantifying 11 rangeland components (including total vegetation, forb, grass, shrub, litter, and bare soil) and distinguishing among 6 long-term grazing treatments of sagebrush steppe. In general, all 4 data types predicted similar values for each rangeland cover component. Multiple regression models usually had little advantage over simple regression models for predicting cover, particularly for abundant cover components, although this trend was inconsistent among components. Consequently, simple predictive models are recommended for quantifying rangeland indicator components using remotely-sensed data. The use of NB spectral data resulted in lower standard errors of prediction (SEP), although these reductions were inconsistent among rangeland components. Although both data types distinguished among grazing treatments with major plant compositional differences ($P < 0.00$) using a multivariate analysis of variance (MANOVA), only the NB data distinguished between grazing treatments with minor ecological differences ($P < 0.01$). These results suggest that in a practical context, NB data are advantageous for quantifying rangeland cover components and distinguishing among grazing treatments under the condition of our study.

Key Words: indicators, long-term grazing, predictability, sagebrush steppe

Resumen

Se evaluaron relaciones predictivas calibradas obtenidas a través de regresiones simples y múltiples de datos de mapas temáticos de banda amplia (BA) y banda estrecha (BE) de 1.4 nm de intervalo. El objetivo fue evaluarlas para cuantificar 11 componentes del pastizal (incluyendo vegetación total, hierbas, zacates, arbustos, mantillo y suelo desnudo) y distinguir entre 6 tratamientos de apacentamiento de largo plazo en una estepa de "sagebrush". En general los 4 tipos de datos predijeron valores similares para cada uno de los componentes de cobertura del pastizal. Los modelos de regresión múltiple usualmente tuvieron poca ventaja sobre los modelos de regresión simple para predecir cobertura, especialmente para los componentes de cobertura abundante, aunque esta tendencia fue inconsistente entre componentes. Consecuentemente, para cuantificar los componentes indicadores del pastizal mediante el uso de datos de sensores remotos se recomienda modelos predictivos simples. El uso de datos de espectro de BE produjeron errores estandard de prediccion mas bajos (ESP), aunque estas reducciones fueron inconsistentes entre componentes del pastizal. A pesar de que ambos tipos de datos y utilizando el análisis multivariado (MANOVA) distinguieron los tratamientos de apacentamiento con mayores diferencias de composición de plantas ($P<0.001$) solo los datos de BE distinguieron los tratamientos de apacentamiento con diferencias ecológicas menores ($P<0.01$). Estos resultados sugieren que en un contexto practico y bajo las condiciones de nuestro estudio, los datos de BE son ventajosos para cuantificar los componentes de cobertura del pastizal y distinguir entre tratamientos de apacentamiento.

Remote sensing of western U.S. rangelands has increased the speed and efficiency of gathering information on this extensive resource (Tueller 1989). In addition to collecting baseline inventory data, this technology can be used as a monitoring tool for evaluating the influence of disturbances (e.g., livestock grazing) on vegetation composition, productivity, and soil degradation (e.g., Bastin et al. 1993, Pickup et al. 1993). In part, remote sensing is viewed as a favorable alternative to the traditional, ground reconnaisance monitoring methods because the latter are slow, laborious, limited to localized areas, and subject to great variation (West and Smith 1997).

Previous remote sensing of rangelands has been particularly successful at monitoring simple biological attributes such as

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total vegetational cover (e.g., Curran 1980, Gamon et al. 1993). The definition and conceptualization of rangeland "health" or condition, however, has changed to include the amount of bare soil, litter, microphytes (algae, lichen, and moss), standing dead vegetation, and various living plant growth forms (e.g., grasses, forbs, and shrubs) as well (National Research Council, 1994). Soil-based information is necessary to protect the long-term sustainability of the ecosystem, such as ensuring that the minimum threshold of vegetational cover on the soil (e.g., Packer 1951) is maintained. Quantitative information on the relative abundances of plant growth forms are particularly important for managing livestock because they are not only indicative of previous grazing activities (e.g., Mueggler 1950, Laycock 1967, Bork et al. 1998a), but also differ in palatability and nutritional value to livestock.

Rangeland assessment using remote sensing has typically been done using small spatial-scale (i.e., coarse-grained, large pixel size) data collected from broad-band (BB) sensors such as Landsat TM and MSS. These data have been effective in classifying and quantifying total vegetational cover and phytomass (e.g., Mouat et al. 1981, Curran and Williamson 1985, Ustin et al. 1986, Lloyd 1990, Paruelo and Lauenroth 1995) and the cover of growth forms such as shrub (Boyd 1986) and grass (Paruelo and Golluscio 1994). More detailed plant community information has also been obtained from coarse spatial resolution, remotely sensed data using spectral unmixing models, which interpolate the amount of contributing surficial sub-components from either BB spectra (Huete 1986, Pech et al. 1986a, 1986b, Ustin et al. 1986) or narrow-band (NB) spectra (Gamon et al. 1993, Mustard 1993, Roberts et al. 1993, Wessman et al. 1997). These models, however, are not without problems. For example, they are often created under simplified, contrived conditions where only one (or a few) primary vegetation component(s) vary for investigational purposes (e.g., Elvidge and Chen 1995). Because rangelands are complex environments with a great diversity of cover components (and thus, component combinations), the accuracy of these models under practical field conditions is often limited (Price 1994). Another problem with mixture models is that non-linear spectral mixing can occur (Roberts et al. 1993, Borel and Gerstl 1994, Ray and Murray 1996), particularly in arid environments.

A possible alternative to the spectral unmixing approach for quantifying rangeland cover components (e.g., plant growth forms) is alternative spectral variables obtained from the increased spectral resolution of NB remotely-sensed data. These data are collected over many more, but narrower, spectral bandwidths within each ground resolution element (or pixel) than BB data. Because the accuracy of quantifying individual cover components depends directly on the potential for establishing relationships between the abundance of each component and the spectral information within individual pixels, an increased number of spectral bands may improve the ability to quantify individual surface components. Price et al. (1992) used this technology to establish relationships between NB reflectance and total plant cover and leaf area index in a tall grass prairie. Testing is needed, however, within more structurally complex vegetation types such as the sagebrush steppe, where plant cover is substantially lower. In addition to having less living cover, vegetational features are discontinuous and mixed with varying proportions of litter, rock, and bare ground (Tueller 1987), creating a heterogeneous environment that complicates the use of remotely-sensed data.

This study evaluated the accuracy and reliability of broad-band (BB) and narrow-band (NB) spectra for quantifying indicator cover components, particularly those required to evaluate rangeland "health" (NRC 1994) and biological integrity (EPA 1994, West et al. 1994). A previous investigation indicated that calibrated predictive relationships obtained from NB spectral data may improve the quantification of detailed cover components (i.e., increase R^2) relative to BB spectral data (Bork 1997). The general objective of this study was to examine whether these apparent improvements, when applied to a series of historical grazing treatments, translated into more accurate quantification of rangeland cover components.

The specific objectives of this investigation were to, (1) determine whether the leading BB and NB spectral variables predict similar cover values per component relative to point-based sampling methods, and (2) determine whether the NB spectral variables improved differentiation among grazing treatments compared with BB spectral variables.

Methods

Study Site

This research was conducted over 2 years at the U.S. Sheep Experiment Station, 10 km north of Dubois, Ida. (44°14'44" N. Latitude, 112°12'47" W. Longitude). This rangeland is situated at about 1,650 m elevation in the northeastern portion of the sagebrush steppe ecosystem type (West 1983). The climate is semiarid with cold winters and warm summers. Average annual precipation was 324.6 mm over the past 64 years, including 70 cm of snow, with an average annual temperature of 6.1°C (NOAA 1993). About 44% of the annual precipitation falls from May to August, with peak precipitation in May and June. In the year of this study, precipitation was 30 mm below average, with April and May slightly above average and June through August slightly below.

Data for this study were collected from 6 long-term seasonal grazing treatments, in fenced paddocks varying in size from 4 to 12.5 ha, located near the station headquarters. Vegetation in the area is dominated by three-tip sagebrush (*Artemisia tripartita* Rydb.), bluebunch wheatgrass (*Pseudoroegnaria spicata* [Pursh] A Löve), and arrowleaf balsamroot (*Balsamorhiza saggitata* [Pursh] Nutt.) (Laycock 1963; with currently preferred latin names of Kartesz 1994). All of the grazing treatments were established between 1923 and 1950, resulting in a minimum of 46 consecutive years of treatment. Of the 6 treatments currently in place, one has been annually fall-grazed and one annually spring-grazed since 1923. Two others have been fall-grazed and spring-grazed since 1950, respectively, but were previously grazed during the opposite season between 1923 and 1950. These 4 treatments will hereafter be referred to as the old fall, old spring, new fall, and new spring, respectively. The final 2 treatments were exclosures ungrazed by livestock, created in 1940 and 1950, respectively. Prior to establishment, the newer exclosure was spring-grazed, while the

Table 1. Abundance of cover components within each grazing treatment based on 1995 and 1996 cover data (from Bork et al. 1998a).

	Cover (by Grazing Treatment[1])					
Component	O-Fall	N-Fall	O-Spring	N-Spring	O-Excl.	N-Excl.
Vegetational:			(%)			
Live Forb	14.6	11.8	6.4	8.0	13.3	7.1
Live Grass	16.3	17.8	20.0	11.5	13.3	16.0
Total Herb	30.9	29.7	26.4	19.5	26.6	23.0
Live Shrub	17.4	20.5	25.6	28.8	20.5	22.2
Total Veg.	48.3	50.2	52.0	48.3	47.0	45.3
Other:						
Dead Shrub	3.6	6.6	9.2	10.1	7.4	8.5
Lichen	7.1	4.6	3.3	3.2	3.9	3.9
Litter	16.6	15.0	18.3	18.5	17.9	17.0
Moss	1.5	1.1	2.4	1.1	3.3	5.2
Rock	1.1	1.5	1.3	0.8	0.7	0.8
Soil (bare)	21.7	20.9	13.5	17.9	19.6	19.1

[1]Treatments are as follows: O-Fall, annually fall-grazed since 1923; N-Fall, annually fall-grazed since 1950 but spring-grazed from 1923–1950; O-Spring, annually spring-grazed since 1923; N-Spring, annually spring-grazed since 1950 but fall-grazed from 1923 to 1950; O-Excl, no sheep grazing since 1940 with fall-grazing from 1923 to 1940; N-Excl., no sheep grazing since 1950 with spring-grazing from 1923–1950.

older, fall-grazed. All livestock grazing within the treatments since the start of the long-term study has been by sheep. For a complete history of the timing and stocking rates on each grazing treatment, see Bork et al. (1998a).

Based on a previous study, average cover values within each grazing treatment are summarized in Table 1 for each of the 11 cover components. In general, repeated spring-grazing by sheep has removed the perennial forbs such as balsamroot, resulting in a heavy cover of sagebrush with abundant annual herbs such as cheatgrass. Annual fall-grazing by sheep has maintained the native herbs and removed shrubs, producing a more balanced mixture of perennial grasses, forbs, and shrubs (Mueggler 1950, Laycock 1967, Bork et al. 1998a). The exclosures are intermediate in composition between the fall- and spring-grazed areas. Additional residual effects are evident within the 3 switchover treatments (i.e., the new exclosure, fall, and spring paddocks). In particular, the new exclosure and new fall-grazed paddock remain greater in shrub cover than their older counterparts (Laycock 1967, Bork et al. 1998a). The significant historical precedent and information available from this grazing trial make it an ideal location to test the effectiveness of BB and NB spectral data for distinguishing among rangelands (i.e., treatments) with distinctly different vegetational compositions.

Soils in the area have been derived from wind-blown loess, residuum, or alluvium overlying basalt bedrock . All 6 soil types within the study area are Mollisols, with soil characteristics heterogeneous across the landscape because of the variable thickness of unconsolidated parent material (Natural Resources Conservation Service or NRCS, 1995). The mix of soils within pastures, however, is similar (Bork et al. 1998b). Litter, lichen, moss, bare soil, and exposed rock are relatively common.

Spectral Sampling

Repeated, close-range multispectral measurements were made on cloud free days at 30 randomly-positioned circular plots in each of the 6 grazing treatments, during mid June, July, and August of 1996. All plots were clearly marked to facilitate re-sampling. The sampling dates were selected to maximize the phenological separation documented among the major vegetational components within the study area (Blaisdell 1958), and coincided with peak greenness of all growth forms (early to mid June), moderate herb senescence (mid July), and advanced herb senescence (late August), respectively. A Personal Spectrometer II (Analytical Spectral Devices [ASD] Inc., Boulder, Colorado, 1991), mounted on a light-weight, portable aluminum boom, was used to measure each plot between the peak sunshine hours of 1100 hours and 1500 hours MDT (i.e., within 2 hours of solar noon). The spectral receptor had a 25° field of view. It was oriented vertically 3.4 m directly over the center of each plot at the end of the boom using a water-level and plumb-bob. This produced a circular instantaneous field-of-view (IFOV) with a diameter of 1.51 m and ground surface area of approximately 1.75 m^2. The observers and frame were consistently positioned on the north side of the plot to avoid shadowing and disturbing the vegetation.

Spectal sampling was preceded by calibration of the spectrometer using a standardized white *SPECTRALON*™[1] panel and dark reading adjustment. Integration time per reading was 175 milliseconds. Calibration was redone at least every 30 min. during each sampling session. Each spectral file was recorded as the average of 5 readings over a 2 second period to minimize the impact of plant movement by wind or other factors (e.g., insects) on the readings.

Spectral readings were recorded as the proportion (%) of incident spectral energy reflected, from 380 to 1075 nm wavelength in consecutive 1.4 nm wide bandwidths (i.e., 500 bands). The shortest wavelength measured was 400 nm to eliminate the ultraviolet region. The upper range was set at 960 nm to include the minor water absorption band at this upper limit (Hoffer 1978), but eliminate the noisy bands beyond this range. In addition to the narrow-band (NB) data, the software used with the spectrometer provided simulated broad-band (BB) values (i.e., thematic mapper) that were used as a benchmark to which the NB measurements could be compared. Simulated thematic mapper data consisted of the relative percent reflectance over the same waveband intervals as on the Landsat thematic mapper sensor, but as measured by the PS-II, over the intervals 450–520, 520–600, 630–690, and 760–900 nm, respectively (ASD 1991). These data were not adjusted for differences in gains, etc., between instruments, nor to top of atmosphere equivalent.

Cover Component Sampling

Cover data were collected from each of the 180 plots within 48 hours following June spectral sampling. Cover data were measured using a variation of the point sampling method (Floyd and Anderson 1982), with the minimum

[1]Registered trademark of Labsphere Inc., North Sutton, N.H. 03260-0070.

number of points determined from a pilot study (Bork 1997). Each plot was sampled with a point-frame containing 164 equally-spaced points, 10.5 cm apart. Two layers of cross wires 20 cm apart were used to facilitate vertical cross-sighting and reduce parallax.

The surface feature immediately below each point was recorded, with the data compiled into average cover values per component per plot. All 11 surface cover components (Table 1, left column) examined were rangeland soil and vegetation indicators that had either been previously linked directly to rangeland condition within the study area (Mueggler 1950, Laycock 1967, Bork et al. 1998a), or were important on the basis of current rangeland condition theory (NRC 1994).

Data Analysis

Previous work (Bork 1997) had analyzed one-third of the study plots, 10 from each grazing treatment (N = 60), with simple and stepwise multiple regression, to determine, within each of the 11 cover components, the potential improvement in predictability from using narrow-band (NB) as compared with broad-band (BB) spectral data. Data analysis evaluated a wide range of spectral variables from each sampling date in each type of spectral data (BB and NB), including isolated spectral reflectances (i.e., simple variables), as well as composite variables involving more than one reflectance (i.e., complex variables). Examples of the latter included ratio indices such as the Difference Vegetation Index (near infrared [NIR]-red), Normalized Difference Vegetation Index ([NIR-red]/[NIR+red]) (Tucker 1979), and the Soil Adjusted Vegetation Index ([NIR-red]*[1+L]/[NIR+red+L]; where L is an adjustment for bare soil effects) (Huete 1988), as well as derivative (i.e., slope-based) indices for the NB data. Multi-date measurements were used to determine the change in each spectral variable between June and July, July and August, and June and August. From these analyses, 4 regressions were established for each cover component, 2 based on the leading simple regression using single spectral variables (one for each data type) and 2 multiple regression models (one for each data type). These regressions are provided in Table 2.

In the present study, the unique history of each grazing treatment allowed evaluation of how well the calibrated spectral data could address the 2 primary management questions that had been identified within the study area (Bork et al. 1998a). The first of these questions examined the impact of seasonal sheep grazing since 1950 (i.e., the general differences among the fall, spring, and exclosed areas). The second question examined the residual impact of the seasonality of sheep grazing prior to 1950 (i.e., rangeland resilience), wherein the original fall, spring, and exclosed areas were compared to the new fall, new spring, and new exclosed treatments, respectively. Note that our objective was not to document the comprehensive differences in cover components among the treatments as that has been done elsewhere (Bork et al. 1998a), but rather to evaluate how the BB and NB spectral data may differentiate among treatments relative to the 2 primary management questions.

To test the regressions for distinguishing among treatments and contrast the calibrations from each data type, spectral data from the plots not used in the initial calibration procedure (N = 119; 20 in each treatment except the new spring paddock, where the marker for 1 plot was lost due to wind) were used to predict the cover of each component using all 4 regressions (i.e., of the variables in Table 2). This was done by inserting the required spectral variable(s) into each regression and calculating the predicted cover in each plot. Predicted cover from each regression (BB simple and multiple, and NB simple and multiple) within each plot was subsequently compared to measured cover to evaluate the accuracy of the calibrations within each cover component. Overall accuracy was determined for each component by computing the adjusted standard error of predicted cover across all 119 validation plots using the formula:

Table 2. Summary of the leading spectral variables used to predict each cover component with broad-band (BB) and narrow-band (NB) data, using simple and multiple regression.

Component:	Broad-Band[1] Simple	Broad-Band[1] Multiple	Narrow-Band[1] Simple	Narrow-Band[1] Multiple
Vegetational:				
Forb	Jn-Aug DVI[2]	Jn Green; Jn NIR	Jn-Aug SL32	Jn B769; Jn B784; Aug B755; Aug B897
Herb	Jn-Jy SAVI	Aug Blue; Aug Red; Jn Blue; Jn NIR	Jn-Aug SL16	Jn B769; Aug B599; AugB684
Grass	Aug NIR	Aug NIR	Jn-Jy SL8	Aug B954
Shrub	Aug NDVI	Aug Red; Aug NIR	Aug SAVI 698/670	Aug B670; Aug B698; Aug B883
Total Veg.	Jn NDVI*	Jn Blue; Jn NIR	Jn SAVI 698/670*	Jn B542; Jn B613; Jn B698
Other:				
Dead Shrub	Aug Red*	Aug Blue; Aug Red; Jn Green	Aug SLPA*	Jn B585; Aug B514; Aug B670
Lichen	Jn Blue	Jn Blue	Jn B499	Jn B443; Jn B457; Jn 528; Jn B542; Jn B883
Litter	Jn Red	Jn Red	Jn ARred	Jn B641
Moss	Jy G/B NDVI	Jy G/B NDVI	Jy SAVI 570/400	Jy B755
Rock	Jy Blue	Jy Blue	Jy SAVI 698/670*	Jy B400
Soil (bare)	AugNDVI*	Aug Blue	Aug NDVI Max NIR/MinRed*	Aug B514; Aug B570; Aug B954

[1]Simple regressions marked with a '*' are 2nd-order, curvilinear functions.
[2]Spectral variables derived from multi-temporal sampling dates are represented by differences between data on those dates.

$$\text{St. Error Prediction Sqrt} = \frac{\{[\,\text{Sum}_{i=1..N}(PC_i - MC_i)^2] - [\,(\text{Sum}_{i=1..N}(PC_i - MC_i))^2/N\,]\,\}}{\text{Sqrt}[\,N - 1\,]} \qquad \textbf{(1)}$$

where:
PC = predicted cover,
MC = measured cover,
N = total number of plots, and
i = the ith plot.

To determine whether the spectral data could distinguish among the 6 grazing treatments, a Multivariate Analysis of Variance (MANOVA) using SAS proc GLM (SAS Institute Inc. 1988) was performed on the set of leading BB spectral variables isolated from the simple regressions (Bork 1997). A similar procedure was done on the NB data (Bork 1997). Six single degree-of-freedom contrasts were used within the model to address the management-based questions. Three contrasts examined the data for main grazing treatment differences (i.e., fall vs spring, fall vs exclosed, and spring vs exclosed) and 3 assessed the residual effects of management prior to 1950 (i.e., the original fall, spring, and exclosure vs newer fall, spring, and exclosure, respectively). As a result, the MANOVA tested the ability of each spectral data type (BB and NB) to distinguish significant differences among treatments, both overall and within the specific contrasts (i.e., questions) of interest. Roy's greatest root, a test statistic derived from comparing the among-grazing treatment variation (of spectral variables) to within-treatment variation (of spectral variables), was used to evaluate results of the MANOVA (Scheiner 1993).

To directly assess whether any of the 4 regressions of spectral data for each cover component had a practical impact on distinguishing among grazing treatments, the same 6 contrasts were done ($P<0.10$) within each cover component on the BB and NB predicted values from both the simple and multiple regressions. Contrasts among treatments of the measured cover values ($P<0.10$) provided the benchmark against which

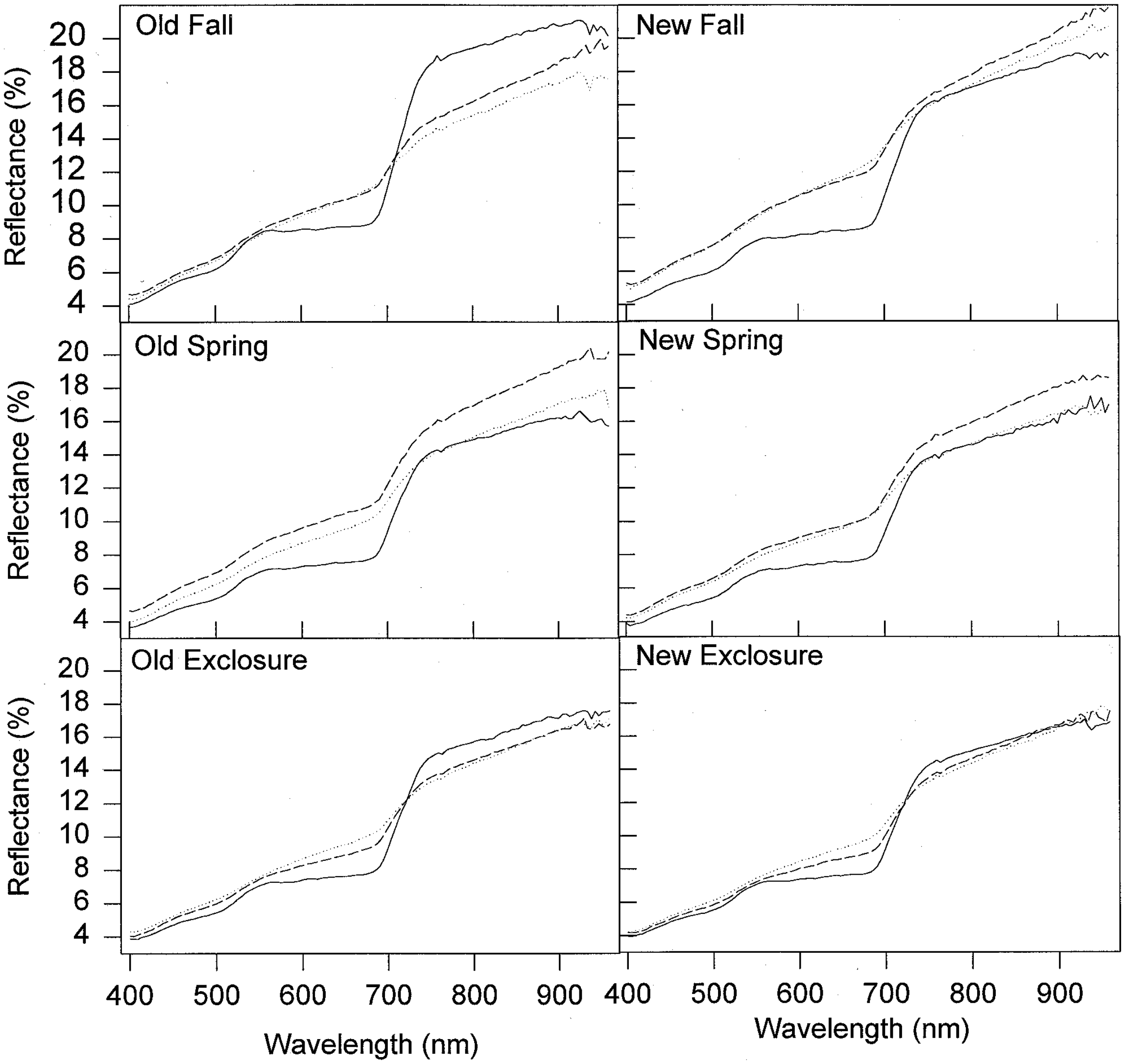

Fig. 1. Mean narrow-band spectral response curves for June (solid line), July (dashed line), and August (dotted line) 1996, for each grazing treatment (n = 30).

Table 3. Mean measured and predicted cover (standard error of prediction [SEP] in parentheses for predicted cover) using the simple and multiple regression calibrations of the broad-band (BB) and narrow-band (NB) data within each of the 11 cover components examined.

Cover Component	Actual Cover (N = 119)	Predicted Cover Simple Regression		Multiple Regression	
		BB Data	NB Data	BB Data	NB Data
	- - - - - - - - - -	- - - - - - - - - -	- - - (%) - - -	- - - - - - - - - -	- - - - - - - - - -
Vegetational:					
Forb	8.8	8 (5.62)	4.7 (5.80)	8 (4.99)	8.3 (5.84)
Grass	15.6	15.5 (7.59)	15.3 (7.17)	15.6 (7.59)	15.4 (7.75)
Herb	24.2	17.9 (7.62)	23.4 (7.64)	23.6 (7.16)	23.1 (7.14)
Live Shrub	21.7	22.7 (7.87)	21.3 (7.33)	22.8 (7.86)	23.1 (7.14)
Total Vegetation	45.9	46.2 (6.52)	47.2 (6.27)	47.4 (7.14)	47.2 (6.78)
Other / Soil-Based:					
Dead Shrub	7.2	7.4 (4.88)	7.4 (4.81)	7.6 (4.92)	7.6 (4.92)
Lichen	4.7	4.1 (9.02)	4.1 (9.04)	4.1 (9.02)	6.4 (9.03)
Litter	19.2	19.6 (5.91)	19.6 (5.93)	19.5 (5.92)	19.6 (5.89)
Moss	2.7	3.1 (2.91)	2.9 (2.93)	n/a[1] (2.92)	2.9
Rock	1.4	0.8 (2.73)	0.8 (2.64)	0.7 (2.74)	0.7 (2.72)
Soil (bare)	18.9	18.8 (7.09)	19.1 (7.47)	18.5 (7.54)	19.2 (7.20)

[1]No BB spectral variables met the minimum significance level for entry using multiple regression.

to check for any practical differences within the 4 calibrated regressions. This procedure evaluated the calibrated regressions at a practical level, and facilitated testing of the NB data for improved predictability of cover components among treatments. For each cover component, we determined, (1) the number of contrasts per calibrated regression that correctly represented measured cover differences, (2) the number of contrasts significant in the measured data that were missed (i.e., found not significant) within the contrasts of predicted data, and (3) the number of non-significant contrasts within the measured data that were found significant in the predicted data. These values represented correct classifications, omission errors, and commission errors, respectively.

Results

The mean narrow-band (NB) spectral response curves from June, July, and August for each grazing treatment are depicted in Fig. 1. Several notable differences are apparent, both between main treatment types and within treatment replicates (i.e., old vs new). Among all 6 treatments, the 2 fall-grazed areas had sine wave-like spectral response curves in June, which flattened by July (mid-summer). While the response curve of the old fall treatment flattened out from a drop in the near infrared and increase in red reflectance, the new fall curve changed almost exclusively in visible reflectance (i.e., near infrared was stable). This latter pattern of temporal change was also apparent in the spectral response curves of both spring-grazed treatments. Interestingly, both spring treatments had increased in reflectance in July and declined in August, with the old spring showing greater changes over time. Both exclosures had spectral response curves similar to the old fall treatment, although the magnitude of change was less than that found in the latter.

Average predicted cover values within each cover component were similar to measured cover regardless of regression type (Table 3). Only 3 noticeable exceptions were found. Predicted forb cover was under-estimated using the leading single NB spectral variable while herb cover was under-estimated by the leading single broad-band (BB) spectral variable. In contrast, lichen was over-estimated using multiple regression of the NB data.

In general, the standard error of prediction calculated for each of the 4 regression types did not appear to differ within individual cover components (Table 3). In only one case did multiple regression reduce the standard error of prediction by at least 10% relative to simple regression (BB forb, from 5.62 to 4.99). Other decreases in the standard error of prediction from using multiple regression occurred for bare soil (NB), live shrub (NB), and herb (BB and NB) (Table 3). In several situations, the standard error of prediction was greater as a result of using multiple regression. For example, the error for grass using NB data went from 7.17 to 7.75. Other increases in the standard error were evident for bare soil (BB) and total live vegetation (both BB and NB) (Table 3).

Little difference was observed in the standard error of prediction from using NB data (Table 3). Of the differences that did occur, results were mixed regarding the type of spectral data. For example, when NB data were used, the standard error for forb was greater using either simple or multiple regression, but lower for live shrub and total vegetation using each regression strategy (Table 3). While the herb component showed virtually no difference in standard error, grass had a mixed response with only simple regression of NB data resulting in a lower SEP. Among the non-living and soil-based cover components, differences in the SEP from using NB data were minimal, with the only exception being bare soil (Table 3).

Results of the MANOVA showed significant differences between the BB and NB subsets of simple spectral variables among the 6 grazing treatments (Table 4). Furthermore, these significant differences ($P<0.001$) were apparent in all the main effect contrasts using both data types (Table 4). This trend, however, did not continue into the 3 contrasts addressing the differences among grazing treatments grazed similarly since 1950, but differently before then (i.e., examining residual effects or rangeland resilience). Although all 3 of these contrasts were significant using the NB

Table 4. Results of the overall and contrast-based MANOVA for the broad-band (BB) and narrow-band (NB) data.

Test:	BB Spectra (N = 10)		NB Spectra (N = 11)	
	F - Value[1]	P	F - Value[1]	P
Overall Model[2]	10.98	$p < 0.001$	13.72	$p < 0.001$
Main Effect Contrasts:				
Fall vs Spring	5.83	$p < 0.001$	9.11	$p < 0.001$
Fall vs Excl.	5.44	$p < 0.001$	6.03	$p < 0.001$
Spring vs Excl.	4.68	$p < 0.001$	4.69	$p < 0.001$
Residual Effect Contrasts:				
Old Fall vs New Fall	6.88	$p < 0.001$	7.3	$p < 0.001$
Old Spring vs New Spring	1.44	$p = 0.18$	2.45	$p < 0.01$
Old Excl. vs New Excl.	1.27	$p = 0.26$	5.38	$p < 0.001$

[1]F - values are based on Roy's greatest root.
[2]The overall model tests collective spectral differences among all 6 grazing treatments.

data, when the BB spectral data were used, only the comparison between the old and new fall-grazed treatment was significant (Table 4).

Statistical contrasts among the grazing treatments based on the measured and predicted cover from the 4 regressions were also compared to determine the number of significant contrasts within each type of predicted cover data that were correct, commission errors, and omission errors, relative to the contrasts of measured data (data not shown). In general, the number of correctly predicted significant contrasts were highly variable among the cover components, regardless of data type and regression strategy. Living cover components were particularly poor, with the number of contrasts correctly predicted ranging from 25% (total vegetation) to 75% (forb and shrub). Non-living and soil-based components were not much better, ranging from 50% (litter) to 83% (dead shrub). As might be expected given the low proportion of correct predictions, commission and omission errors were also common among nearly all predicted contrasts for all cover components, with relatively greater errors associated with the vegetational components.

Comparison of the detailed contrasts among grazing treatments using predicted and measured cover values showed that the use of NB data instead of BB data, resulted in an increase in the number of correct contrasts (from 63 to 79% and from 52 to 63% for simple and multiple regression, respectively). A corresponding reduction was evident in the number of commission, and in particular, omission errors, from using NB data (ommission errors changed from 38 to 21%, and 42 to 38%, for simple and multiple regression, respectively).

Discussion

This study is unique in that it simultaneously evaluated both narrow-band (NB) and broad-band (BB) spectral data for quantifying rangeland cover components (e.g., growth forms) through the use of localized plots. The results indicated not only how well these data predict various cover components, but facilitated the subsequent separation of grazing treatments. Although previous remote sensing work has addressed the task of quantifying plant growth forms such as shrubs (e.g., Boyd 1986) and grasses (e.g., Paruelo and Golluscio 1995) on rangelands, these studies have used coarse resolution satellite data and ocular estimates of component cover, making them more difficult to interpret.

The prominent changes in spectral response curves within each of the grazing treatments early in the summer (from June to July) are consistent with the relatively rapid progression of phenologies among most range plants common in the area (Blaisdell 1958). The fall-grazed treatments, particularly the old fall, had the greatest herb cover (Bork et al. 1998a), resulting in these treatments exhibiting the largest degree of temporal change in reflectance within the spectral response curve. Although the exclosures were also high in herb cover, these areas had abundant shrub cover as well. The higher shrub:herb ratio likely produced more shadow and overtopping of the herbaceous understory, reducing green vegetation reflectance (Wilson and Tueller 1987). As a result, the spectral response curves of these treatments varied less throughout the growing season.

The lack of temporal change in the near infrared spectral region of the old spring-, new spring-, and new fall-grazed treatments was somewhat surprising. There are, however, several possible explanations for this observation. These paddocks had the greatest annual herb cover (both forb and grass) (Bork et al. 1998a). Rapid senescence of annuals may have increased the relative reflectance from soil-based components over time, thereby increasing near infrared reflectance. In contrast, the long-term fall-grazed treatment and 2 exclosures, which were dominated by deep-rooted perennial herbs, may have remained green longer into the summer and produced abundant litter in the shrub interspaces that persisted (Comanor and Staffeldt 1979), thus concealing more of the soil surface. Litter from perennial species may also have contributed to a greater organic matter content at the soil surface although this notion has not been independently verified. Finally, surface soil moisture may have played a role, particularly if spectral observations were obtained before the soil surface fully dried following precipitation events during the summer.

Within individual cover components, mean predicted cover was similar to measured cover, regardless of the regression type used. Inspection of the residual differences between predicted and measured cover data at the plot level, however, showed that deviations (i.e., predicted-measured) were highly variable among sampling plots. These differences continue to reflect the inherent "white-noise" of the data within the study area. These results indicate that while the average predictability of components among many plots may be maintained under various regression strategies, caution should be used when trying to extrapolate to the individual plot level. For those cover components where predicted cover and measured cover showed greater discrepancies (e.g., forb, herb, and lichen), the independent spectral variables used to predict cover may be less reliable. In the case of lichen, 5 NBs were selected into the multiple regression model indicating the poor predictability may be due to regression overfitting.

Overall, the standard error of predictions within cover components varied little among the 4 regression types evaluated. The smallest differences occurred within the less abundant cover components (i.e., rock, moss, lichen, and dead shrub) in Table 3. Where differences did occur, the use of multiple regression and NB data did not consistently reduce the standard error, indicating that the ideal type of regression strategy for predicting cover varies among components. Furthermore, changes in standard error appeared to depend on (i.e., interact with) both the mode of regression (simple and multiple) and data type (BB and NB). Multiple regression frequently produced lower standard errors for the more detailed components, particularly plant growth forms (i.e., forb, herb, and shrub). Interestingly, multiple regression within the more general cover components [e.g., total vegetation and bare soil (BB only)] often failed to reduce the standard error of prediction. Hence, it appears that complex predictive models containing multiple spectral variables may only be beneficial for rangeland monitoring when more detailed cover components are of biological interest.

The use of NB data relative to BB data more often than not reduced the standard error of prediction. Unlike the trend for simple and multiple regression, however, NB data were more advantageous for quantifying total living vegetation and other relatively abundant living growth forms. Components that did not have a lower standard error using NB data included those with relatively little cover, such as forb.

Examination of the spectral data using a MANOVA provided a qualitative method to directly examine the grazing treatments for the ecological differences of concern to rangeland managers. Significant differences showed that when either the BB or NB spectral variables from the simple regressions were collectively examined, all of the main effect contrasts among grazing treatments were significant. These results are supportive of the fact that the fall, spring, and exclosed areas have the greatest vegetation compositional differences (Bork et al. 1998a) and hence, are easily separable. However, significant differences among the old and new paddocks within each main treatment were not consistent among the BB and NB data. Using BB data, only the 2 fall-grazed treatments differed. The lack of differences within the 2 exclosed and 2 spring-grazed areas indicated that the BB data were unable to detect the residual effects of management prior to 1950. Interestingly, of the 3 contrasts evaluating residual effects, the old and new fall-grazed treatments had the most dissimilar cover component compositions (Bork et al. 1998a) due to the slow recovery following spring-grazing prior to 1950 in the latter (Laycock 1967). Unlike the BB data, the MANOVA with NB data showed all 3 contrasts for residual effects were significant. This is despite the 2 spring-grazed treatments both being near-monocultures of shrub and the 2 exclosures being similar stands of spatially mixed shrub and perennial herb. Thus, it appears that while BB and NB spectral data are both useful for qualitatively distinguishing among grazing treatments with prominent compositional differences, the increased spectral resolution associated with NB data may improve the qualitative separability of grazing treatments that are dissimilar with respect to more subtle, but managerially important, ecological characteristics.

The increased number of correct contrasts and decreased number of omission errors as a result of using NB data suggests that despite the lack of differences between BB and NB standard errors of prediction, the NB data may still confer an advantage within practical remote sensing applications designed to quantitatively distinguish among grazing treatments. The extent to which NB data may be beneficial, however, will depend on both the a priori degree of inherent differences among treatments and the required extent of separability during application. The lack of consistent improvements also suggests that to determine whether NB data will be advantageous, a direct comparison between BB and NB data relevant to the problem will be necessary within the area of interest (i.e., on a case study basis).

Conclusion

This study utilized a "bottom-up" framework as an alternative to the traditional "top-down" scientific approach for problem solving in natural resource management (Shrader-Frechette and McCoy 1993). Top-down monitoring of rangelands using remote sensing has typically used coarse resolution spectral data and poorly ground-truthed information on ecosystem characteristics (e.g., Boyd 1986, Paruelo and Golluscio 1995). In contrast, collecting localized data in well-defined plots and correlating it directly with broad-band (BB) and narrow-band (NB) spectral data circumvents the logistical problems associated with coarse-resolution data, such as georectification and ground-truthing. As a result, this study was able to evaluate the potential of NB remotely sensed data for assessing rangeland condition.

This study indicates that NB spectral data offer an advantage over BB data for qualitatively distinguishing among sagebrush steppe rangelands in different vegetational states, particularly when ecologically-induced differences from grazing are subtle. The advantage of NB data for quantitatively predicting rangeland cover components and distinguishing among unique grazing treatments, however, remains questionable due to highly inconsistent results among data types within cover components. Consequently, at present, it is doubtful that NB data can fill the needs of rangeland managers to accurately quantify specific cover components (i.e., growth forms that serve as indicators) (NRC 1994) any better than BB spectral data. Despite this conclusion, further research and testing is clearly needed using both BB and NB data at various spatial scales in order to identify strategies through which remote sensing technology may offer a practical advantage for assessing rangeland condition.

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