Can. J. Remote Sensing, Vol. 33, No. 2, pp. 109–115, 2007

Ecological site descriptions and remotely sensed imagery as a tool for rangeland evaluation

Catherine Lee Maynard, Rick L. Lawrence, Gerald A. Nielsen, and Gorden Decker

Abstract. We classified Landsat-7 enhanced thematic mapper plus (ETM+) satellite imagery within ecological site descriptions to identify spectrally anomalous locations and determine whether these correlated with anomalous ground locations. Sites located in the Montana plains were classified by their departure from mean values in tasseled cap brightness, greenness, and wetness components, stratified by ecological site description. The classification had 98% overall accuracy in identifying locations that were or were not outside the norm in productivity and exposed soil for their ecological site description. Success was explained by the high correlations between field measures of productivity and exposed soil compared with tasseled cap components. Using this modeling technique might help rangeland managers identify sites needing more detailed field inventory and (or) management attention.

Résumé. Nous avons classifié des images satellitaires ETM+ de Landsat 7 dans le contexte des descriptions écologiques de site pour identifier les zones spectralement anormales et pour déterminer si ces dernières étaient corrélées avec des zones d'anomalies au sol. Des sites situés dans les plaines du Montana ont été classifiés en fonction de leur écart par rapport aux valeurs moyennes des composantes de brillance, de verdure et d'humidité de l'espace indiciel stratifiées selon la description écologique du site. La classification affichait une précision globale de 98 % pour l'identification des sites qui étaient ou qui n'étaient pas à l'extérieur de la norme en termes de productivité et de sol exposé en fonction de la description écologique du site. Cette bonne performance résultait des fortes corrélations observées entre les mesures de productivité et de sol exposé réalisées sur le terrain comparativement aux composantes de l'espace indiciel. L'utilisation de cette technique de modélisation pourrait aider les gestionnaires de pâturages à identifier les sites nécessitant des inventaires plus détaillés sur le terrain et/ou une attention au plan de la gestion.
[Traduit par la Rédaction]

Introduction

The ecological health, defined as "the degree to which the integrity of the soil and ecological processes of rangeland ecosystems are maintained" (National Research Council Committee on Rangeland Classification, 1994), and sustainability of rangeland used for livestock grazing require effective management, which is dependent upon accurate and timely inventory data to support assessment and monitoring (Graetz, 1987; West and Smith, 1997). Systematic and spatially accurate techniques for consistently evaluating rangeland ecological health over large geographic areas have been slow to emerge due to many practical and institutional obstacles (West and Smith, 1997; Tanser and Palmer, 1999; Hunt et al., 2003).

Spectral data from the Landsat multispectral scanner (MSS), thematic mapper (TM), and enhanced thematic mapper plus (ETM+) sensors have been available and tested as a potential information source for rangeland inventories for over 30 years. Varying levels of success in providing estimates of rangeland cover, biomass, and species composition have been achieved using individual spectral bands, band combinations, and vegetation indices (Graetz et al., 1983; Anderson et al., 1993; Paruelo and Golluscio, 1994; Palacios-Orueta et al., 1999; Thoma et al., 2002). Multispectral imagery, aerial photography, and videography have also been used to distinguish varying soil conditions and to identify the presence of selected invasive plant species often associated with declining ecological stability (Everitt and Nixon, 1985; Tueller, 1989; Everitt et al., 1992; 1995).

The level of detailed species and community type identification and productivity measurements required for input into similarity index calculations commonly used by range managers is not considered within the current or anticipated future capability of moderate-resolution multispectral satellite systems (Hunt et al., 2003). Moderate-resolution satellite imagery also is not directly sensitive to soil organic matter content (Coleman and Montgomery, 1987; van Deventer et al., 1997), which helps to regulate nutrient availability and is closely related to soil quality, litter movement, and soil surface resistance to erosion (Dormaar and Willms, 1998; Brady and Weil, 2000). Spectral response, however, is correlated highly with differences in the relative amounts of exposed soil, and increases in the extent and distribution of exposed soil heterogeneity have been used to indicate declining ecological

Received 12 July 2006. Accepted 26 January 2007.

C.L. Maynard and G. Decker.[1] US Department of Agriculture, Natural Resource Conservation Service (USDA-NRCS), Montana, 1515 East 6th Avenue, Helena, MT 59620, USA.

R.L. Lawrence[2] **and G.A. Nielsen.** Montana State University, PO Box 173490, Bozeman, MT 59717, USA.

[1]Present address: 6700 Springhill Road, Belgrade, MT 59714, USA.
[2]Corresponding author (e-mail: rickl@montana.edu).

stability in rangelands (Cipra et al., 1980; Smith et al., 1990; Todd and Hoffman, 1999; Schlesinger et al., 1990).

Spatial data analyses using standardized geographic information system (GIS) themes such as soil maps, digital elevation models, and hydrography are valuable rangeland inventory and monitoring tools. Models using slope, distance to water, and the distribution of potential vegetation types have been used to calculate carrying capacity and evaluate livestock use patterns (Holecheck, 1988; Hunt et al., 2003). Remote sensing data have been combined with relevant GIS themes to detect changes in rangeland condition in limited experimental situations, but standardized methodologies have not been adopted by rangeland specialists and managers (Maxwell, 1976; Pickup and Chewings, 1988; Henebry, 1993; Creque et al., 1999; Tueller, 2001). This is due in part to the difficulties past researchers have faced in acquiring consistent digitally formatted, appropriately scaled, environmental data that could be readily incorporated into image analysis models. Today, however, ecological site description (ESD) polygons representing unique geographic expressions of environments with differing soil properties and potential vegetation types can be generated using standardized digital soil maps from the Soil Survey Geographic Database (SSURGO) and the soil map unit attributes stored in the National Soil Information System (NASIS) databases. ESDs might also provide a framework for developing remotely sensed directed rangeland evaluations.

Multispectral estimates of vegetation biomass and cover often rely on the normalized differenced vegetation index or its soil-adjusted derivatives (Curran, 1980; Carneggie et al., 1983; Huete, 1988; Richardson and Everitt, 1992; Qi et al., 1994). The tasseled cap orthogonally transformed indices, which produce components of brightness (BI), greenness (GI), and wetness (WI), have also been successfully used to estimate cover and biomass and to identify rangeland sites exhibiting signs of degradation (Graetz and Gentle, 1982; Crist and Cicone, 1984). The tasseled cap BI component has demonstrated sensitivity to differing soil backgrounds and has shown positive correlation with changes in amounts of exposed soil due to decreased green vegetation (Todd and Hoffman, 1999). The moving standard deviation index and the red wavelength (0.63–0.69 µm) have also been used to successfully detect differences between rangeland in an acceptable condition and that in a degraded condition (Tanser and Palmer, 1999).

Our objective was to determine whether variation in brightness, greenness, and wetness within ESDs, as determined from Landsat ETM+ imagery, was correlated with variations in ground measurements of biomass and exposed soil. This method might substantially reduce the time and effort required to conduct rangeland inventories by remotely identifying sites with average or acceptable field conditions and sites that might be indicative of anomalous range conditions and possibly requiring more intensive field inventory.

Methods

Our study sites included 24 ESDs distributed across five Montana ranches (**Figure 1**). Mean annual precipitation ranged from 250 to 480 mm, and the topography varied from steep foothills to rolling plains, with elevations between 460 and 1280 m. The dominant potential grassland vegetation ranged from wheatgrass–fescue–needlegrass to grama–needlegrass–wheatgrass (Shiflet, 1973).

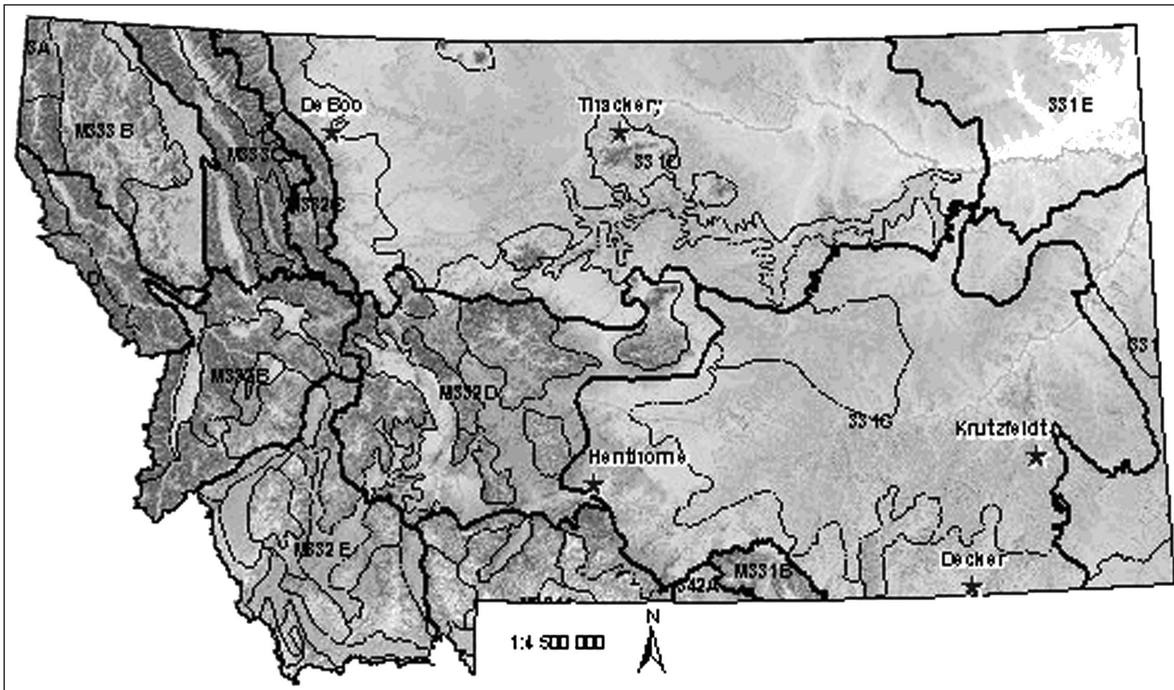

Figure 1. Location of study sites in Montana. The five ranches are indicated by stars. The bold lines are ESD section boundaries, and the lighter lines are ESD subsection boundaries.

Each of the 13 ETM+ scenes analyzed, dating from June 2000 to August 2002, was converted to exoatmospheric reflectance and transformed to the tasseled cap components using the Landsat-7 ETM+ coefficients (Huang et al., 2002). ESD polygons were generated using standard methods developed by the Natural Resource Conservation Service by aggregating individual soil map units based on their published attributes (Shiflet, 1973; Laurenroth, 1979; Natural Resource Conservation Service, 1997).

We classified the imagery by evaluating whether each pixel was within 1.5 standard deviations of the mean for BI, GI, and WI for its ESD. This was accomplished for each ESD by extracting all tasseled cap values for the ESD, calculating the mean and standard deviation for each component, and evaluating the pixel values relative to this standard. We believed that the methodology developed in this study would be more robust if an a priori objective standard could be applied for determining pixels outside the norm, initially defined by two standard deviations, a commonly used statistical measure that, when applied to normally distributed data, would result in approximately 95% of the data being considered within the norm. Our evaluation of a two standard deviation threshold, however, showed that many sites well outside of prevailing conditions were within this range and that sites outside two standard deviations mostly were rock outcrops and water bodies. Conversely, a one standard deviation threshold resulted in numerous data points within prevailing conditions being misclassified as anomalous. Nevertheless, the selection of 1.5 standard deviations was subjective, and an analyst could select a higher or lower value depending on the conditions to be tested; a higher or lower level would result in more or fewer sites being classified as anomalous, and the appropriate standard would have to be applied to ground data for comparison. Sites falling within the standard for all three indices were classified as non-anomalous, and those falling outside for any one index were classified as anomalous. There were no clouds over our sites in any of the images acquired. We therefore were not concerned with clouds being classified as anomalous locations. A cloud mask would be required if this were not the case, as clouds would likely be anomalous in all tasseled cap components.

Field data were collected from 6 June 2000 to 14 August 2002 at 263 plots (plot area 0.75 m^2) randomly located on the five ranches and included measurements of total dry biomass and percentages of exposed soil. Vegetation for each plot was clipped, dried, and weighed to derive total dry biomass, and the percentage of exposed soil was derived as a continuous variable by ocular estimation. Field samples were classified as anomalous or non-anomalous based on their published characteristics (Natural Resource Conservation Service, 2000). Published estimates of plant community productivity include ranges for the categories of “favorable”, “average”, and “unfavorable”, corresponding primarily to average annual precipitation for the growing season. The published ranges for unfavorable were used because extreme drought conditions persisted in all study locations during the field sampling periods (2000–2002). A preliminary assessment was performed to determine an appropriate standard deviation from the mean for field biomass and exposed soil values similar to the assessment made for spectral responses. Use of the same standard deviation threshold for spectral and field measurements was not appropriate because the variability in the measurements was not the same. The field measurements, in particular, had less variability because features such as rock outcrops and water bodies were not sampled. A narrower standard deviation than the 1.5 applied to spectral data was, therefore, more appropriate, and one standard deviation was applied for field biomass and exposed soil values. Sites falling within the standard deviation threshold for field biomass and exposed soil were classified as non-anomalous, and those falling outside for either measurement were classified as anomalous. The classifications of anomalous or non-anomalous sites were compared in a standard error matrix for agreement, with field values used as reference values for error assessment.

Results and discussion

Of the 263 sample points collected over the 3-year period, 191 (72%) occurred within spectrally non-anomalous pixels for each of their respective ESDs and image dates. The remaining 72 field data points (28%) were located in anomalous pixels. There was substantial variation in mean tasseled cap responses among the 24 ESDs sampled (**Table 1**).

For pixels classified as non-anomalous, three locations were determined to be misclassified, as the site attributes measured were outside one standard deviation for the mean of either productivity or exposed soil for their respective ESDs. Vegetation on one of these sites was dominated by Russian thistle (*Salsola kali*), and productivity was within the established average; the exposed soil, however, which made up 85% of the plot, was substantially higher than the mean. The two other misclassified non-anomalous points exhibited exposed soil percentages within the average range but lower than average biomass at the time of sampling. Both of these sites were grazed between the image and field collection dates. A single data point was erroneously classified as anomalous, having field values within average for both productivity and exposed soil. An examination of the BI, GI, and WI values for this pixel indicated the GI was slightly under the 1.5 standard deviation threshold. The classification accuracy assessment performed on the anomalous and non-anomalous categories resulted in an overall accuracy of 98.4% (**Table 2**).

An examination of our sites revealed several common types of anomalies. Field sites with low BI combined with high or mean GI and WI exhibited higher than average relative productivity and lower than average exposed soil percentages. Included among these were sites where native rangeland had been converted to cultivated alfalfa and crested wheatgrass and inclusions of shrub communities within ESDs otherwise dominated by grass communities (**Figure 2a**). Productivity on sites with low brightness and high greenness and wetness

Table 1. Mean and standard deviation of tasseled cap components and number of plots for each of the ecological site descriptions (ESD) in the study.

	Brightness, BI		Greenness, GI		Wetness, WI		No. of
ESD	Mean	SD	Mean	SD	Mean	SD	plots
1	0.364	0.031	–0.027	0.025	–0.228	0.039	12
2	0.360	0.015	–0.040	0.016	–0.235	0.026	9
3	0.352	0.022	–0.017	0.042	–0.207	0.048	11
4	0.344	0.024	–0.025	0.022	–0.205	0.029	19
5	0.383	0.022	–0.017	0.054	–0.215	0.054	11
6	0.383	0.031	–0.080	0.008	–0.218	0.024	3
7	0.369	0.004	–0.013	0.044	–0.184	0.044	2
8	0.395	0.034	–0.028	0.026	–0.237	0.020	3
9	0.382	0.024	–0.010	0.032	–0.224	0.040	12
10	0.370	0.035	–0.037	0.031	–0.228	0.051	10
11	0.438	0.019	–0.066	0.012	–0.305	0.035	3
12	0.434	0.033	–0.078	0.014	–0.289	0.026	17
13	0.389	0.040	–0.046	0.056	–0.257	0.066	5
14	0.459	0.011	–0.089	0.010	–0.323	0.013	2
15	0.407	0.042	–0.053	0.028	–0.267	0.044	44
16	0.397	0.028	–0.046	0.045	–0.240	0.093	30
17	0.407	0.053	–0.049	0.058	–0.252	0.086	4
18	0.408	0.086	–0.058	0.020	–0.265	0.055	3
19	0.402	0.043	–0.066	0.018	–0.267	0.031	8
20	0.376	0.020	–0.044	0.022	–0.241	0.034	7
21	0.416	0.046	–0.069	0.018	–0.269	0.040	36
22	0.366	0.005	–0.053	0.010	–0.223	0.019	2
23	0.399	0.047	–0.067	0.015	–0.275	0.055	6
24	0.375	0.021	–0.033	0.025	–0.233	0.041	4

Table 2. Error matrix for tasseled cap classification of anomalous and non-anomalous spectral categories.

	Reference data		
Classified data	Anomalous	Non-anomalous	Total
Anomalous	71	1	72
Non-anomalous	3	188	191
Total	74	189	263

Note: The producer's accuracy was 71/74 = 95.9% for anomalous sample points and 188/189 = 99.0% for non-anomalous sample points; the user's accuracy was 71/72 = 98.6% for anomalous sample points and 188/191 = 98.4% for non-anomalous sample points. The overall accuracy was (71 + 188)/263 = 98.4%, with a kappa statistic of K_{hat} = 0.96.

ranged from 2000 to 3000 kg/ha, and high amounts of litter covered the soil surfaces.

Sites characterized by values within 1.5 standard deviations of the mean BI combined with low or mean GI and WI had consistently less than average productivity, with exposed soil ranging from 35% to 80%. Spectral classes also characterized by values within 1.5 standard deviations of the mean BI, but with GI and WI within or greater than the 1.5 standard deviation threshold, had above-average productivity, yet exposed soil percentages within the average for their ESD.

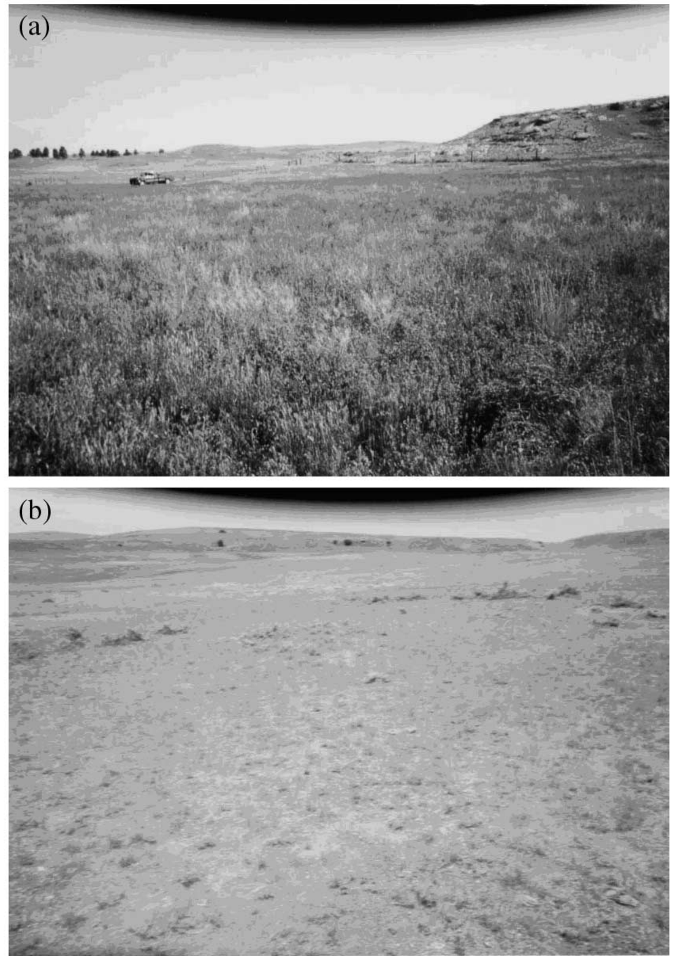

Figure 2. Certain anomaly classes were common. (a) Sites with a low brightness component but high greenness and wetness components had above-average total dry biomass and below-average percent bare soil. (b) Sites with a high brightness component but low greenness and wetness components had below-average total dry biomass and above-average percent bare soil.

Sites within this group included riparian or shrub communities and sites with limited or no grazing use.

A final group of anomalies was distinguished by having high BI values combined with average or low GI and WI values. These sites were characterized by low productivity (overall average of 375 kg/ha) and higher than average percentages of exposed soil (> 60% overall) for their respective ESDs (**Figure 2b**). Sites within this group included prairie dog towns, locations with active soil erosion, and pastures with concentrated grazing use.

This remotely sensed screening of rangeland successfully identified sites within the range of average values for biomass and exposed soil, which can be considered proxies for relative productivity and site–soil stability. The success of this method is largely explained by the correlation between tasseled cap components and the field measurements. Biomass was found to be significantly correlated with both GI and WI (**Figure 3**), and exposed soil was significantly correlated with each of the tasseled cap coefficients (**Figure 4**; all p-values < 0.05). The

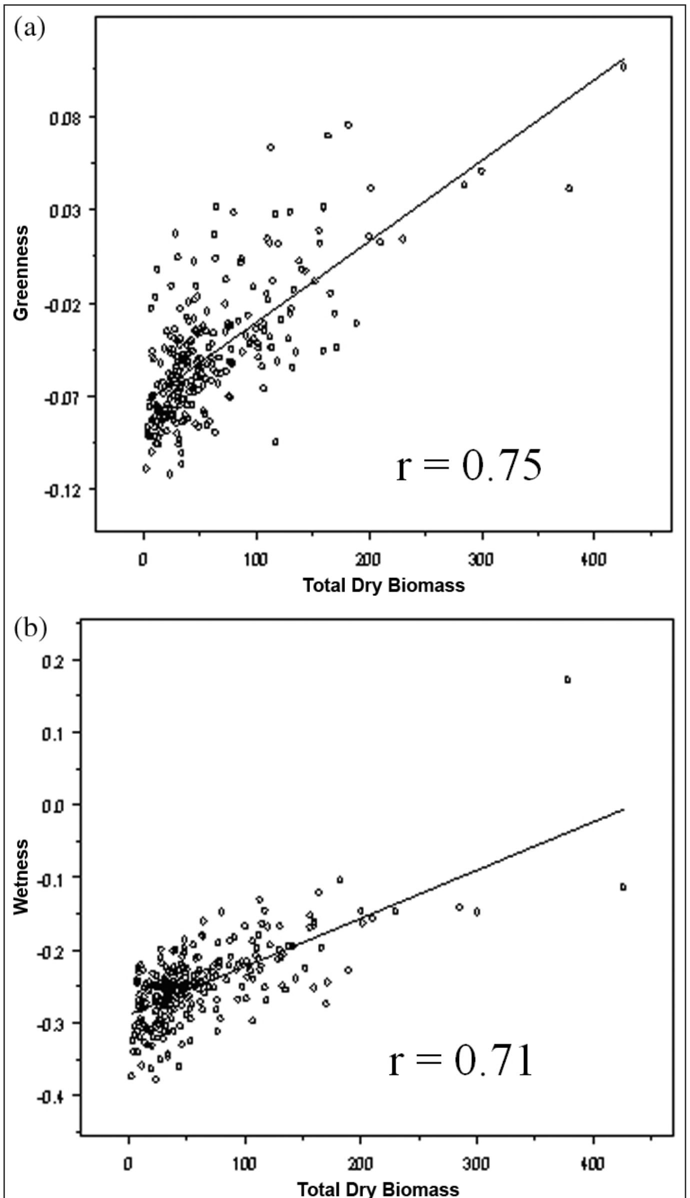

Figure 3. Plots of total dry biomass (in kg/ha) measured in the field against tasseled cap (a) greenness and (b) wetness components derived from Landsat data.

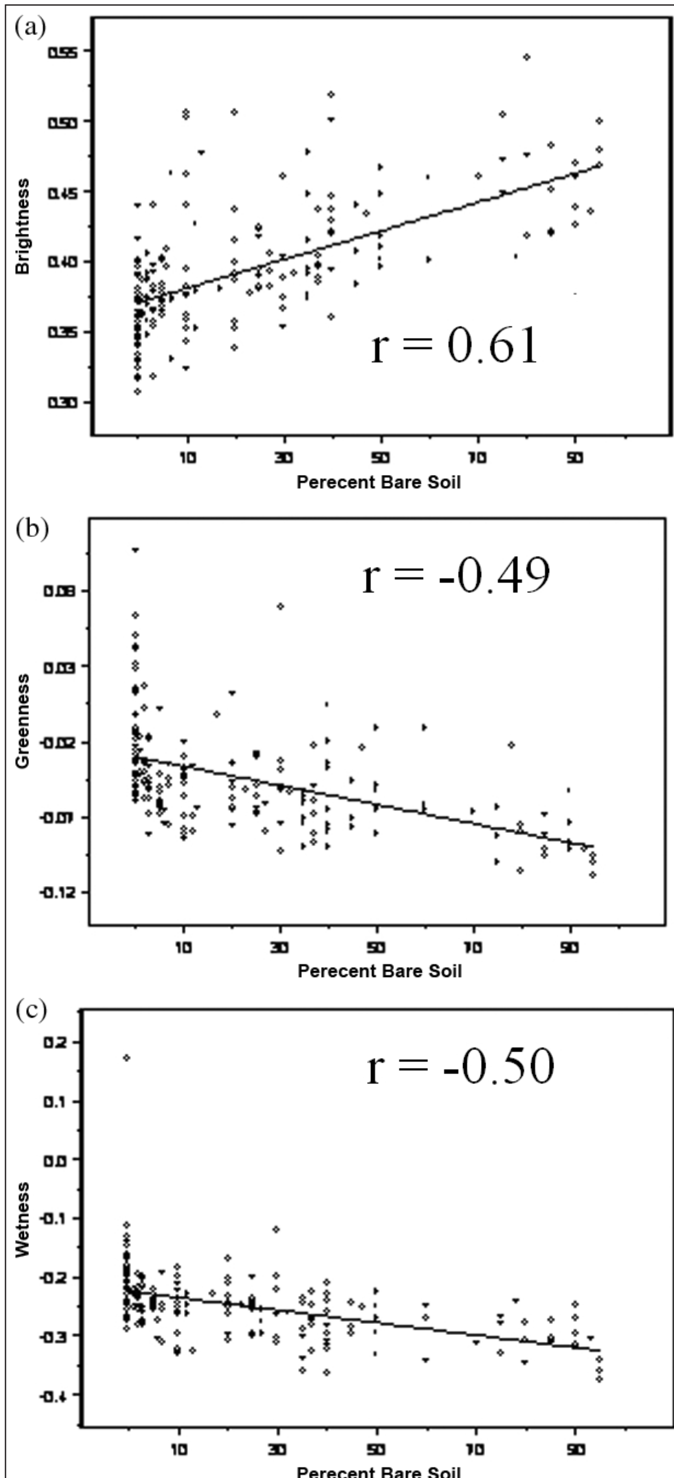

Figure 4. Plots of percent bare soil measured in the field against tasseled cap (a) brightness, (b) greenness, and (c) wetness components from Landsat data.

reliability of this method over highly diverse rangeland environments suggests it has the potential to improve the efficiency of rangeland inventories. Field inventory efforts can be prioritized by status and location by identifying sites within normal ranges for biomass and exposed soil, and areas of management concern might be identified more quickly and consistently.

Users of this method should take special care in determining thresholds for classifying sites and pixels as anomalous. The thresholds used with our imagery and field sites were determined post priori and are therefore specific to these spectral and field data. Future research needs to be conducted to find more objective means for such determinations.

This method accounts for site potential and spectral response differences by making comparisons between spectra and field conditions within locations expected to have similar soil backgrounds and vegetation types. This enables linking spectral response to distinctions among these units in sensitivity and resiliency and with differing responses to natural and management-related use and disturbance (Bestelmeyer et al., 2003).

The sensitivity of this spectral analysis method to site distinctions in soil background and relative productivity allows flexibility in refining the spectral sensitivity thresholds (standard deviations) of each tasseled cap component and gives the range manager the opportunity to adjust field class parameters to further distinguish site differences. It also provides a consistent baseline of spectral and site data that can be used for monitoring change over time. Highly productive or underutilized sites can be identified easily and assessed in relationship to adjacent use and management patterns. Images from different dates can be compared using the same spectral criteria and field parameters to detect changes over a growing season and between years that are needed for monitoring. Values for tasseled cap components are scene and date dependent because of atmospheric variability. This method, however, compares values within ESDs contained within individual scenes to the mean values within each ESD and therefore is a relative assessment not affected by scene-to-scene or date-to-date variations.

This method also identifies sites outside the range of normal conditions for the selected indicators. The remote identification of the extent and distribution of these rangeland characteristics might identify locations that require comprehensive site evaluations and those where existing field data are sufficient. This information could greatly increase the efficiency of the field time of land managers. There is the potential, as with all classifications, of false positives and false negatives. The primary impact of excessive errors in this method would be to decrease the field time advantage created by this method, as field analysts might find themselves examining a purportedly anomalous site that was actually within normal expected ranges.

Extension of this method to other sensors that do not have published tasseled cap coefficients would require the use of other spectral indices. Sensors that lack middle-infrared capability, in particular, would not have an equivalent wetness index. Extension of this method to other sensors and indices is an area that we are continuing to research.

Precision agriculture techniques for farm management have evolved to adopt the use of remote sensing data, global positioning systems (GPS), and digital soil and site mapping to identify management zones, manipulate productivity, and improve the efficiency, accuracy, and ecological sensitivity of farming practices. Rangeland managers, whose resource information questions must be answered for physically large, highly diverse, and often remote locations, have previously lacked the remote sensing and geospatial data analysis tools needed to address their management information needs. Our approach demonstrates the ability to provide accurate site and spectral distinctions that might be used to support the advancement of precision ranching methods.

References

Anderson, G.L., Hanson, J.D., and Haas, R.H. 1993. Derived vegetation indices for estimating above-ground biomass on semiarid rangelands. *Remote Sensing of Environment*, Vol. 45, pp. 165–175.

Bestelmeyer, B.T., Brown, J.R., Havstad, K.M., Alexander, R., Chavez, G., and Herrick, J.E. 2003. Development and use of state-and-transition models for rangeland. *Journal of Range Management*, Vol. 56, pp. 114–126.

Brady, N.C., and Weil, R.R. 2000. *Elements of the nature and property of soils*. 13th ed. Prentice Hall Inc., Upper Saddle River, N.J.

Carneggie, D.M., Schrumpf, B.J., and Mouat, D.M. 1983. Rangeland applications. In *Manual of remote sensing.* Edited by R.N. Colwell. American Society of Photogrammetry, Falls Church, Va. Vol. 2, pp. 2325–2384.

Cipra, J.E., Franzmeier, D.P., Bauer, M.E., and Boyd, R.K. 1980. Comparison of multi-spectral measurements from some non-vegetated soils using Landsat digital data and a spectroradiometer. *Soil Science Society of America Journal*, Vol. 44, pp. 80–84.

Coleman, T.L., and Montgomery, O.L. 1987. Soil moisture, organic matter, and iron content effect on the spectral characteristics of selected vertisols and alfisols in Alabama. *Photogrammetric Engineering & Remote Sensing*, Vol. 53, pp. 1659–1663.

Creque, J.A., Bassett, S.D., and West, N.E. 1999. Viewpoint: delineating ecological sites. *Journal of Range Management*, Vol. 52, pp. 546–549.

Crist, E.P., and Cicone, R.C. 1984. Application of the tasseled cap concept to simulated thematic mapper data. *Photogrammetric Engineering & Remote Sensing*, Vol. 50, pp. 343–352.

Curran, P. 1980. Multi-spectral remote sensing of vegetation amount. *Progress in Physical Geography*, Vol. 4, pp. 315–340.

Dormaar, J.F., and Willms, W.D. 1998. Effect of forty-four years of grazing on fescue grassland soils. *Journal of Range Management*, Vol. 51, pp. 122–126.

Everitt, J.H., and Nixon, P.R. 1985. Video imagery: a new remote sensing tool for range management. *Journal of Range Management*, Vol. 38, pp. 421–424.

Everitt, J.H., Alaniz, M.A., Escobar, D.E., and Davis, M.R. 1992. Using remote sensing to distinguish common (*Isocoma cornophifia*) and Drummon goldenweed (*Isocoma drummondii*). *Weed Science*, Vol. 40, pp. 621–628.

Everitt, J.H., Anderson, G.L., Escobar, D.E., Davis, M.R., Spencer, N.R., and Andrascik, R.J. 1995. Using remote sensing for detecting and mapping leafy spurge (*Euphorbia esula*). *Weed Technology*, Vol. 7, pp. 981–987.

Graetz, R.D. 1987. Satellite remote sensing of Australian rangelands. *Remote Sensing of Environment*, Vol. 23, pp. 313–331.

Graetz, R.D., and Gentle, M.R. 1982. The relationships between reflectance in the Landsat wavebands and the composition of an Australian semi-arid shrub rangeland. *Photogrammetric Engineering and Remote Sensing*, Vol. 48, pp. 1721–1730.

Graetz, R.D., Gentle, M.R., Pech, R.P., O'Callagahan, J.R., and Drewien, G. 1983. The application of Landsat image data to rangeland assessment and monitoring: an example from South Australia. *Australian Rangeland Journal*, Vol. 5, pp. 63–73.

Henebry, G. 1993. Detecting change in grasslands using measures of spatial dependence with Landsat TM data. *Remote Sensing of Environment*, Vol. 46, pp. 223–234.

Holecheck, J.L. 1988. An approach for setting the stocking rate. *Rangelands*, Vol. 10, pp. 10–14.

Huang, C., Wylie, B., Homer, C., and Zylstra, G. 2002. Derivation of a tasseled cap transformation based on Landsat 7 at-satellite reflectance. *International Journal of Remote Sensing*, Vol. 23, pp. 1741–1748.

Huete, A.R. 1988. A soil-adjusted vegetation index (SAVI). *Remote Sensing of Environment*, Vol. 29, pp. 295–309.

Hunt, E.R., Jr., Everitt, J.H., Ritchie, J.C., Moran, S.M., Booth, D.T., Anderson, G.L., Clark, P.E., and Seyfried, M.S. 2003. Applications and research using remote sensing for rangeland management. *Photogrammetric Engineering & Remote Sensing*, Vol. 69, pp. 675–693.

Laurenroth, W.K. 1979. Grassland primary production: North American grasslands in perspective. In *Perspectives in grassland ecology*. Edited by N. French. Springer-Verlag, New York. pp. 3–24.

Maxwell, E.L. 1976. A remote rangeland analysis system. *Journal of Range Management*, Vol. 29, pp. 66–73.

National Research Council Committee on Rangeland Classification. 1994. *Rangeland health: new methods to classify, inventory, and monitor rangelands*. National Academy Press, Washington, D.C.

Natural Resource Conservation Service. 1997. *Range and pasture management handbook*. US Government Printing Office, Fort Worth, Tex.

Natural Resource Conservation Service. 2000. *Soil Survey Geographic Database (SSURGO), and the National Soil Information System (NASIS), soil data viewer, version 1*. US Department of Agriculture, Washington, D.C.

Palacios-Orueta, A., Pinzón, J.E., Ustin, S.L., and Roberts, D.A. 1999. Remote sensing of soils in the Santa Monica Mountains: II. Hierarchical foreground and background analysis. *Remote Sensing of Environment*, Vol. 68, pp. 138–151.

Paruelo, J.M., and Golluscio, R.A. 1994. Range assessment using remote sensing in northwest Patagonia (Argentina). *Journal of Range Management*, Vol. 47, pp. 498–502.

Pickup, G., and Chewings, W.H. 1988. Forecasting patterns of erosion in arid lands from Landsat MSS data. *International Journal of Remote Sensing*, Vol. 63, pp. 515–521.

Qi, J., Chehbouni, A., Huete, A.R., and Kerr, Y.H. 1994. A modified soil adjusted vegetation index. *Remote Sensing of Environment*, Vol. 48, pp. 119–126.

Richardson, A.J., and Everitt, J.H. 1992. Using spectral vegetation indices to estimate rangeland productivity. *Geocarto International*, Vol. 1, pp. 63–69.

Schlesinger, W.H., Reynolds, J.F., Cunningham, G.L., Huenneke, L.F., Jarrell, W.M., Virginia, R.A., and Whitford, W.G. 1990. Biological feedbacks in global desertification. *Science (Washington, D.C.)*, Vol. 247, pp. 1043–1048.

Shiflet, T.N. 1973. Range sites and soils in the United States. In *Arid Shrublands, Proceedings of the 3rd Annual Workshop of the US/Australia Rangelands Panel*, 26 March – 15 April 1973, Tucson, Ariz. Edited by D.N. Hyder. Society for Range Management, Denver, Colo. pp. 26–33.

Smith, M.O., Ustin, S.L., Adams, J.B., and Gillespie, A.R. 1990. Vegetation in deserts: I. A regional measure of abundance from multi-spectral images. *Remote Sensing of Environment*, Vol. 31, pp. 1–26.

Tanser, F.C., and Palmer, A.R. 1999. The application of a remotely-sensed diversity index to monitor degradation patterns in a semi-arid heterogenous, South African landscape. *Journal of Arid Environments*, Vol. 43, pp. 447–484.

Thoma, D.P., Bailey, D.W., Long, D.S., Nielsen, G.A., Henry, M.P., Breneman, M.C., and Montagne, C. 2002. Short-term monitoring of rangeland forage conditions with AVHRR imagery. *Journal of Range Management*, Vol. 55, pp. 383–389.

Todd, S.W., and Hoffman, M.T. 1999. A fence-line contrast reveals effects of heavy grazing on plant diversity and community composition in Namaqualand, South Africa. *Plant Ecology*, Vol. 142, pp. 169–178.

Tueller, P.T. 1989. Remote sensing technology for rangeland management applications. *Journal of Range Management*, Vol. 42, pp. 442–453.

Tueller, P.T. 2001. Remote sensing of range production and utilization. *Journal of Range Management*, Vol. 54, pp. 77–89.

van Deventer, A.P., Ward, A.D., Gowda, P.H., and Lyon, J.G. 1997. Using thematic mapper data to identify contrasting soil plains and tillage practices. *Photogrammetric Engineering & Remote Sensing*, Vol. 63, pp. 87–93.

West, N.E., and Smith, E.L. 1997. Improving the monitoring of rangelands. *Rangelands*, Vol. 19, pp. 9–14.